FOREWORD

This Handbook was prepared by Syracuse University under USAF Contract No. AF 33(616)-7736. This contract was initiated under Project No. 7381, "Materials Application", Task No. 738103, "Materials Information Development, Collection and Processing." The work was administered under the direction of the AF Materials Laboratory, Research and Technology Division with Mr. T. J. Reinhart, Jr., acting as project engineer.

This report covers work conducted from November 1960 to February 1963.

Specific Acknowledgements and appropiate listing of contributors will be found in Manual IA of this handbook. The Associate Editors are indebted to many persons who contributed freely to the efforts of the staff and to representatives of various companies who cooperated enthusiastically and unselfishly.

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ABSTRACT

The purpose of this technical documentary report is to partially satisfy the need for a design handbook specifically tailored for structural plastic applications in aerospace vehicles for the Air Force. This first edition contains a preliminary collection of technical data and information on these materials. The format and organization has been developed, based on consultation with a wide variety of industrial and government concerns, to be rapidly useable and concise. Information presented has been categorized into seven Manuals discussing topics such as material properties, theoretical analysis, design procedures, processing and testing.

This technical documentary report has been reviewed and is approved.

D. A. SHINN
Chief, Materials Information Branch
Materials Applications Division
AF Materials Laboratory

TABLE OF CONTENTS

MANUAL IA ....INTRODUCTION

MANUAL IB ....BASIC DESIGN

MANUAL IC ....PRIMARY MATERIALS

MANUAL ID ....MATERIAL SYSTEMS

MANUAL IE ....THEORETICAL ANALYSIS

MANUAL IF ....PROCESSES AND TOOLING

MANUAL IG ....TESTING AND QUALITY CONTROL

Note: Complete contents of entire handbook will be found in Manual IA. The introduction to each individual Manual gives the contents for that Manual.

MANUAL IA INTRODUCTION	GENERAL DISCUSSION	IA D
	GLOSSARY, ABBREVIATIONS, INDEX, SOURCE REFERENCES	IA G, A, I, S, etc.
MANUAL IB	BASIC DESIGN	IB
MANUAL IC PRIMARY MATERIALS	RESINS	IC R/
	REINFORCEMENTS	IC /R
MANUAL ID MATERIAL SYSTEMS	POLYESTER	ID Po
	EPOXY	ID Ep
	PHENOLIC	ID Ph
	SILICONE	ID Si
		ID
	OTHER	ID O
MANUAL IE	THEORETICAL ANALYSIS	IE
MANUAL IF	PROCESSES AND TOOLING	IF
MANUAL IG TESTING AND QUALITY CONTROL	TESTS	IG T
	QUALITY CONTROL	IG QC

MANUAL IA INTRODUCTION	GENERAL DISCUSSION	IA D
	GLOSSARY, ABBREVIATIONS, INDEX, SOURCE REFERENCES	IA G, A, I, S, etc

0.0 INTRODUCTION

0.01 Purpose of Manual

0.011 The general purpose of this Manual is to present various general items of information pertaining to DIVISION I - Structural Plastics - of the MATERIALS DESIGN HANDBOOK. Such items as summary contents, abbreviations, glossary, specifications and the like are presented.

0.012 As with other Manuals of this handbook the material presented is a result of review of formal and informal literature, published data, personal visits to a majority of the reinforced plastics industry, including all phases, and project developed concepts and procedures.

0.013 The primary purpose of this Manual is to provide a background of philosophy and procedure for the potential user of this handbook division.

0.02 Identification Code

0.021 For the purpose of organization and cross referencing, the information presented in this Manual is divided into sections as indicated in the Table of Contents which follows.

0.022 Each section is coded to identify its contents. The titles indicated in the Table of Contents will clarify this procedure.

0.03 Contents of Manual IA

0.031 This Manual is divided into sections as follows:

Section No.	Subject
0.0	INTRODUCTION....Code: INTRO
1.0	ACKNOWLEDGEMENTS....Code: ACK
2.0	SUMMARY CONTENTS OF DIVISION I....Code: CONT
3.0	BACKGROUND....Code: BACK
4.0	USE OF DIVISION I....Code: USE
5.0	SUMMARY ABBREVATIONS....Code: ABBR
6.0	SUMMARY GLOSSARY....Code: GLOS
7.0	SUMMARY SPECIFICATIONS....Code: SPEC
8.0	SOURCE REFERENCES....Code: REF

0.032 Each of the above sections of this Manual is subdivided as appropriate to its subject.

1.0 ACKNOWLEDGEMENTS

1.01 General

1.011 The first edition of Division I of the Materials Application Handbook would not have been possible without the consistent and untiring efforts of a great many individuals and organizations across the country. Industry, in particular, has voluntarily given advice, information and manpower time. A considerable number of individuals from governmental agencies and industry have given freely of their own time.

1.012 It would be impossible to acknowledge every individid individual or organization. The following only indicates a few of the many to whom the editors owe so much. A complete listing of contributors of data and information will be found in Section 8.0 of this Introduction.

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1.04 Acknowledgement

To the foregoing and to all others who have helped in this work; to the various organizations and industrial concerns without whom this first edition would have been impossible; the editors wish to express their sincere appreciation.

2.0 SUMMARY CONTENTS OF DIVISION I

2.01 General

2.011 This section will present only a summary of the contents of DIVISION I of the handbook. For detailed contents of each Manual, Section 0.03, "Contents", of the Introduction to the Manual in question should be referred to.

2.012 Discussion of various identification codes and subject subdivisions will be found in the Introduction to each Manual.

2.02 Division I Contents

DIVISION I - STRUCTURAL PLASTICS

MANUAL IA	INTRODUCTION	IA
0.0	INTRODUCTION	INTRO
1.0	ACKNOWLEDGEMENTS	ACK
2.0	SUMMARY CONTENTS OF DIVISION I	CONT
3.0	BACKGROUND	BACK
4.0	USE OF DIVISION I	USE
5.0	SUMMARY ABBREVIATIONS	ABBR
6.0	SUMMARY GLOSSARY	GLOS
7.0	SUMMARY SPECIFICATIONS	SPEC
8.0	SOURCE REFERENCES	REF

MANUAL IB	BASIC DESIGN	IB
0.0	INTRODUCTION	INTRO
3.0	LAMINATES - ORTHOTROPIC, FLAT PLATES	LII

MANUAL IC	PRIMARY MATERIALS	IC
0.0	INTRODUCTION	INTRO
1.0*	GENERAL	
2.0*	PHYSICAL AND CHEMICAL PROPERTIES	
3.0*	MECHANICAL PROPERTIES	
4.0*	FABRICATION	

* Subjects repeated for each material

Materials covered in this first edition:

Polyester Resin - General Purpose	Pol

MANUAL ID	MATERIAL SYSTEMS	ID
0.0	INTRODUCTION	INTRO
1.0*	GENERAL	
2.0*	PHYSICAL AND CHEMICAL PROPERTIES	
3.0*	MECHANICAL PROPERTIES	
4.0*	FABRICATION	

* Subjects repeated for each material

Materials covered in this first edition:

Polyester, General Purpose/Glass Cloth	PolGc
Polyester, Improved Property/Glass Cloth	Po2Gc

MANUAL IE	THEORETICAL ANALYSIS	IE
0.0	INTRODUCTION	INTRO
2.0	LAMINATES - ISOTROPIC	LI
3.0	LAMINATES - ORTHOTROPIC, FLAT PLATES	LII
4.0	LAMINATES - BUCKLING	LIII
20.0	FILAMENT WINDING - SIMPLE PRESSURE BOTTLES	FI
21.0	FILAMENT WINDING - BOTTLES WITH END PORTS	FII

MANUAL IF	PROCESSES AND TOOLING	IF
0.0	INTRODUCTION	INTRO
1.0	CONTACT MOLDING	CM
10.0	BAG MOLDING	B
11.0	VACUUM BAG MOLDING	VB
12.0	PRESSURE BAG MOLDING	PB
13.0	AUTOCLAVE BAG MOLDING	AB
20.0	PRESS MOLDING	PM
21.0	PRESS MOLDING - CONTACT PRESSURE	PM-C
22.0	PRESS MOLDING - AGAINST STOPS	PM-S
23.0	PRESS MOLDING - HIGH PRESSURE	PM-H
27.0	CONTINUOUS PROCESS MOLDING	CPM

MANUAL IG	TESTING AND QUALITY CONTROL	IG
0.0	INTRODUCTION	INTRO
2.0	TEST METHODS - PHYSICAL PROPERTIES	T2.
3.0	TEST METHODS - CHEMICAL PROPERTIES	T3.
4.0	TEST METHODS - THERMAL PROPERTIES	T4.
5.0	TEST METHODS - ELECTRICAL PROPERTIES	T5.
6.0	TEST METHODS - MECHANICAL PROPERTIES	T6.
7.0	TEST METHODS-MISCELLANEOUS PROPERTIES	T7.
10.0	SUMMARY OF STANDARD TEST PROCEDURES	S10.

2.03 Discussion

It is emphasized that the contents of this first edition are far from complete with respect to projected and anticipated coverage in Division I. The Table of Contents in the Introduction to each Manual will indicate intended coverage as well as that contained in the first edition. The contents listed above only include those headings under which entries have been made.

3.0 BACKGROUND

3.01 General

The following discussion depicts the history behind the development of this handbook, its contents and its format.

3.02 Preliminary Survey Study

On the basis of the recent survey study, "Information Requirements for Application of Non-Metallic Structural Materials to Aerospace Vehicles" [AF 18 (600)-1876, WADD TR 60-446] completed in 1960, it was concluded that a definite need existed for a handbook, manual, or a series of them, specifically tailored for non-metallic materials applications in aerospace vehicles for the Air Force. Virtually all contacts in industry agreed that a comprehensive effort had to be made to produce such a handbook. Since this effort was and is to fulfill the needs of all types of engineers involved in aerospace vehicle design work, its wide potential acceptance and use is indicated.

It was concluded from the above survey that existing handbooks or mauals fell short of fulfilling the needs of Air Force designers for several basic reasons. First, they were not specifically designed for Air Force applications. Second, they did not incorporate the format and organization of information and data necessary for easy use. Third, and perhaps most important, the information contained in these manuals was too frequently more than several years old and, therefore, of reduced value.

As a result of the current rapid growth of highly specialized materials and design procedures for Air Force applications, the engineers involved in this field must be able to secure pertinent reliable information quickly. The then current predominantly generalized type of handbook necessitated considerable searching by the engineer often resulting in the use of materials and designs not intended for application to his particular problem. The use of general handbooks by the inexperienced engineer could also create additional problems.

It was determined that the task of obtaining, organizing and correlating the immense amount of data available from scattered sources into a handbook, although a vast undertaking, could be accomplished. The need for order and the whole problem of the design and use of non-metallic materials were and are such that a worthwhile attempt would definitely be an improvement over existing conditions. The amount of data available is increasing every day and the task of compiling this information into a handbook will become more and more difficult as time goes on. It was, therefore, felt that it was time to start organizing and presenting existing information in such a handbook, thus making an up-to-date source of information readily available.

The format of data evaluation, organization and presentation was determined to be critical to the acceptance and use of the handbook or manuals. The format, as now adopted is, therefore, carefully designed to meet the needs of the engineer. A general criticism of existing handbooks was that they fail to do this with respect to specific use in the field of Air Force applications.

In the field of non-metallic structural materials, advancements and improvements are made so rapidly that current data quickly becomes obsolete. A minimum delay in dissemination of handbook information was and is therefore essential. For this handbook to be valuable, it <u>must</u> be kept up to date and <u>must</u> be continually revised to include new information.

The survey results indicated a definite need for a handbook on <u>all</u> non-metallic materials applicable to air and space vehicle design. It was obvious, however, that such a book would be voluminous and unwieldy. This was overcome by dividing the handbook into a series of Divisions, each organized for a specific material classification. Furthermore, because of the complexities within one material classification, further division of each into manuals was planned to facilitate use.

Based on the consideration of collected data, the consensus of contacts, and the analysis by project personnel, it was concluded that the general material classification of Structural Plastics was the first handbook Division to undertake. Hence, Division I, Structural Plastics was put under contract by ASD.

The needs of the flight vehicle designer have placed an important and substantial burden on material evaluation and dat dissemination techniques. This burden must be satisfactorily handled to insure the continued growth and influence of non-metallics as engineering materials for structural applications in aerospace vehicles.

In summary, it was concluded from the results of the survey study, contact opinion, and research personnel consideration, that any handbook attempt must include the following features to insure its acceptance and use:

1. Limitation of data and information to specific applications within the field of aerospace vehicle design for Air Force programs.
2. Provision for rapid dissemination of handbook parts to provide up-to-date information.
3. Provision for constant revision and updating of previously published handbook parts.
4. Format design to provide for 1 through 3 above.
5. Format design to provide the greatest possible ease of use of handbook.
6. Provision for data and information in the handbook on all of the following:
   a. General information and application of materials.
   b. Design criteria for specific applications, including human factors where pertinent.
   c. Properties of basic materials and combinations of same.
   d. Stress analysis for specific applications.
   e. Processing information and its influence on properties and design.
   f. Tooling information and its influence on properties and design.
   g. Testing and quality control.
7. Provision for adequate editorial coverage by experts from various industries and agencies.
8. Provision for adequate data and information collection, evaluation, correlation and dissemination to writers and editors.
9. Provision for full, direct and rapid coordination of all handbook parts during all phases of processing and dissemination.

3.03 Outline of Division I Program

It was realized that the task of preparing a handbook and design manual for the use of designers and engineers of aerospace vehicles in the field of structural non-metallic materials would be arduous and could not be accomplished in a short period of time. It was further realized that new data and information were being continuously developed and would need to be included as rapidly as available, in continuously revised sections. The following coordinated and correlated approach was adopted for development of a workable system and format and for preparation of the initial edition of Division I - "Structural Plastics".

The work which was included under this program is outlined as follows:

1. Development of MATERIALS DESIGN HANDBOOK - DIVISION I - STRUCTURAL PLASTICS.
2. Writing of MANUALS IA through IG for a number areas to include flat and curved laminates, plates and filament wound tubes as time and additional data would permit.

3. Further investigation and establishment of format, etc., for above Division.

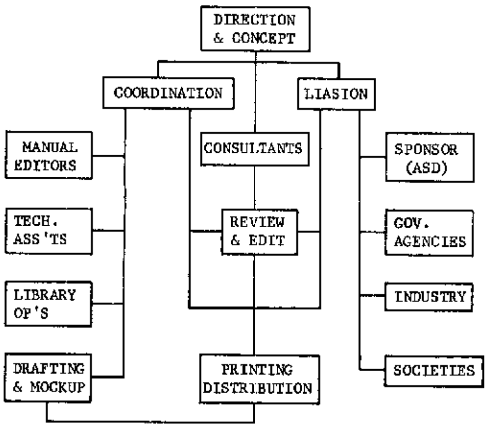
4. Further investigation and establishment of standard data filing systems to permit rapid correlation, evaluation and dissemination of information and data.

5. Continuation of personal contact liaison to obtain information and data and to coordinate production of a "useable" Handbook.

6. Consultants and sub-contracts as required to utilize the best possible sources and to include all available "up-to-date" data.

7. Continued collection and filing of data and information on all types of non-metallic structural materials.

To achieve the foregoing a project organization was built up to function as follows



3.04 Handbook Outline

In order to obtain the features required for a working handbook, careful consideration was given to the outline. As previously indicated, one handbook on the whole subject of non-metallic materials in aerospace vehicle design would be impractical. Therefore, the breakdown of the Handbook into major material divisions was devised as indicated below.

MATERIALS DESIGN HANDBOOK

MAJOR DIVISIONS

DIVISION I -	Structural Plastics
DIVISION II -	Structural Adhesives
DIVISION III -	Structural Ceramics
DIVISION IV -	Other Structural Non-Metallics
DIVISION V -	Structural Combinations of Metallics and Non-Metallics
DIVISION VI -	Secondary Structural Components
DIVISION VII -	Non-Structural Applications (Insulations, Coatings, etc.)

When the organization of any one Division of the Handbook was considered, the features required became particularly important. The requirements and use of a Handbook Division dictate sectionalization by general topic. The breakdown of Division I into a series of Manuals was created as indicated below.

DIVISION I - STRUCTURAL PLASTICS

MANUAL BREAKDOWN

MANUAL IA -	Introduction
MANUAL IB -	Basic Design
MANUAL IC -	Primary Materials
MANUAL ID -	Material Systems
MANUAL IE -	Theoretical Analysis
MANUAL IF -	Processes and Tooling
MANUAL IG -	Testing and Quality Control

As can be seen, additional topic Manuals may be added at a later date if and when deemed necessary and advisable.

A specific philosophy of intended Manual content was developed at the start of the project. This is summarized in the following discussion.

The survey proved that there was a fundamental need for information relative to specific applications of reinforced plastics in structural situations. Past experience, design approach, guides to material selection, and similar items needed to be gathered in one reference. The attempt to accomplish this resulted in Manual IB, Basic Design.

Discussion of applications, etc., involves generalities and broad coverage which, for planning and preliminary design, might be sufficient. However, additional supporting detail is required for complete coverage. Since application involves materials, the designer requires definitive information on those materials involved. To support design and material selection, Manuals IC and ID were conceived to depict Primary Materials and Material Systems respectively. In the majority of cases information on the material systems (resin combined with reinforcements) will be sufficient. However, the materials engineer, in particular, may have a need for more detailed data on the primary materials (resins and reinforcements separately) to assist him in selection and development of new or better combinations.

It is well known that presentation of detailed data on reinforced plastic materials requires a knowledge of both processes and testing methods since material properties are directly affected by both of these. To satisfy this requirement and to support Manuals IB, IC and ID further, Manuals IF and IG were created. IF covers Processes and Tooling while IG presents Testing and Quality Control. These sections will further help the designer, should he desire more detail, but they will be more directly helpful to materials engineer, production or fabrication departments and testing laboratories.

Good design requires knowledge of analysis and the understanding of the theory behind same. To complement the design approach and procedure presented in Manual IB, a discussion of Theoretical Analysis is collected in Manual IE. The development of accepted theory and derivation of design and analysis formulas are presented in condensed and outline form for background of the designer and use by the analyst.

A certain amount of general information is basic to such a comprehensive coverage as attempted in this Handbook. Such information as abbreviations, sources, introduction and the like are collected in Manual IA, Introduction. IA attempts to set the philosophy for the whole series of Manuals and to give the user a "lead in" for them.

3.05 Results

This document contains the results of the first effort to achieve the objectives created as part of the background. It is again emphasized that this is a first attempt and the Handbook is far from complete. Innumerable problems were forthcoming during the project operation. Solutions to these have been attempted, perhaps unsuccessfully in some cases.

However, it is agreed that a start has been made with a positive result. Appropriate continuation will develop the Handbook into a complete document fulfilling all objectives.

One point must be emphasized here. The future fulfillment of objectives by this document will be directly dependent upon and assisted by constructive criticism from those people who receive and conscientiously attempt to use the volume. The assistance of such individuals and organizations is sincerely solicited by those who created this first edition. It is suggested that comments and criticisms be addressed to the Project Engineer at ASD as indicated in the Abstract at the beginning of this volume.

4.0 USE OF DIVISION I

4.01 General

The purpose of this section is to give a brief discussion of the Handbook's organizational format and effective use of same. Appropriate specific details are included in the Introduction to each individual Manual.

4.02 Use by Content

The content of this handbook is organized according to the basic functional activities involved in most phases of the structural plastics endeavor, namely: Design, Analysis, Materials, Processing, and Testing.

4.021 Design

The design function involves planning (preliminary design), design calculation, and selection of materials and processes.

4.021.1 Planning, or preliminary design, requires background knowledge of typical applications and the designs and materials used for same. Part 2, titled Application, of Manual IB contains the type of information necessary for this function. The information is organized according to structural classifications such as various types of laminates, wound structures and the like. A detailed outline of contents is indicated in the Introduction to Manual IB, Code IB INTRO, paragraphs 0.031 and 0.033.

4.021.2 Design calculation requires application of formulas and charts developed by theoretical analysis. Part 1, titled Design, contains the type of information necessary for this function. The information according to structural classifications such as various types of laminates, wound structures and the like. A detailed outline of contents is indicated in the Introduction to Manual IB, Code IB INTRO, paragraphs 0.031 and 0.033.

Support for the design procedures will be found in the Manual on Theoretical Analysis.

4.021.3 Selection of materials and processes requires general knowledge of previous uses and detailed information on specific properties. Information, organized according to structural applications, on previous uses of materials and their typical properties and processes is found in Part 2, titled Applications of Manual IB. The detailed outline of contents is found in the Introduction to this Manual, Code IB, INTRO, paragraphs 0.031 and 0.033.

Specific information on material systems applicable to structural use is organized according to material type in Manual ID. A detailed outline of contents is found in the Introduction to this Manual, Code ID, INTRO, paragraphs 0.02 and 0.034.

To support the data presented on material systems, information on the primary materials is found in Manual IC. A detailed outline of contents is found in the Introduction to this Manual, Code IC, INTRO, paragraphs 0.02 and 0.034.

General information on various processes is found in Manual IF and is organized according to category of process. A detailed outline of contents is found in the Introduction to this Manual, Code IF, INTRO, paragraphs 0.031 and 0.033.

4.022 Analysis

Analysis involves both an understanding of the physical behavior of the materials involved and a detailed knowledge of theoretical approaches and derivations required. This information is found in Manual IE, organized according to structural classification. A detailed outline of contents is found in the Introduction to this Manual, Code IE, INTRO, paragraphs 0.031 and 0.033.

Design procedures and formulas derived in Manual IE are used in Manual IB for various design applications.

4.023 Materials

Structural applications of reinforced plastics requires a detailed knowledge of the properties of material systems, primary materials, processes and testing methods used to obtain the property data.

4.023.1 Presentation of detailed property information is organized according to material classification in both Manual ID, Material Systems and Manual IC, Primary Materials. A detailed outline of contents is found in the Introduction to these Manuals, Codes ID, INTRO, and IC, INTRO, respectively.

4.023.2 Property data is not valuable without knowledge of the process used. The information presented in Manuals ID and IC includes identification of the process used in each case. Process information is organized by category in Manual IF. A detailed outline of contents is found in the Introduction to this Manual, Code IF, INTRO, paragraphs 0.031 and 0.033.

4.023.3 Property data must be supported by knowledge of the test method used. Test methods are cross referenced to Manual IG. A detailed outline of contents is found in the Introduction to this Manual, Code IG, INTRO, paragraphs 0.021 and 0.022.

4.024 Processing

Information on and discussions of various processes applicable to producing structural reinforced plastics are found in Manual IF. A detailed outline of contents is found in the Introduction to this Manual, Code IF, INTRO, paragraphs 0.031 and 0.033.

4.025 Testing

The subject of testing may be considered as involving three areas, namely: individual test methods, standard test procedures, and quality control methods. Information on and discussion of all three of these areas is found in Manual IG. A detailed outline of contents is found in the Introduction to this Manual, Code IG, INTRO, paragraphs 0.021 and 0.022.

4.03 Use by Code

The content of this handbook is organized in such a way that the information on each page is quickly identified by various basic codes. These codes are found in the upper outside corner of each page and identify three areas: Manual, Subject Classification and pages involved.

4.031 Manual Code

Each page is individually identified as to the Handbook Division and Manual in which it is located. An identification code is found in bold face print in the upper outside corner of each page. For example, ID identifies that page as belonging to Division I, Structural Plastics, and Manual D, Material Systems. A complete outline of Division and Manual coding is found in the Summary Contents Section of this Manual, IA.

4.032 Subject Classification

The basic subject contained on the page is coded, also in bold face underlined print in the upper outside corner of each page, by various systems developed for the handbook. These systems identify material, structure type, process, or test method, as appropriate. It will be noted also that each write up uses the same codes to provide a means of cross indexing between various manuals. Detailed discussions of the code systems is found in the Introduction to the appropriate Manuals.

4.033 Page Number

Under the Subject Classification code is an indication of the page number and total pages involved in the particular writeup.

4.04 Use by Format

A two column format with decimal paragraph numbering was adopted to facilitate use of this handbook. The two columns permits incorporation of graphical information immediately adjacent to the text concerning same. Once familiar with the handbook, it will be realized that the same paragraph number will indicate the same topic anywhere within a Manual. The manual introductions clarify this. In addition, each page is thumb indexed with the key for same found immediately in front of Manual IA.

4.05 Use by Insertion

It will be noted that each detail subject covered is contained on its own set of pages and individually coded for reference and location in the handbook. It is suggested, even recommended, that the user take advantage of this system by inserting additional data, information, charts, etc., that he is familiar with and uses often and as he sees fit to assist him in his work.

8.0 SOURCE REFERENCES

8.01 General

This section lists all sources that were considered and used during the compilation of information contained in this first edition of the handbook.

8.02 Organizations

This list includes all sources contacted during both the preliminary survey and the handbook project. Technical data was not received from all of these, but other valuable assistance was.

Acme Resin Corporation
Aerojet-General Corp., Azusa
Aerojet-General Corp., Sacramento
Aeronautical Division, Ford Motor Company
ASD - Aeronautical Systems Division, AFSC, USAF
ARDC - Air Research and Development Command
Allegany Ballistics Laboratory, Hercules Powder Co.
Allied Chemical Corporation, Plastics Division
American Cyanamid Company, Plastics & Resins Division
AIChE - American Institute of Chemical Engineers
American Marietta Company, Adhesive, Resin & Chemical Division
American Reinforced Plastics
ASTM - American Society of Testing Materials
Applied Physics Laboratory, The Johns Hopkins University
Archer-Daniels-Midland Company, Resin Division
ASTIA - Armed Services Technical Information Agency
Atlantic Research Corporation
Atlas Chemical Industries, Inc., Chemical Division

Battelle Memorial Institute
Bendix Corporation
Benson-Lehner Corporation
Birma Manufacturing Co., Inc., Reinforced Plastics Division
Boeing Company, Transport Division
Boeing Company, Aerospace Division
Borden Chemical Company, The
Brunswick Corporation

Cadillac Plastic & Chemical Co.
Carborundum Company, The, Ceramic Fiber Plant
Celanese Polymer Company, Division of Celanese Corporation of America
Chance-Vought Aircraft, Inc., Structures Department
Chemical Process Co.
Ciba Products Corporation
Cimastra Division, Cincinati Milling & Grinding Machines, Inc.
Coast Manufacturing and Supply Co., Plastics Division
Comco Plastics, Inc., Division of Commercial Plastics & Supply Corp.
Commerce, Department of, Office of Technical Service
Continental Diamond Fibre Corp.
Convair Astronautics Division, General Dynamics Corporation
Convair San Diego Division, General Dynamics Corporation
Convair Fort Worth Division, General Dynamics Corporation
Cordo Chemical Corp.
Cordo Molding Products, Inc.
CTL, Incorporated, Division of Studebaker-Packard Corp.
Curtiss-Wright Corporation, Propeller Division

Dama Plastics, Swarthmore Industrial Center
D-C Reinforced Plastics Co.
DeBell & Richardson, Inc., Consulting Engineers
Douglas Aircraft Company, Inc., Santa Monica Division
Dow Chemical Company, The, Midland
Dow Chemical Company, The, Texas Division
Dow Corning Corporation
Dumont Manufacturing Corp.
DuPont, E. I., De Nemours & Company
Durez Plastics Division, Hooker Chemical Corporation

Eastman Chemical Products, Inc., Subsidiary of Eastman Kodak Co.
Esso Research & Engineering Co.

Fabricon Products, Division of Eagle-Picher Co.
Fairchild-Stratos Corp., Aircraft & Missiles Division
Ferro Corporation, Fiber Glass Division
Fibercast Co.
Fiberite Corporation, The, Division of Universal Manufacturing Co.
Food Machinery & Chemical Corporation, Chemicals & Plastics Division
FPL - Forest Products Laboratory, U. S. Department of Agriculture
Formica Corporation
Freeman Chemical Corporation
Furane Plastic, Inc.

General Dynamics Astronautics
General Electric Company, Burlington
General Electric Company, Philadelphia
General Electric Company, Schenectady
General Electric Company, Valley Forge Space Technology Center ell
General Mills, Chemical Division
General Precision, Inc.
General Tire and Rubber Co.
Gibbs Cox, Inc.
Glascoat
Glastic Corporation, The
Glidden Company, The, Plastics
Goodrich Company, B. F.
Goodrich Chemical Company, B. F.
Goodyear Aircraft Corp., Arizona Division
Grumman Aircraft Company

Hamilton Standard, Division of United Aircraft Corp.
Hartford Fibers Company, Division of Bigelow-Sanford Carpet Co.
Haveg Industries, Chemical Materials Division
Hercules Powder Company
Hexal Products, Inc.
Hooker Chemical Corporation, Durez Plastics Division
Honeycomb Corporation
Hughes Aircraft Company

Interchemical Corporation

JPL - Jet Propulsion Laboratory, California Institute of Technology
Johns-Manville
Jones Dabney Company, Resins & Chemicals Division

Kalwal Corporation
KDK Plastics Company
Kelco Company
Kerr Products, Division of Space Equipment Co.

Lamtex Industries, Inc.
Libbey-Owens-Ford Glass Fibers Company
Little, Arthur D., Inc.
Lockheed Aircraft Corporation, California Division
Lockheed Aircraft Corporation, Missiles & Space Division
Lockheed Aircraft Corporation, Georgia Division
Lucidol Division, Wallace & Tiernan, Inc.
Lunn Laminates

MCA - Manufacture Chemists' Association, Inc.
Marine Plastics
Marquart Corporation, The
Martin Company, The
M. I. T. - Massachusetts Institute of Technology
Minerals and Chemicals, Phillip Corporation
Minneapolis-Honeywell Regulator Company, Plastics Research
3M - Minnesota Mining & Manufacturing Company, Zenith Plastics Division
3M - Minnesota Mining & Manufacturing Company, St. Paul
Mobay Chemical Company
Molded Fiber Glass Body Company
Modular Molding Corporation
Monsanto Chemical Company, Plastics Division
Murtex, Inc.

Narmco Research & Development Division, Telecomputing Corp.
Narmco Materials Division, Telecomputing Corp.

NASA - National Aeronautics & Space Administration
NBS - National Bureau of Standards
NSF - National Science Foundation
National Vulcanized Fibre Company
NOL - Naval Ordnance Laboratory
Naval Torpedo Station
Navy Bureau of Aeronautics (Bu Aer)
Navy Bureau of Mines
Navy Bureau of Ships (Bu Ships)
Navy, New York Naval Shipyard d
Navy, Philadelphia Naval Shipyard
Naugatuck Chemical Division, U. S. Rubber Company
North American Aviation, Inc., Rocketdyne Division
North American Aviation, Inc., Missile Division
North American Aviation, Inc., Los Angeles Division
Northrop Corporation, Norair Division

OOR - Office of Ordnance Research, U. S. Army
Omohundro, Paul, Company
OMRO - Ordnance Materials Research Office
Owens-Corning Fiberglass Corporation

Philadelphia Naval Shipyard, Design Division
Pittsburgh Plate Glass Company, Fiber Glass Division
Plastic Products Corporation
PLASTEC - Plastics Technical Evaluation Center
Plastic Tooling Corporation

Quartermaster Research & Engineering Command, U. S. Army

Raybestos-Manhattan, Inc., Reinforced Plastics Division
Raytheon Company, Research Division
Reichold Chemicals, Inc.
Reinhold Engineering & Plastics Company
Ren Plastics, Inc.
Republic Aircraft Corporation
Resistoflex Corporation
Rezolin, Inc.
Robertson, H. H., Company
Rohn & Haas Company
Ryan Aeronautical Company

Shell Development Company
Shell Chemical Company
Sherwin-Williams Company
Sierracin Corporation, The
Smith, A. O., Corporation, Plastics Research Laboratory
Solar Aircraft Company
Southern Plastics Company
STL - Space Technology Laboratories, Inc.
SPE - Society of Plastics Engineers
SPI - Society of Plastics Industry, Inc.
Specialty Resins Company
Standard Insulation Company, Inc.
Stark, H., & Sons
Sundstrand Plastics, Division of Sundstrand Corporation
Swedlow, Inc.
Swift & Company
Sythane Corporation

Taylor Fiber Company
Telecomputing Corporation
Thickol Chemical Corporation
Thompson, H. I., Fiber Glass Company

Union Carbide Corporation
United Merchants Industrial Fabric
United States Rubber Company
United Technology Corporation
U. S. Polymeric Chemical Corporation

Western Plastics Magazine
Wyandotte Chemicals Corporation

Zenith Plastics Company, Division of 3M Co.

5.0 SUMMARY ABBREVIATIONS

5.01 General

This section collects all abbreviations used in the handbook. These are presented in alphabetical order and include all code symbols used in the various indexing or identification systems.

5.02 Alpha Abbreviations

A = Area, cross sectional area.
A = constant
A = Manual A, Introduction, as used in Manual identification code.
A = Stress ratio in fatigue = σ_{alt}/σ_{mf}
a, b = Axes
AB = Autoclave bag molding, as used in process identification code
Abbr = Abbreviation(s)
Ack = Acknowledgment(s)
Alt = Alternating, alternate
ASD = Aerospace Systems Division
Avg = Average

B = Bag molding, as used in process identification code.
B = Manual B, Basic Design, as used in Manual identification code.
b = Bearing (first subscript)
b = linear dimension, usually width
BHN = Brinell hardness number
Btu = British thermal units

C = Cotton reinforcement, as used in material identification code.
C = Degree(s) Centigrate, temperature
C = Manual C, Primary Materials, as used in Manual identification code.
C = Sandwich cores, as used in process identification code.
c = Chopped (when following other lower case letter), as used in material identification code.
c = Cloth, as used in material identification code.
c = Compression (first subscript)
c = Cycle
CM = Contact molding, as used in process identification code.
cm = Centimeter
CP = Centapoises, measure of viscosity.
CPM = Continuous press molding, as used in process identification code.
cu = Cubic

D = Deflection, particularly as used in Manual IG.
D = Density, particularly as used in Manual IG.
D = Diameter
D = Manual D, Material Systems, as used in Manual identification code.
d = linear dimension, usually depth.
dimen = Dimension

E = Manual E, Theoretical Analysis, as used in Manual identification code.
E = Modulus of elasticity
E = Stiffness, particularly as used in Manual IG.
e = edge or end distance
e = Elongation
Ep = Epoxy resin, as used in material identification code.
etc = And so forth

F = Degree(s) Fahrenheit, temperature
F = Force
F = Manual F, Processes and Tooling, as used in Manual identification code.
f = Fatigue (second subscript)
f = Filament, as used in material identification code.
f = Flexure or bending (first subscript)
FI = Filament Winding, Class FI, Simple pressure bottles with and without integral end closures, as used in structure classification code.
FII = Filament Winding, Class FII, Bottles with end ports.
FIII = Filament Winding, Class FIII, Conventional structural applications.
FIV = Filament Winding, Class FIV, Contoured shapes.
FV = Filament Winding, Class FV, Joining of wound structures.
FVI = Filament Winding, Class FVI, Openings in wound structures.
FbI = Fabric Winding, Class FbI, Shingle wound structures, as used in structure classification code.
FbII = Fabric Winding, Class FbII, Tape wound structures, as used in structure classification code.
ft = Foot, feet
ft^2 = Square feet
ft^3 = Cubic feet
ft-lb = Foot pounds
ft/sec = Feet per second
FW = Filament winding, as used in process identification code.

G = Glass reinforcement, standard E or similar, as used in material identification code.
G = Manual G, Testing and Quality Control, as used in Manual identification code.
G = Modulus of rigidity
Glos = Glossary
Gr = Graphite reinforcement, as used in material identification code.
gr = Gram

H = High temperature, as used in material identification code.
H = Horizontal shear, particularly as used in Manual IG.
h = Hoop tension (first subscript)
hr = Hour(s)
hrs = Hours

I = Moment of inertia
(i) = Initial property characteristics
ID = Inside diameter
in = inch, inches
in^2 = Square inches
in^3 = Cubic inches
in/in = Measure of strain, inches per inch
in-lb = Inch pound(s)
in/min = Inches per minute
Intro = Introduction

K = Kip(s), 1000 pounds
K = Stress concentration factor
k = Thermal conductivity, particularly as used in Manual IG.
kg = Kilograms
ksi = Kips per square inch or thousands of pounds per square inch.

L = Length
L = Load
L = Longitudinal
L = Span
L I = Laminates, Class I, Laminates as isotropic materials, as used in structure classification code.
L II = Laminates, Class II, Orthotropic materials in flat plates, as used in structure classification code.
L III = Laminates, Class III, Buckling of laminates.
L IV = Laminates, Class IV, Laminates as curved plates.
L V = Laminates, Class V, Joining of laminates.
L VI = Laminates, Class VI, Openings in laminates.

l = linear dimension, usually length
lb = Pound(s), weight
L/D = Span to depth ratio
l/r = Slenderness radio, length divided by radius of gyration.

M = Constant
M = High modulus, as used in material identification code.
M = Metallic reinforcement, as used in material identification code.
M = Moisture content, particularly as used in Manual IG.
M = Moment, force times a lever arm, bending moment.
m = constant
max = Maximum
MC = Megacycles
mf = Mean, as in mean stress
mil = Military
min = minimum
min = Minute(s), time or angular
MMD = Matched metal die process (same as PM), as used in process identification code.

N = Nylon reinforcement, as used in material identification code.
nom = Nominal
OD = Outside diameter

P = Load, axial load
p = Page
p = Pressure, internal pressure
p = Proportional limit (second subscript)
PB = Pressure bag molding, particularly as used in process identification code.
PC = Post cure, as used in process identification code.
Ph = Phenolic resin, as used in material identification code.
pl = Ply, plies, as in plies of reinforcement in a laminate.
PM = Press molding, as used in process identification code.
PM-C = Press molding-contact pressure, as used in process identification code.
PM-H = Press molding-high pressure, as used in process identification code.
PM-S = Press molding-against stops, as used in process identification code.
Po = Polyester resin, as used in material identification code.
pph = Parts per hundred
ppm = Parts per million
psi = Pounds per square inch

Q = Quality control procedure as used in indexing code.
Q = Total quantity of heat, particularly as used in Manual IG.
q = Quantity of heat per unit time, particularly as used in Manual IG.
QC = Quality control

R = Radius
R = Stress ratio in fatigue = $\sigma_{max}/\sigma_{min}$
r = radius, radius of curvature.
r = Radius of gyration
r = Roving, as used in material identification code.
r = Strain, particularly as used in Manual IG.
rc = Resin content
Red = Reduction
Ref = Reference(s)
Rev = Reversed
RH = Relative humidity, particularly as used in Manual IG.
Rot = Rotating
R/P = Reinforced plastic(s), a combination of resin and reinforcement such as glass cloth, chopped fibers, etc.
rpm = Revolutions per minute

RT = Room temperature
RW = Roving winding, as used in process identification code.

S = Failure (ultimate) stress, particularly as used in Manual IE.
S = Maximum fiber stress, particularly as used in Manual IG.
S = Sandwich parts, as used in process identification code.
S = Silica reinforcement, as used in material identification code.
S = Span, particularly as used in Manual IG.
S = Standard test procedure, as used in indexing code.
S I = Sandwich Construction, Class SI, Honeycomb cores, as used in structure classification code.
S II = Sandwich Construction, Class SII, Foam cores.
S III = Sandwich Construction, Class SIII, Honeycomb plus foam cores.
S IV = Sandwich Construction, Class SIV, Paral Parallel cores.
s = Secant (second subscript)
(s) = Secondary property characteristics
s = Shear (first subscript)
scr = Screw, a fastener
S.E. = Self extinguishing
sec = Second(s), time or angles or temperature
Si = Silicone resin, as used in material identification code.
spec = Specification(s)
sp g = Specific gravity
S-N = Stress vs number of cycles curve for presenting fatigue test results
sq = Square

T = High temperature, as used in material identification code.
T = Temperature
T = Test method, as used in indexing code
T = Thickness
T = Transverse
t = linear dimension, usually thickness
t = Tangent (second subscript)
t = Tension (first subscript)
t = Time
Temp = Temperature
TW = Tape winding, as used in process identification code
Typ = Typical

U = Ultimate (second subscript)
V = Vertical shear, particularly as used in Manual IG.
V = Volan A finish on glass reinforcing material.
VB = Vacuum bag molding, as used in process identification code.
vc = Void content

W = Width
W = Winding process, as used in process identification code.
W_s = Energy of distortion, particularly as used in Manual IE.
w = Density, specific weight
w = Weight
w = Woven roving, as used in material identification code.
XL = Cross laminated
x, y = Axes
y = Yield (second subscript)
z = Strain rate, particularly as used in Manual IG.

5.03 Greek Letters Abbreviations

α = Angle
α = Helix angle
α,β = Axes, particularly as used in Manual IE.

β = Angle

γ = Shear strain

Δ = Change in
δ = Deformation or deflection, particularly as used in Manual IE

ϵ = Direct strain

θ = Angle
θ = Angle of load to major axis of material

μ = Poisson's ratio

Σ = Summation or sum of
σ = Stress, unit stress, direct stress

τ = Shear stress

ϕ = Angle
ϕ = Angular deflection, particularly as used in Manual IG.

5.04 Numeric Abbreviations

I = (Roman Numeral) Division I of the Materials Application Handbook

1 = General purpose, as used in material identification code.

2 = Improved mechanical or thermal properties, as used in material identification code.

3 = Other categories, as used in material identification code.

5.05 Symbol Abbreviations

^{o} = Degrees, angle or temperature

% = Percent

/ = Per, as in in/min

x = By, as in 5in x 3in

$\pm$ = Plus or minus

$\cong$ = Equivalent

$>$ = Greater than, as in $a>b$ or a is greater than b

$<$ = Less than, as in $a<b$ or a is less than b

7.0 SUMMARY SPECIFICATIONS

7.01 General

This section will collect all specifications covering various aspects of reinforced plastics. Since minimum reference to specifications was required in this first edition and since several useful publications exist on the subject, project efforts in this area were delayed until a latter edition is undertaken.

6.0 SUMMARY GLOSSARY

6.01 General

This section will collect all terms requiring definition or discussion to clarify their use throughout the handbook. In this first edition, a minimum of such terms have been used. These are appropriately defined when they are introduced into the text.

MANUAL 1B BASIC DESIGN 1B

0.0 INTRODUCTION

0.01 Purpose of Manual

0.011 The purpose of this Manual is to present various procedures as they are particularly applicable to the design of reinforced plastics as structural materials. Emphasis is placed on those procedures which are most commonly accepted or which provide simplification or time savings in design work. Application of theoretical analysis developed in Manual IE is discussed in this Manual. In addition helpful design charts and tables are included.

0.012 Included in this first edition of Manual IB are discussions of only the more basic laminated materials. Future editions will expand coverage to include additional material forms as well as typical applications and the like.

0.013 The information included herein has been developed from the results of published work on research programs and basic design texts. However, considerable influence of actual design procedures as used within industry has been allowed where deemed appropiate and worthwhile. When future editions expand writeups to include application and the like, the bulk of the material presented will be drawn directly from industry experience and files on actual performance data.

0.014 Where appropiate, alternative approaches to design are presented and discussed. Also, suggestions are made for the individual development of design aids based on the user's own needs and desires.

0.015 It is considered unnecessary to detail each mathematical or elementary step in the development of a design approach. These are left to the reader.

0.02 Identification Code

0.021 For purposes of organization and cross reference the information presented in this Manual is divided into sections as indicated in the table of contents which follows.

0.022 Each section is coded to identify the structural form of the material and the analysis involved. The titles indicated in the table of contents will clarify this procedure.

0.023 The coding system in this Manual follows that used in Manual IE.

0.03 Contents of Manual IB

0.031 This Manual is divided into two Parts and each part further divided into Sections as follows:

Section No.	Subject
0.0	INTRODUCTION
Part 1:	DESIGN
2.0	LAMINATES, Class L II Laminates as Isotropic Materials
3.0	LAMINATES, Class L II Orthotropic Materials in Flat Plates
4.0	LAMINATES, Class L III Buckling of Laminates
5.0	LAMINATES, Class L IV Laminates as Curved Plates
6.0	LAMINATES, Class L V Joining of Laminates
7.0	LAMINATES, Class L VI Openings in Laminates
20.0	FILAMENT WINDING, Class F I Simple Pressure Bottles with and without Integral End Closures
21.0	FILAMENT WINDING, Class F II Bottles with End Ports
22.0	FILAMENT WINDING, Class F III Conventional Structural Applications
23.0	FILAMENT WINDING, Class F IV Contoured Shapes
24.0	FILAMENT WINDING, Class F V Joining of Wound Structures
25.0	FILAMENT WINDING, Class F VI Openings in Wound Structures
30.0	FABRIC WINDING, Class Fb I Shingle Wound Structures
31.0	FABRIC WINDING, Class Fb II Tape Wound Structures
40.0	SANDWICH CONSTRUCTION, Class S I Honeycomb Cores
41.0	SANDWICH CONSTRUCTION, Class S II Foam Cores
42.0	SANDWICH CONSTRUCTION, Class S III Honeycomb plus Foam Cores
43.0	SANDWICH CONSTRUCTION, Class S IV Parallel Cores
Part 2:	APPLICATION
102.0	LAMINATES, Class L II
103.0	LAMINATES, Class L II
104.0	LAMINATES, Class L III
105.0	LAMINATES, Class L IV
106.0	LAMINATES, Class L V
107.0	LAMINATES, Class L VI
120.0	FILAMENT WINDING, Class F I
121.0	FILAMENT WINDING, Class F II
122.0	FILAMENT WINDING, Class F III
123.0	FILAMENT WINDING, Class F IV
124.0	FILAMENT WINDING, Class F V
125.0	FILAMENT WINDING, Class F VI
130.0	FABRIC WINDING, Class Fb I
131.0	FABRIC WINDING, Class Fb II
140.0	SANDWICH CONSTRUCTION, Class S I
141.0	SANDWICH CONSTRUCTION, Class S II
142.0	SANDWICH CONSTRUCTION, Class S III
143.0	SANDWICH CONSTRUCTION, Class S IV

0.032 Only the initial section on the design of Laminates, Class LII is included in this first edition. However, the Table of Contents will indicate future expanded coverage.

0.033 Each Section of this Manual is sub-divided into major subjects as follows:

Part 1: DESIGN

Paragraph	Subject
2.0	SECTION TITLE
2.01	Introduction
2.02	Design for Axial Loads
2.03	Design for Flexure
2.04	Design for Shear
2.05	Design for Load Combination
2.06	Design for Load Duration
2.061	Short Time - Impact
2.062	Long Time - Creep
2.063	Repeated - Fatigue
2.07	Design for Environmental Effects
2.071	Elevated Temperature
2.072	Low Temperature
2.073	Atmosphere
2.08	Design for Concentration Effects
2.09	Typical Design Charts

Part 2: APPLICATION

Paragraph	Subject
102.0	SECTION TITLE
102.01	Introduction
102.02	Description
102.03	Typical Applications
102.031	Past
102.032	Present
102.033	Future

102.04	Structural Analysis
102.041	Potential Loading Conditions
102.042	Potential Environmental Conditions
102.05	Typical Applicable Materials
102.06	Typical Applicable Production Methods
102.07	Typical Applicable Quality Control and Testing Procedures

0.034 It will be noted that for each structural classification one paragraph number will always indicate the same subject. This will facilitate the use of this Manual.

0.035 It will be further noted that the section numbers for Parts 1 and 2 parallel each other being different only in the addition of 100 to those in Part 1 to derive those in Part 2.

0.036 For complete Table of Contents for the entire Handbook, see Manual IA.

0.04 Abbreviations and Glossary

0.041 The procedure for various symbols adopted in this Manual is identical to that used in Manual IE. The system involved is adopted from accepted procedures familiar within industry and research.

0.041.1 Standard symbols for design are as follows:

A	= cross sectional area
A	= constant
C	= constant
E	= Modulus of elasticity
F	= Force
G	= Modulus of rigidity
I	= Moment of inertia
K	= constant
L	= Length
m,M	= Constant
P	= Axial load
Q	= constant
S	= Failure (ultimate) stress
t	= Thickness
W_s	= Energy of distortion
α,β,θ,ϕ	= Angles
γ	= Shear strain
δ	= deformation or deflection
ϵ	= Direct strain
μ	= Poisson's Ratio
Σ	= Sum of or summation
σ	= Direct stress
τ	= Shear stress
$\cong$	= Equivalent

0.041.2 These symbols are modified by subscripts relating the symbol to a set of coordinate axes or classifying the symbol as to type of item identified. These are clarified in the text or as indicated in Manual ID, Introduction, Section 0.04.

0.042 For complete listing of all abbreviations and definitions used throughout the handbook, see Manual IA.

0.05 Information Sources

0.051 Where particularly important, the information source is footnoted directly within the text.

0.052 A complete source index is given in Manual IA.

3.0 DESIGN OF FLAT PLATE LAMINATES

3.01 Introduction

3.011 This section discusses the design of Laminates Class L II in flate plate configurations. Class L II refers to laminates as orthotropic materials and includes those laminates composed of resin reinforced with woven cloth of fiberous-glass or similar material. A discussion of the theoretical analysis of this class of laminates will be found in Section 3.0 of Manual IE.

3.012 Glass reinforced plastics are a group of modern materials that have achieved wide acceptance in the aircraft industry as structural materials mainly on the basis of their high strength to weight ratios. The combination of materials discussed in this section are orthotropic exhibiting physical and mechanical properties that vary according to the orientation of load direction with respect to that of the reinforcement. Therefore, designers must always be mindful of the direction of the loading. On the other hand, this property of these materials permits them to be tailored to meet a wide variety of design requirements. There are almost no factors related to design criteria that increase the strength; all of them lower the strength below the values obtained at room temperature under standard conditions.

3.02 Design for Axial Loads

3.021 Introduction

3.021.1 When glass cloth or filaments are used as reinforcement for plastics, the resulting properties of the combination provide strengths which make them excellent load carrying materials. The strengths, however, depend upon the orientation of load with respect to the direction of reinforcing. In addition to this dependency, the stress-strain curve shows some interesting characteristics. For some combinations of resin and reinforcement, stress may be taken as proportional to strain up to failure. However, for other combinations, the stress-strain curve exhibits a break requiring two proportionality constants to define the relation between stress and strain. These constants are known as the initial and secondary elastic moduli; the secondary value being smaller than the initial value. Specific stress-strain curves illustrating the foregoing will be found in Sections 3.03 and 3.04 of Manual ID.

3.021.2 Application of preload to a reinforced plastic laminate may result in properties and in a stress-strain curve that are substantially different from those that are obtained under initial loading. When the effect of a preload results in an increase in the value of the properties, use of initial values will be conservative. On the other hand, if preloading reduces the values, the design must be based on the lower values.

3.021.3 Several possibilities exist for the design of members subjected to axial loads. Choice of the method must be based on the design data that is available, the extent to which load conditions are known, and the time available to complete the computations.

3.022 Design Analysis - Tension

3.022.1 The simplest method of design for axial load is based on the generally known relationship:

$$A = \frac{P}{\sigma_{all}}$$

Where: A = Required cross-sectional area
P = Axial load to be carried
σ_{all} = Allowable stress for the material subjected to the particular kind of axial load involved.

3.022.2 If the axial load is tension, the allowable stress will depend on:

a. The resin and reinforcing used in fabricating the laminate (Tabular values of strengths, etc. of various combinations of resin and reinforcing may be found in Manual ID.);
b. The angle which the load makes to the principal axes of the laminate;
c. The duration of the loading from short to long time (See Section 3.06);
d. The temperature and other conditions of the environment to which the member will be subjected (See Section 3.07);
e. The number of times the load may be repeated (see Section 3.06);

It should be noted that many of these factors have not been evaluated sufficiently to provide the specific information the designer needs to arrive at a design stress.

3.022.3 Example Calculation

Given: 5 K axial tension load applied at $\theta = 45$ PolGc (Selectron 5003/143-114, 26 pl, 0.25 in) laminate
Required factor of safety = 2
Reference: Manual ID - PolGc - Figs 3.031.2 and 3.061.1
Manual IE - LII - Fig 3.051a, Eq 3.044.2
Find: Required cross-sectional area and width and the change in length under load.
Calculations:
From Manual ID Figs referenced above:
at $\theta = 0$, $\sigma_{tu} = 88$ksi and at $\theta = 90$, $\sigma_{tu} = 8$ksi
at $\theta = 0$, $\sigma_{su} = 11$ksi
From Manual IE Eq 3.044.2:

$$\frac{1}{S_{45}^2} = \frac{\cos^4\phi}{S_\alpha^2} + \frac{\sin^4\phi}{S_\beta^2} + \frac{\sin^2\phi\cos^2\phi}{T_{\alpha\beta}^2}$$

$$\frac{1}{S_{45}^2} = \frac{1/4}{(88)^2} + \frac{1/4}{(8)^2} + \frac{1/4}{(11)^2}$$

or $S_{45} = 12.9$ksi

(Ed. Note: This computation illustrates the application of the failure equations developed in Manual IE. It will be noted that Fig. 3.031.2 in Manual ID-PolGc gives a value for σ_{tu} at $\theta = 45$ of 12 ksi (+). This gives at least one indication of the validity of the equation.)

With a laminate thickness of 0.25 in and a factor of safety of n = 2:

$$A = \frac{P}{\sigma_{tu}/n} = \frac{5}{12.9/2} = 0.775 \text{ sq in}$$

therefore: width = A/t = 0.775/0.25 = 3.1 in... Ans

Elongation may be determined by using Fig. 3.051a in Manual IE which gives a value for $E_{45} = 1.2 \times 10^3$ ksi; therefore:

$$\Sigma = \frac{P}{AE} = \frac{5}{0.775 \times 1.2 \times 10^3} = 0.0054 \text{ in/in...}$$ Ans

3.022.4 When other factors mentioned in Section 2.022.2 must be considered in design, their effect will be to change the design stress from the value 12.9/2 ksi used in this example. Elevated temperatures, long term loading, wet environment or repeated loadings will tend to decrease this design stress. Indications of their effects may be found in the appropriate sections of Manual ID and later in this manual.

3.023 Design Analysis - Compression

3.023.1 For short compression members, a design approach similar to the foregoing may be applied. The Philadelphia Navy Yard has developed additional procedures for handling design through the use of charts which are discussed in a later Section.

3.023.2 When the compression member is long and slender, its stability must be considered. For the present, Euler's equation for critical stress offers the best approach to design in this case. This equation gives the critical buckling stress, σ_{cr}, of a long, slender member as:

$$\sigma_{cr} = \frac{\pi^2 E}{(\frac{L}{r})^2}$$

Where: E = Modulus of Elasticity in ksi
L = Unsupported length of the member in inches
r = Radius of gyration of the cross-section in inches
σ_{cr} = Stress at which elastic buckling is imminent in ksi

For design purposes, a factor of safety, n, must be applied resulting in $\sigma_{all} = \sigma_{cr}/n$. However, σ_{all} (allowable stress) cannot be greater than the compressive stress permitted when there is no danger of buckling.

Since σ_{cr} is inversely affected by $\frac{L}{r}$, the values of L and corresponding r must be chosen to make L/r a maximum.

3.023.3 Example Calculation

Given: 2K axial compression load applied at θ = 45 PolGc (Selectron 5003/143-114, 26 pl, 0.25 in) laminate
L = 15 inches
Required factor of safety = 2

References: Manual IE-LII, Fig. 3.051a

Find: Required cross-sectional area and width

Calculations:
From Manual IE, Fig 3.051a, $E_{45} = 1.2 x 10^3$ ksi and "r" for rectangular section $= \sqrt{I/A}$:

$$\sigma_{all} = \frac{\pi^2 E}{n\ (\frac{L}{r})^2} = \frac{\pi^2 \times 1.2 \times 10^3}{2\ (\frac{15}{r})^2}$$

where: $r = \sqrt{I/A} = \frac{t}{\sqrt{12}} = \frac{0.25}{\sqrt{12}}$

therefore: $\sigma_{all} = 1.37$ ksi

$$A = \frac{P}{\sigma_{all}} = \frac{2}{1.37} = 1.46 \text{ sq in}$$

therefore: width = A/t=1.46/0.25 = 6 in...Ans

3.024 Design Analysis - Composite Laminates

3.024.1 If the member is composed of a more than one laminate bonded together in a composite in such a way that one set of laminates have their properties oriented in one direction, and another set in another direction, the approach to design may be any one of several possibilities.

3.024.2 When axial load is applied to the composite, the procedures previously given may be followed if the properties of the composite are known in the direction of load. These properties may most easily be determined from a simple testing.

3.024.3 When the properties of the composite laminate are not known in the direction of the loading, but are known for the principal axes of each laminate, the equations or charts of Manual IE may be used to determine the properties in the direction of loading for each laminate separately, and then combined through the concept of the transformed section as outlined in Manual IE Section. In applying the transformed section concept to a composite laminate, the following example illustrates the approach.

3.024.4 Example Calculation

Given: Composite shown in Fig. 3.024.4 formed of two laminates, "n" and "p", each with a different orientation. Laminate "n" = PolGc (143-114)

$E_{\alpha n}$ = 4,400,000 psi.
$E_{\beta n}$ = 1,350,000 psi.
E_{45n} = 1,340,000 psi.
$\mu_{\alpha\beta n}$ = 0.22
$\mu_{\beta\alpha n}$ = 0.06

Laminate "p" = PolGc (181-114)

$E_{\alpha p}$ = 2,900,000 psi.
$E_{\beta p}$ = 2,950,000 psi.
E_{45p} = 1,570,000 psi.
$\mu_{\alpha\beta p}$ = 0.107
$\mu_{\beta\alpha p}$ = 0.097

Load = 10K axial tension applied along the x-axis (θ = o)
Width = w = 2 in.

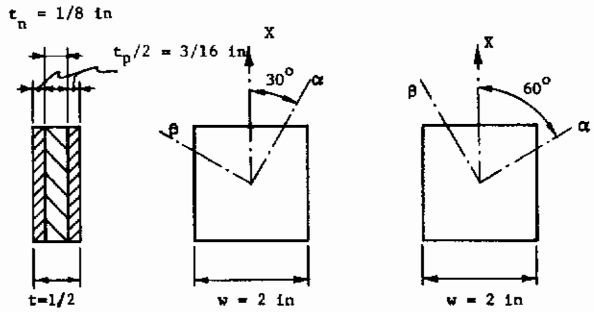


FIG. 3.024.4 COMPOSITE LAMINATE FOR EXAMPLE CALCULATION

References: Manual IE-LII

Find: Stress in each laminate layer

Calculations:
From Manual IE-LII, Eq. 3.041.9b, for laminate "n":

$$\frac{E_\alpha}{G_{\alpha\beta}} = \frac{4E_\alpha}{E_{45}} - \frac{E_\alpha}{E_\beta}(1 - \mu_{\beta\alpha}) - (1 - \mu_{\alpha\beta})$$

$$= \frac{4(4.4 x 10^6)}{1.34 \times 10^6} - \frac{4.4}{1.35}(1-0.06)-(1 - 0.22)$$

$$= 9.26$$

or $G_{\alpha\beta} = \frac{E_\alpha}{9.26} = 475,000 \text{ psi} = G_{\alpha\beta\ n}$

laminate "p" similarly:

$G_{\alpha\beta}$ = 516,000 psi = $G_{\alpha\beta p}$

From Manual IE-LII, Figs 3.051a and 3.051b design charts:

Laminate n:

For properties about the x-axis, $\phi = 30$

$\mu_{xyn} = 0.448$
$E_{xn} = 1,830,000$ psi.
$M_{xn} = +1.97$
$G_{xyn} = 754,000$ psi.

Laminate p:

For properties about the x-axis, $\phi = 60$

$\mu_{xyp} = 0.459$
$E_{xp} = 1,780,000$ psi.
$M_{xp} = 0.745$
$G_{xyp} = 0.949 \times 10^6$ psi.

Laminate n:

For properties about the y-axis, $\phi = 60$

$\mu_{yxn} = 0.303$
$E_{yn} = 1,240,000$ psi.
$M_{yn} = 0.02$
$G_{xyn} = 754,000$ psi.

Laminate p:

For properties about the y-axis, $\phi = 30$

$\mu_{yxp} = 0.457$
$E_{yp} = 1,770,000$ psi.
$M_{yp} = +0.728$
$G_{xyp} = 949,000$ psi.

Now the stress in each laminate may be approximated by transforming the area of laminate "p" to an equivalent area of laminate "n" by use of Eq. 3.045.2 from Manual IE-LII:

$$\text{Equiv. } A_n = A_p \frac{E_{xp}}{E_{xn}} = 2 \times 3/8 \times \frac{1.78}{1.83} = 0.73 \text{ sq in}$$

$$\text{Actual } A_n = 2 \times 1/8 \qquad = 0.25$$

Hence: Total transformed area = 0.98 sq in

therefore:

$$\sigma_n = P/A = 10,000/0.98 = \underline{10,204 \text{ psi}} \ldots\ldots \quad \text{Ans}$$

From Eq. 3.045.1 in Manual IE:

$$\sigma_p = \sigma_n \frac{E_{xp}}{E_{xn}} = 10,204 \frac{1.78}{1.83} = \underline{9,925 \text{ psi}} \ldots\ldots \quad \text{Ans}$$

3.024.5 When a composite laminate of the type shown in Fig. 3.024.4 is subjected to load, the interaction between plies caused by the different physical constants of the plies sets up stresses that are more complex than the analysis presented in the previous section reveals. If these additional stresses are deemed important, the procedure outlined in Section 3.042 of Manual IE is recommended. The following example illustrates this:

3.024.6 Example Calculation

Given: Composite laminate and physical data used in Example in Section 3.022.4.

References: Manual IE-LII, Section 3.042

Find: Evaluate the total stress picture if $\sigma_x = 1000$ psi for the composite described.

Calculations:

Applying the previously computed physical data to Eq. 3.042.4 in Manual IE, results in the evaluation of the various constants, A, as follows:

$$A_{11} = \frac{1}{E_{xn} t_n} + \frac{1}{E_{xp} t_p} = +5.85 \times 10^{-6}$$
$$A_{12} = A_{21} = 2.65 \times 10^{-6}$$
$$A_{13} = A_{31} = 2.89 \times 10^{-6}$$
$$A_{22} = +7.96 \times 10^{-6}$$
$$A_{23} = A_{32} = -0.634 \times 10^{-6}$$
$$A_{33} = +13.43 \times 10^{-6}$$

Substitution of the values of these constants into the equations results in the following set of simultaneous equations:

Equation 1:

$$5.85\sigma_{xn} - 2.65\sigma_{yn} - 2.89\tau_{xyn} = 6000$$

Equation 2:

$$-2.65\sigma_{xn} + 7.96\sigma_{yn} - 0.634\tau_{xyn} = -2750$$

Equation 3:

$$-2.89\sigma_{xn} - \sigma\, 0.634\sigma_{yn} + 3.87\tau_{xyn} = +2740$$

The solution of these equations gives:

$\sigma_{xn} = +1334$ psi
$\sigma_{yn} = +138.3$ psi
$\tau_{xyn} = +498$ psi

The corresponding values for Laminate p may be obtained by substituting the values determined above into Equations 3.042.5 in Manual IE. These results are:

$\sigma_{xp} = +889$ psi
$\sigma_{yp} = -46.1$ psi
$\tau_{xyp} = -166$ psi

3.03 Design for Flexure

3.04 Design for Shear

3.05 Design for Load Combinations

3.06 Design for Load Duration

3.061 Short Time - Impact

3.061.1 The Izod apparatus commonly used for impact testing of homogeneous materials has proven to be unsatisfactory for use with reinforced plastics because they tear and shred. Modifications of this method of test, such as the method using a heavy falling weight directed at the center of a simply supported plate, have resulted in slight, if any, improvement.

3.061.2 Test results obtained by methods employing high rates of strain are more promising and as the strain rate increases, the test approaches closer and closer to impact conditions. Using this technique, Richard Ely has shown that this type of high speed testing has very marked effects on the tensile properties of thermoplastic materials. When strain rates were increased from 1100 in/in/sec to 5000 in/in/sec, the maximum stress increased from 6500 psi to 16,500 psi, ultimate strain decreased from 22 t- 12%, and little change in strain energy was recorded. An inspection of stress-strain curves based on this data clearly indicates that a considerable increase in the modulus of elasticity must have taken place. Advantage may be taken of this phenomenon in design under appropriate loading conditions.

3.062 Long Time - Creep

3.062.1 Reinforced plastics are in the category of visco-elastic materials. Creep of all materials in this category is quite pronounced and becomes increasingly more important as the temperature is elevated.

3.062.2 Creep tests show that at standard conditions cloth laminates endure sustained loads better than either mat or woven roving laminates. When designing for elevated temperatures particularly, a creep problem may be encountered and common practice requires that the design stress be taken at less than 20 to 30 percent of the static ultimate strength of the material. A stressed component, subjected to an aqueous environment, must be designed for even lower stresses. Changes in creep characteristics must also be expected. Furthermore, a cloth laminate suffers greater loss in properties under conditions of creep and moisture than either mat or woven roving.

3.062.3 In tests conducted at the Forest Products Laboratory, a specimen subjected to sustained load for one year along the warp showed only 67 percent of its short-time strength. Tests carried up to four years indicate that the curve of stress vs. time to failure is a straight line on semi-log paper. These tests were carried out for tension, flexure, and shear. The relation between stress, strain, and time to failure appears to be a hyperbolic sine function of stress and an exponential function of time.

3.063 Repeated - Fatigue

3.063.1 Fatigue of a material results from frequent loading and unloading over long periods of time. In the case of metals, the most critical fatigue loading occurs during cycles creating complete reversal of stress. There is some indication that plastics behave differently from metals in that they may tend to deteriorate faster and under fewer cycles of load when an initial preload has been applied. However, there is also evidence to support the opposite conclusion.

3.063.2 Fatigue fracture may be a result of manufacturing flaws, initial cracks, or other defects which serve as the origin of minute cracks. Continued application of the cyclical loading causes these cracks to propagate until failure occurs. Latest theories on crack arrest indicate that stranded materials such as glass fiber reinforced plastics are ideally suited for interrupting the pattern that would otherwise lead to failure. Failure by fatigue may also be caused by disrupting the bond between laminates, but this type of failure is not documented at this time.

3.063.3 In general, reinforced plastics exhibit a fatigue strength of 10 million cycles of loading that is from 20 to 30 percent of their ultimate static strength. Indications are that no endurance limit exists for these materials. Mat reinforcement yields slightly higher strengths when subjected to repeated loads than does cloth reinforcement. There is a tendency for the differences in fatigue strength caused by differences in reinforcement to diminish as the number of load cycles increases; similar to a tendency noted in various resins. Forest Products Laboratory researches have hypothosized, on the basis of these results, that the fatigue strength of all laminates at 10^7 cycles lies between 5 and 15 k.s.i.

3.063.4 The number of cycles of stress that a specimen may sustain prior to failure is influenced considerably by the angle of orientation of fiber to load. Angles not parallel to the natural axes of the material accentuate the fatigue effects. This phenomenon is evidenced by reduced specimen life and is of particular importance when a structural member is fabricated from a number of laminates oriented in different directions. Early breakdown of the element or lower fatigue strength of the part is a result of the differing characteristics of the composite.

3.063.5 Elevated temperatures and water immersion each act to reduce the expected life of reinforced plastics when subjected to fatigue loadings. However, the effect of temperature is less pronounced at high levels of stress than at low levels. When the temperature to which the member is subjected is increased from 70F to 600F at a high stress level, a reduction of 50 percent in fatigue strength may be expected. On the other hand, when the stress level approaches that of the endurance strength and the temperature again is varied between the two extremes, the reduction in strength is between 60 and 80 percent of the original low temperature value.

3.07 <u>Design for Environmental Effects</u>

3.071 Elevated Temperature

3.071.1 It should be realized that elevated temperatures have a two way effect on strength:

a. The effect of the temperature per se, and
b. The effect of temperature combined with time.

This two way effect indicates that strength values for low or room temperature conditions are the only ones really reliable for design purposes. These effects are illustrated in Table 3.071.1 of some typical flexural strength values:

TABLE 3.071.1

Laminate Resin	Flexure Strength - σ_f-Ksi RT	1/2 Hr 500F	Sustained 500F
Epoxy	70	22	18
Phenolic	50	40	20
Polyester	48	30	17
Silicone	35	15	15

3.071.2 It must also be realized that as more information and data are developed on the behavior of reinforced plastics when exposed to elevated temperatures design may be based more reliably on strength values other than for room temperature.

3.072 Low Temperature

3.073 Atmosphere

3.08 <u>Design for Concentration Effects</u>

3.081 Holes and Cut-outs

3.082 Threaded Fasteners

3.083 Adhesive Bonding

3.09 <u>Typical Design Chart</u>

3.091 Introduction. In normal design work, various procedures and calculations often become quite repetitious and routine. Also, if a wide variety of possible solution and data must be considered, the time involved in "search and choose" can become quite considerable. The organization of this Handbook has attempted to reduce the foregoing time as much as feasible. However, additional time savings can be expected by use of appropiately designed charts and tables.

Charts and tables can be made to condense a wealth of information into a concise usable format. Their final design will be completely dependent upon the data involved, the intended use and, perhaps most important, the desires and ideas of the individual user. Custom tailored charts and tables are often much more valuable to the designer than those created by others and considered as "standard".

This Section of Manual IB will present typical charts which have proven valuable to others. These may be used directly by the reader or may serve as nuclei for his own chart creation. The reader is also refered to Manual IE and the analysis charts presented therein. Future editions of this Manual will expand this Section.

3.092 P.N.S. Charts and Their Use

3.092.1 The P.N.S. Charts were develped by the Philadelphia Naval Shipyard in an attempt to combine many of the factors effecting design stresses into a set of equations, tables and charts. Presented here are those used to compute design values when long term loads are applied at some angle to the natural axes. The material presented herein is virtually identical to that supplied by the Philadelphia Naval Shipyard except that terms and symbols have been changed to agree with those used in Manuals ID and IE of this handbook.

3.092.2 Equations. The equations involved in the P.N.S. system are presented in two groups dependent on the range of loading angle to warp.

<u>Curve Range</u>: $\theta = 15$ to 75

$$\sigma = \sigma_a (C_T - K_T \log t)(C_D + K_D) \ldots \text{Eq. } 3.092.2a$$

<u>Interpolation Range 1</u>: $\theta = 0$ to 15

$$\sigma = \sigma_a (C_T - K_T \log t)\left(C_D + K_D \frac{\theta}{15}\right) \ldots \text{Eq. } 3.092.2b$$

<u>Interpolation Range 2</u>: $\theta = 75$ to 90

$$\sigma = \sigma_a (C_T - K_T \log t)\left(C_D + K_D \frac{\theta - 75}{15}\right) \ldots \text{Eq. } 3.092.2c$$

In the foregoing:

- σ = design ultimate stress at angle θ, ksi
- σ_a = Specified (allowable) design stress for a given loading condition, ksi (Table 3.092.3a)
- θ = Angle of loading with respect to the warp direction, degrees
- t = time, hours
- C_t = Reduction constant for duration of load (Table 3.092.3b)
- K_t = Reduction coefficient for duration of load (Table 3.092.3b)
- C_D = Reduction constant for direction of load (Fig. 3.092.3d)
- K_D = Reduction coefficient for direction of load (Fig. 3.092.3d)

3.092.3 Tables and Charts

a. Specified (allowable) mechanical properties for laminates class LII, Table 3.092.3a. It should be noted that the designer may choose other "specified" values based on actual test results. It should be noted that although Table 3.092.3a provides specification data for mechanical properties in Tension, Compression and flexure, the following charts are expressly labeled for compression.

b. Reduction constants and coefficients for duration of load, Table 3.092.3b.

c. Mantissa of logarithum for various times, Fig. 3.092.3c.

d. Reduction constant and coefficient for direction of compression loading, Fig. 3.092.3d.

e. Modified reduction factor for modulus of elasticity in compression for duration of load, Fig. 3.092.3e.

f. Modified reduction factor for modulus of elasticity in compression for direction of load, Fig. 3.092.3f.

TABLE 3.092.3a

SPECIFIED (ALLOWABLE) MECHANICAL PROPERTIES FOR LAMINATES CLASS LII (SOURCE: P.N.S.)

Laminate Grade	Allowable Strength - ksi							
	σ_{tu} Dry	σ_{tu} Wet	σ_{cu} (edge) Dry	σ_{cu} (edge) Wet	σ_{fu} (flat) Dry	σ_{fu} (flat) Wet	E_f (flat) Dry	E_f (flat) Wet
1	37	--	33	28	50	45	2500	2300
2	28	--	25	23	37	33	2000	1800
3	20	--	21	19	31	27	1450	1250
4	14	--	17	15	23	20	1100	990
5	9	--	16	14	18	15	850	770
W	35	--	18	17	32	29	1650	1500

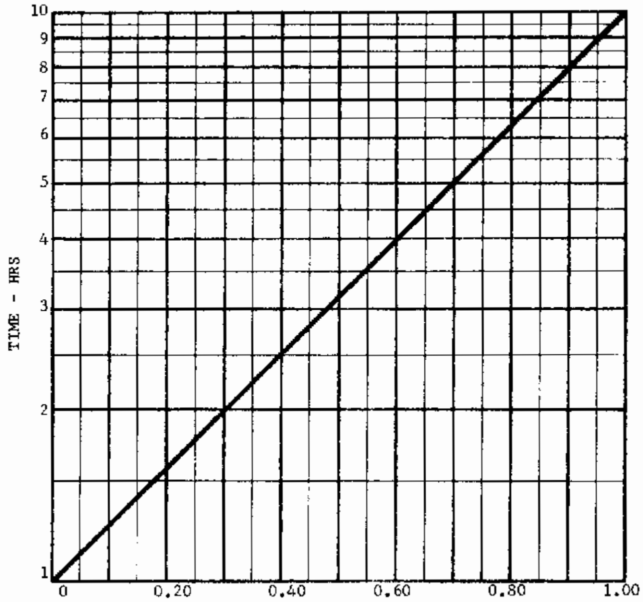
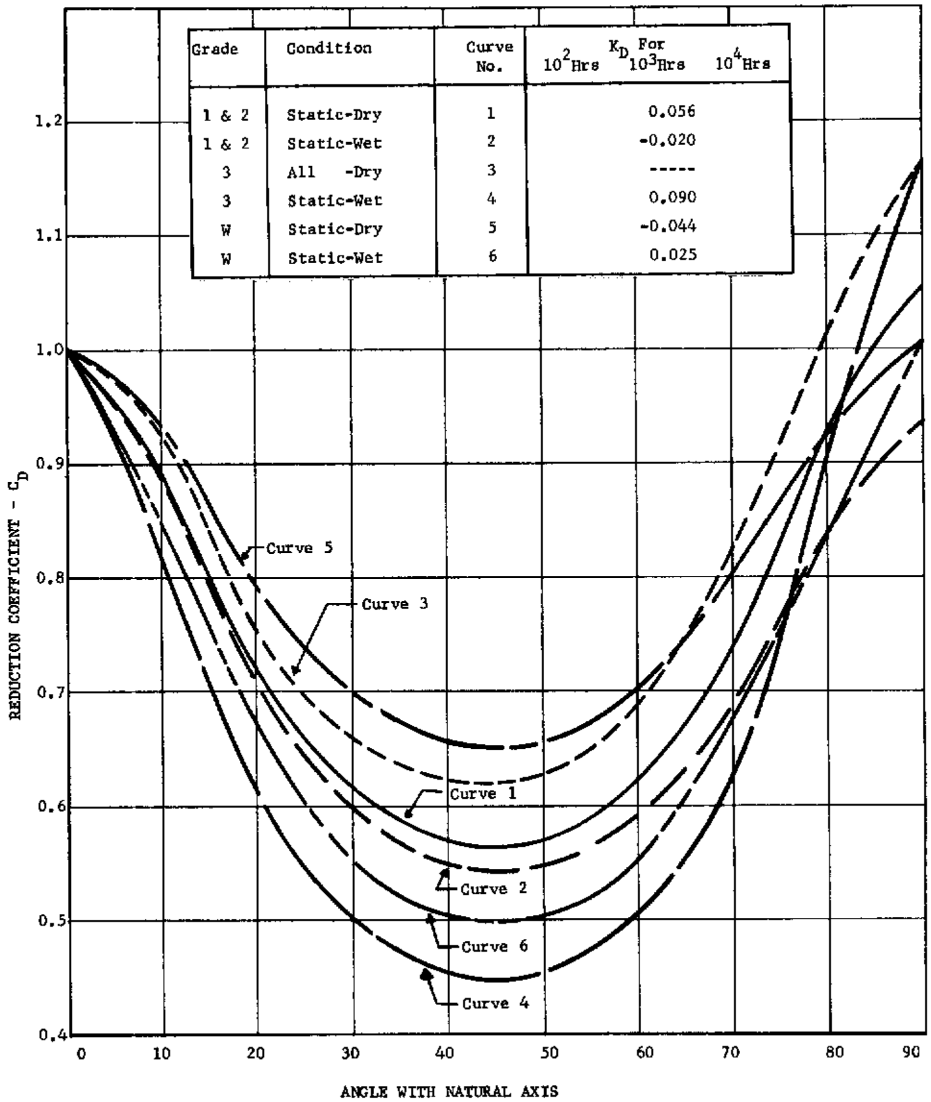


FIG. 3.092.3c MANTISSA OF LOGARITHUM FOR VARIOUS TIMES

TABLE 3.092.3b

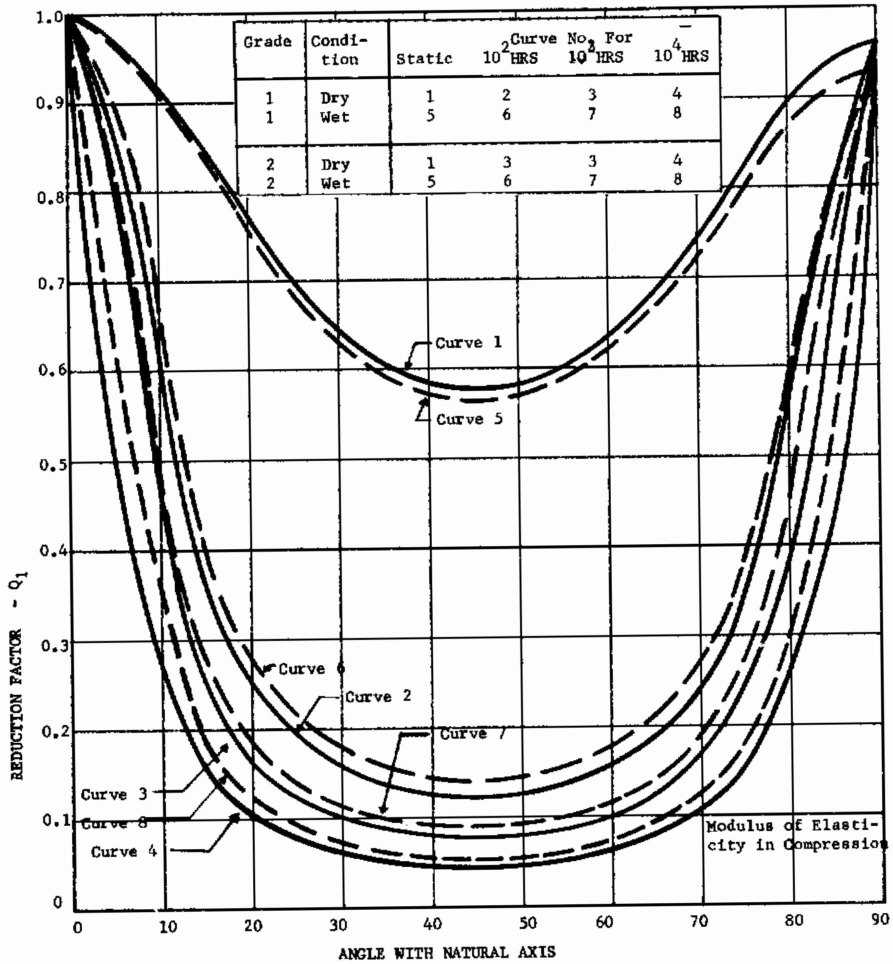
REDUCTION CONSTANTS AND COEFFICIENTS FOR DURATION OF LOAD (SOURCE: P.N.S.)

Laminate Grade	Condition	Tension			Compression			Shear		
		θ	C_T	K_T	θ	C_T	K_T	θ	C_T	K_T
1	Dry	0	0.790	0.059	0	0.790	0.059	-45	0.790	0.059
	Wet	0	0.742	0.0725	0	0.790	0.059	-45	0.774	0.0645
2	Dry	0	0.790	0.059	0	0.790	0.059	-45	0.790	0.059
	Wet	0	0.731	0.071	0	0.790	0.059	-45	0.775	0.065
3	Dry	0	0.814	0.0455	0	0.814	0.0455	-45	0.822	0.0475
	Wet	0	0.748	0.086	0	0.748	0.086	-45	0.748	0.086
W	Dry	0	0.857	0.037	0	0.859	0.0375	-45	0.857	0.037
	Wet	0	0.780	0.077	0	0.780	0.077	-45	0.780	0.077



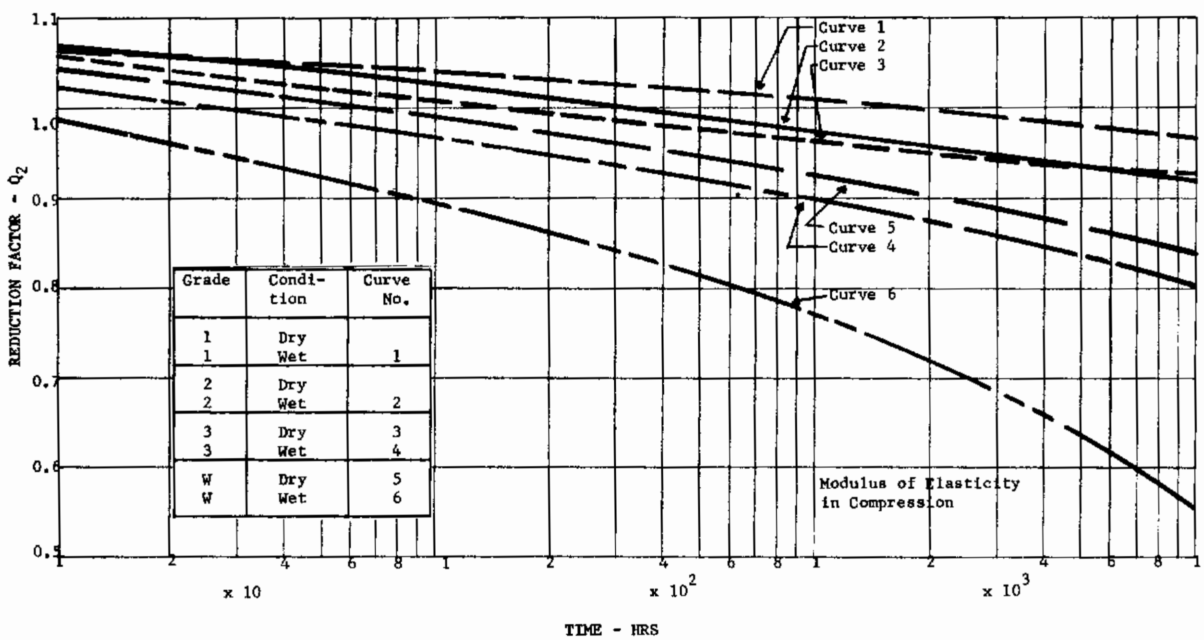
Grade	Condition	Curve No.	K_D For 10^2 Hrs	10^3 Hrs	10^4 Hrs
1 & 2	Static-Dry	1		0.056	
1 & 2	Static-Wet	2		-0.020	
3	All -Dry	3		-----	
3	Static-Wet	4		0.090	
W	Static-Dry	5		-0.044	
W	Static-Wet	6		0.025	

FIG. 3.092.3d REDUCTION CONSTANT AND COEFFICIENT FOR DIRECTION OF COMPRESSION LOADING



Grade	Condition	Curve No. For Static	10^2 HRS	10^3 HRS	10^4 HRS
1	Dry	1	2	3	4
1	Wet	5	6	7	8
2	Dry	1	3	3	4
2	Wet	5	6	7	8

FIG. 3.092.9e MODIFIED REDUCTION FACTOR FOR MODULUS OF ELASTICITY IN COMPRESSION FOR DURATION OF LOAD



Grade	Condition	Curve No.
1	Dry	
1	Wet	1
2	Dry	
2	Wet	2
3	Dry	3
3	Wet	4
W	Dry	5
W	Wet	6

FIG. 3.092.3f MODIFIED REDUCTION FACTOR FOR MODULUS OF ELASTICITY IN COMPRESSION FOR DIRECTION OF LOAD

3.092.4 Example Calculations

Example No. 1

Given: Grade 1, LII, wet laminate with known allowable static compression load applied at $\theta = 0$

Reference: P.N.S. charts and equations

Find: Design ultimate compression stress at $\theta = 30$ after 1000 hours wet exposure

Calculations:

Since $15 < \theta = 30 < 75$, use Eq. 3.092.2a

$$\sigma = \sigma_a (C_T - K_T \log t)\ (C_D + K_D)$$

For explanatory purposes consider the right side of the equation as two parts depicted by the ()'s

Part a: The $(C_T - K_T \log t)$ factor reduces the ultimate stress from static conditions at $\theta=0$ to the ultimate stress at the desired duration of loading and $\theta=0$.

From Table 3.092.3b (Grade 1, compression, wet, $\theta=0$):

$C_T = 0.790$

$K_T = 0.059$

Also: $\log t = \log 1000 = 3.00$
(Note: Fig. 3.092.3c may be used to find the mantissa of the logarithum for other times)

Hence: $(C_T - K_T \log t) = [0.790 - 0.059(3.00)] = 0.613$

Part b: The $(C_D + K_D)$ factor reduces the ultimate stress from 1000 hours conditions at $\theta=0$ to the ultimate stress at the desired loading angle, θ.

From Fig. 3.092.3d (Grade 1, compression, wet, $\theta=30$):

$C_D = 0.597$ (Using Curve #2)

$K_D = -0.020$ (at 1000 hours)

Hence: $(C_D + K_D) = [0.597 + (-0.020)] = 0.577$

To complete the calculation, σ_a is obtained from Table 3.092.3a (Grade 1, compression, wet, $\theta=0$):

$\sigma_a = 28{,}000$ psi

therefore:

$\sigma = 28{,}000(0.613)(0.577) = \underline{9{,}904}$ psi........ Ans

Example No. 2

Given: Same as Example No. 1

Reference: Same as Example No. 1

Find: Design ultimate compression stress at $\theta = 10$ after 1000 hours wet exposure.

Calculations:

Since $0 < \theta = 10 < 15$, use Eq. 3.092.2b

$$\sigma = \sigma_a\ (C_T - K_T \log t)\ (C_D + K_D \frac{\theta}{15})$$

From Table 3.092.3b (Grade 1, compression, wet, $\theta=0$):

$C_T = 0.790$

$K_T = 0.059$

$\log t = \log 1000 = 3.00$

Hence: $(C_T - K_T \log t) = [0.790 - 0.059(3.00)] = 0.613$

From Fig. 3.092.3d (Grade 1, compression, wet, $\theta=10$):

$C_D = 0.883$ (Using Curve #2)

$K_D = -0.020$ (at 1000 hours)

Hence: $(C_D + K_D \frac{\theta}{15}) = [0.883 + (-0.020)(\frac{10}{15})] = 0.870$

Again using $\sigma_a = 28{,}000$ psi:

$\sigma = 28{,}000\ (0.613)(0.870) = \underline{14{,}930}$ psi..... Ans

3.092.5 The modulus of elasticity may be calculated in a manner similar to the foregoing Examples. However, additional charts are presented herein to reduce the basic equation to:

$$E = E_a\ (Q_1 + Q_2)$$

where: Q_1 = Modified reduction factor for duration of load, (Fig. 3.092.3e)
Q_2 = Modified reduction factor for direction of load (Fig. 3.092.3f)

MANUAL IC PRIMARY MATERIALS	RESINS	IC R/
	REINFORCEMENTS	IC /R

0.0 INTRODUCTION

0.01 Purpose of Manual

0.011 The purpose of this Manual is to present detailed information and data on various properties of the primary materials, resins and reinforcements, which are used in producing the material systems discussed in Manual ID. Emphasis is placed on the resins and reinforcements most commonly used in structural applications for aerospace vehicles. For this first edition only minimal information is included, where readily available, primarily to indicate planned format and coverage. The subsequent sections of this Introduction discuss the contents and philosophy of this Manual in more detail.

0.012 Information in this Manual has been carefully chosen prior to inclusion. The following considerations form the criteria for the choices made; the fundamental objective is to present only complete data which satisfy all the criteria.

0.012.1 Material identification must be complete in identifying the particular resin, including additives, or the particular reinforcement, including finishes.

0.012.2 Any special variations in the production of the primary materials must be identified.

0.012.3 Test identification must be complete in identifying specimen configuration, number of specimens tested, preparation and pre-conditioning, test environment, and test method, particularly variations from standard methods which may have been introduced.

0.012.4 Source identification must be complete in identifying the primary source of the data, including Division if a large organization, the type of source, i.e. company, laboratory, government, etc., and the date of the data.

0.012.5 To collate and correlate the data presented it is essential to meet all of the above criteria. Very little information has been taken from periodical literature since the bulk of the critical information required above is unavailable in such sources. A vast amount of non-published information is included in the project files but could not be included in the correlations that follow because one or more of the above criteria could not be met. Attempts are being made to complete these data for inclusion in future editions.

0.012.6 Every effort has been made to include only reliable and factual information in this Manual to assist the user in selection of materials and to confirm design values for various properties. Detailed data on individual materials may be readily obtained from the supplier.

0.012.7 It is not the purpose of this Manual to recommend one material over another. Exclusion or inclusion of a material from a particular source is based only on availability of data which meet the basic criteria as indicated above.

0.02 Identification Code

0.021 The various primary materials are cross-referenced by use of a code system which identifies the material involved.

0.022 Resin Identification Code

0.022.1 Resin i

0.022.1 Resin identification:

- Po = Polyester
- Ep = Epoxy
- Ph = Phenolic
- Si = Silicone

0.022.2 Category identification:

- 1 = General purpose
- 2 = Improved mechanical or thermal properties
- 3 = Other

0.022.3 Example: Pol = General purpose polyester resin.

0.023 Reinforcement Identification Code

0.023.1 Reinforcement identification:

- C = Cotton
- G = Glass, standard E or similar
- Gr = Graphite
- M = Metallic
- N = Nylon
- S = Silica

The above may be modified by upper case letters following the capitals as follows:

- H = High strength
- M = High modulus
- T = High temperature

If not modified by the foregoing, the reinforcement is considered as being basic or "standard".

0.023.2 Form identification

- c = cloth
- cc = chopped cloth
- f = filament
- fc = chopped filaments
- r = roving
- rc = chopped roving
- w = woven roving
- wc = chopped woven roving

0.023.3 Example: Gc = Glass cloth, or GHrc = chopped high strength glass roving.

0.023 The foregoing code identification system can be readily expanded to include additional items.

0.03 Contents of Manual IC

0.031 This first edition of Manual IC contains a skeletal writeup on general purpose polyester resin only. Emphasis was not placed on this Manual during the project period. However, the inclusion of one section will serve to illustrate the type of information which will appear herein.

0.032 Future editions will expand the writeup mentioned above and will include many additional primary materials.

0.033 For convenience this Manual is thumb indexed to separate resins and reinforcements. See thumb index page at start of this Manual or in front of handbook.

0.034 The data for each primary material are arranged according to a definite system selected for the purpose of this Manual. The system used is almost entirely identical to that used in Manual ID. It will be noted that for each material one paragraph number will always indicate the same subject. This will facilitate the use of this Manual and the cross-referencing to other Manuals. A topical outline for this system of data organization is given below.

1. GENERAL

- 1.01 Designation
- 1.011 Handbook Code Designation
- 1.012 Commercial Designations
- 1.013 Alternate Designations
- 1.02 Specifications
- 1.03 Composition
- 1.04 Forms and Conditions Available
- 1.05 Special Considerations

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties
2.011 Degredation
2.012 Conductivity
2.013 Expansion
2.014 Specific Heat
2.015 Diffusivity
2.016 Emissivity
2.017 Ablation
2.018 Other
2.02 Electrical Properties
2.021 Resistivity
2.022 Conductivity
2.023 Dielectric Properties
2.024 Magnetic Properties
2.025 Other
2.03 Other Physical Properties
2.031 Density
2.032 Water Absorption
2.033 Viscosity
2.034 Color
2.035 Other
2.04 Chemical Properties
2.041 Chemical Resistance
2.042 Fire Resistance Properties
2.043 Environmental Properties
2.044 Other
2.05 Nuclear Properties

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties
3.02 Typical Mechanical Properties
3.03 Tension Properties
3.04 Compression Properties
3.05 Flexure Properties
3.06 Shear Properties
3.07 Bearing Properties
3.08 Creep and Creep Rupture Properties
3.09 Fatigue Properties
3.10 Elastic Properties

4. FABRICATION

0.035 For complete Table of Contents for the entire Handbook, see Manual IA.

0.04 Abbreviations and Glossary

0.041 Abbreviations and symbols used for mechanical property and other identification are identical to those used in Manual ID. See Section 0.04, Manual ID.

0.042 For complete listing of all abbreviations and definitions used throughout the handbook, see Manual IA.

0.05 Information Sources

0.051 Each item of data presented in source referenced appropriately.

0.052 A complete source index is given in Manual IA.

0.6 Discussion. Future editions of this Manual will include a general discussion of the outline (See 0.034) for various sections. For the present, reference is made to Sections 1.0 thru 4.0 of the Introduction to Manual ID.

1 GENERAL

1.01 Designations

1.011 Handbook Code Designation: Pol
This code refers to general purpose, polyester resins, dissolved in sytrene.

1.012 Commercial Designations - Interchemical Corp., IC-937 and DUREZ PR-135.

1.013 Alternate Designations

1.02 Specifications

1.03 Composition

1.031 General Chemical Composition - 100% reactive thermosetting, unsaturated alkyd resin, dissolved in sytrene monomer.

1.032 Raw Materials

1.033 General Chemical Structure, See Figures, 1.0331, 1.0332, 1.0333.

1.04 Forms and Conditions Available

1.041 Basic Form - LIQUID.

1.042 Conditions Available

1.05 Special Considerations

1.051 Uncatalzed DUREZ PR-135 is stable for a minimum of six months when stored at 73F or below. DUREZ PR-135 may cause irritation. Avoid prolonged contact with the skin. Avoid prolonged breathing of vapor or dust and use with adequate ventilation.

1.052 IC-937 resin should not be disturbed immediately after gelling in a lay-up mold. The part should remain untouched for a short time or until it is strong enough for handling without damage to the construction. External heat (125F - 150F) can be applied to hasten complete cure and final strength or more cobalt and catalyst can be added if desired. High temperatures should be avoided until after the resin has gelled.

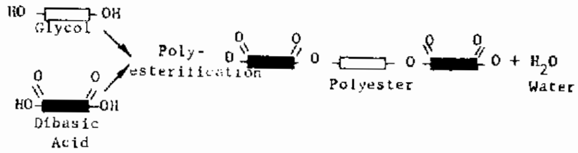


FIG. 1.0331 POLYESTERIFICATION REACTION

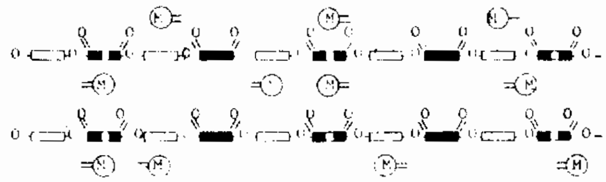


FIG. 1.0332
UNSATURATED POLYESTER RESIN/MONOMER SOLUTION - BEFORE CURE

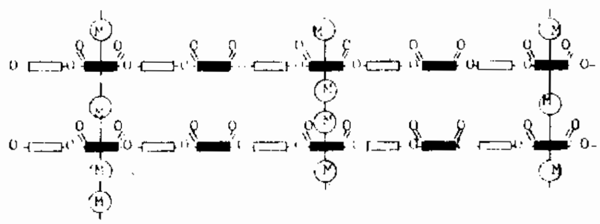


FIG. 1.0333
UNSATURATED POLYESTER RESIN/MONOMER COPOLYMER - AFTER CURE

2 PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Degredation

2.011.1 Heat Distortion Temperatures: PR-135, 215F.

2.012 Conductivity

2.013 Expansion

2.014 Specific Heat

2.015 Diffusivity

2.016 Emissivity

2.017 Ablation

2.018 Other

2.018.1 Gelation, See Table 2.018.1.

2.02 Electrical Properties

2.021 Resistivity

2.022 Conductivity

2.023 Dielectric Properties

2.024 Magnetic Properties - Resin is non magnetic.

2.025 Other

TABLE 2.018.1

Source	Durez Plastics Div.
Material	PR-135
Test Method	Durez Control Test Method #373
SPI Gel Time-Min.	4.5
Time to Peak Exotherine-Min.	7.0
Peak Exotherm Temperature, °F	400

2.03 Other Physical Properties

2.031 Density

2.031.1 Typical specific gravity, Table 2.031.1.

2.032 Water Absorption

2.033 Viscosity

2.033.1 Typical viscosity, Table 2.031.1.

2.034 Color

2.034.1 Typical color, Table 2.031.1.

2.035 Other

2.04 Chemical Properties

2.041 Chemical Resistance

2.042 Fire Resistance Properties

2.043 Environmental Properties

2.044 Other

2.044.1 Acid number of Base Resin PR-135=18

2.05 Nuclear Properties

3 MECHANICAL PROPERTIES

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3.02 Typical Mechanical Properties

3.03 Tension Properties

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3.05 Flexure Properties

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3.07 Bearing Properties

3.08 Creep and Creep Rupture Properties

3.09 Fatigue Properties

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4 FABRICATION

TABLE 2.031.1

Source / Material	Interchemical Corp. IC-937	Durez PR-135	
			Durez Test
Viscosity, Brookfield-CP	750	2300	379
Specific Gravity	1.13	1.11	4
Color, Gardner	----	9.0	377

MANUAL ID MATERIAL SYSTEMS		
	POLYESTER	ID Po
	EPOXY	ID Ep
	PHENOLIC	ID Ph
	SILICONE	ID Si
		ID
	OTHER	ID O

0.0 INTRODUCTION

0.01 Purpose of Manual

0.011 The purpose of this Manual is to present detailed information and data on various properties of resin/reinforcement systems. Emphasis is placed on the systems most commonly used in structural applications for aerospace vehicles. For this first edition, mechanical properties are stressed with minimal information on other properties included where readily available. The subsequent sections of this Introduction discuss the contents and philosophy of this Manual in more detail.

0.012 Information in this Manual has been carefully chosen prior to inclusion. The following considerations form the criteria for the choices made; the fundamental objective is to present only complete data which satisfy all the criteria.

0.012.1 Material identification must be complete in identifying the particular resin, reinforcement, finish, critical additives, thickness and the number of plies where possible.

0.012.2 Process identification must be complete in identifying the particular method, pressure ranges, temperature ranges, time, post cures, and the like.

0.012.3 Test identification must be complete in identifying specimen configuration, number of specimens tested, preparation and pre-conditioning, test environment, and test method, particularly variations from standard methods which may have been introduced.

0.012.4 Source identification must be complete in identifying the primary source of the data, including Division if a large organization, the type of source, i.e. company, laboratory, government, etc., and the date of the data.

0.012.5 To collate and correlate the data presented it is essential to meet all of the above criteria. Very little information has been taken from periodical literature since the bulk of the critical information required above is unavailable in such sources. A vast amount of non-published information is included in the project files but could not be included in the correlations that follow because one or more of the above criteria could not be met. Attempts are being made to complete these data for inclusion in future editions.

0.012.6 Every effort has been made to include only reliable and factual information in this Manual to assist the user in selection of materials and to confirm design values for various properties. Detailed data on individual material systems may be readily obtained from the supplier.

0.012.7 It is not the purpose of this Manual to recommend one material over another. Exclusion or inclusion of a material from a particular source is based only on availability of data which meet the basic criteria as indicated above.

0.02 Identification Code

0.021 The various material systems are cross-referenced by use of a code system which identifies the resin, application category, and reinforcement for the system. This simplified identification system may be illustrated as follows using Po1Gc as an example:

Po1Gc = Identification Code
Po = Resin identification, polyester in this case
1 = Category, general purpose in this case
G = Reinforcement type, glass in this case
c = Reinforcement form, cloth in this case

Therefore, the example code above identifies a general purpose polyester/glass cloth material system.

0.022 Code components assigned

0.022.1 Resin identification:

Po = Polyester
Ep = Epoxy
Ph = Phenolic
Si = Silicone

0.022.2 Category identification:

1 = General purpose
2 = Improved mechanical or thermal properties
3 = Other

0.022.3 Reinforcement type identification:

C = Cotton
G = Glass, standard E or similar
Gr = Graphite
M = Metallic
N = Nylon
S = Silica

The above may be modified by upper case letters following the capitals as follows:

H = high strength
M = high modulus
T = high temperature

If not modified by the foregoing, the reinforcement is considered as being basic or "standard".

0.022.4 Reinforcement form identification:

c = cloth
cc = chopped cloth
f = filament
fc = chopped filaments
r = roving
rc = chopped roving
w = woven roving
wc = chopped woven roving

0.022.5 The foregoing code identification system can be readily expanded to include additional items.

0.03 Contents of Manual ID

0.031 This first edition of this Manual contains write-ups on the following material systems:

Ep1Gc
Ep1Gf
Ph1Gc
Ph1Gf
Po1Gc
Po1Gf
Po2Gc
Si1Gc

0.032 Future editions will expand these correlations and include additional material systems.

0.033 For convenience, this Manual is thumb indexed by resin identification. See thumb index page at start of this Manual or in front of handbook.

0.034 The data for each material system are arranged according to a definite system selected for the purpose of this Manual. It will be noted that for each material system one paragraph number will always indicate the same subject. This will facilitate the use of this Manual and the cross-referencing to other Manuals. A topical outline for this system of data organization is given below.

1.0 GENERAL

1.01 Designations
1.011 Handbook Code Designation
1.012 Commercial Designations
1.013 Alternate Designations
1.02 Specifications
1.03 Composition
1.04 Forms and Conditions Available
1.05 Special Considerations

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2.033 Other
2.04 Chemical Properties
2.041 Chemical Resistance
2.042 Fire Resistance Properties
2.043 Environmental Properties
2.05 Nuclear Properties

3. MECHANICAL PROPERTIES

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3.032 Physical Effects
3.033 Processing Effects
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3.073 Processing Effects
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3.075 Other Effects
3.08 Creep and Creep Rupture Properties
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3.082 Total Strain
3.083 Master Curves
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3.09 Fatigue Properties
3.091 S-N Curves
3.092 Stress Range Diagrams
3.093 Other
3.10 Elastic Properties
3.101 Modulus of Elasticity in Tension
3.102 Modulus of Elasticity in Compression
3.103 Modulus of Elasticity in Flexure
3.104 Modulus of Elasticity in Shear
3.105 Other Elastic Constants

4.0 FABRICATION

0.035 Sections 1 through 4 of this Introduction will follow the above topical outline discussing the contents of each subject heading.

0.036 For complete Table of Contents for the entire Handbook, see Manual IA.

0.04 Abbreviations and Glossary

0.041 A defined procedure for mechanical property symbols has been adopted as standard in this Manual. The following will illustrate this.

0.041.1 Standard symbols for mechanical properties are as follows:

E = Modulus of elasticity
G = Modulus of rigidity
σ = Stress or unit stress

These symbols are modified by a series of subscripts as indicated in the following articles.

0.041.2 The first modifying subscript classifies the type of stress or modulus involved as follows:

b = bearing
c = compression
f = flexure or bending
h = hoop tension
s = shear
t = tension

0.041.3 The second subscript identifies a subclassification of the first subscript as follows:

y = yield (usually at 0.2% offset or at actual yield point if identifiable)
u = ultimate
p = proportional limit
f = fatigue
s = secant (modulus)
t = tangent (modulus)

0.041.4 In addition, because of the particular phenomenon sometimes exhibited by reinforced plastics, initial and secondary characteristics are identified by i or s respectively in parentheses () after the property symbol involved.

0.041.5 Example of the above could be one of the following:

σ_{tu} = ultimate tension stress or strength
σ_{sy} = yield shear stress
E_{tt} = tangent modulus of elasticity in tension
$E_c(s)$ = secondary modulus of elasticity in compression

0.042 For complete listing of all abbreviations and definitions used throughout the handbook, see Manual IA.

0.05 Information Sources

0.051 Each item of data presented is source referenced appropriately.

0.052 A complete source index is given in Manual IA.

0.06 Discussion. A general discussion of the outline for various sections follows with appropriate section numbering.

1.0 GENERAL

1.01 Designations

1.011 Handbook Code Designation. This article includes a brief description of the material system involved and the code identifying same.

1.012 Commercial Designations

1.012.1 There are no apparent standard commercial designations for various resin/reinforcement systems. The code designation system used in this Manual is an effort at classifying or generally identifying these materials. It is anticipated that standard designations will be adopted eventually. These will be incorporated in this article at that time.

1.012.2 This article includes a few trade name designations as examples of the various commercial materials considered as being included in the handbook code indicated in 1.011. This is not meant to be a complete listing of all trade names which may fall into the code classification in question. It should be noted that many of these trade names are TRADEMARKED with all rights thereto retained by the appropriate source. In this Manual these names have been used for identifying purposes only. The reader should be governed by trademark rules in his usage of such names, and should contact the appropriate company owning the trademark if there be any question concerning their use.

1.013 Alternate Designations. In this first edition of this Manual there are no alternate designations listed. At a future date, when standard commercial designations are established and included in article 1.012 above, the typical trade names will be moved to this article as alternate designations.

1.02 <u>Specifications</u>

1.021 The basic specifications used in this Manual are the Military Specifications (MIL) published by various branches of the military services such as Army, Navy, Air Force, etc.

1.022 Where appropriate, other accepted specifications, such as those of American Society of Testing Materials (ASTM), are included.

1.03 <u>Composition</u>. This article includes a summary description of the primary materials which make up the material system in question.

1.04 <u>Forms and Conditions Available</u>. This article indicates in general the availability of the material system in question and the forms it may take. Such items as pre-preg, shapes, and the like are mentioned. In future editions more detailed information will be included in this section.

1.05 <u>Special Considerations</u>. This article will include information on such items as storage, handling and the like. Stressed here are particular problems which may require special consideration.

2.0 PHYSICAL AND CHEMICAL PROPERTIES

Since the first edition of the Manual emphasizes mechanical properties of material systems, only a minimum of information has been included for the various physical and chemical properties. Much of the data on these properties in the project library are incomplete in that they do not meet the basic criteria mentioned earlier in this introduction. Future editions of this manual will expand this section as deemed desirable. The reader is referred to various other reports and handbooks for detailed information on these properties. In reporting physical and chemical properties of reinforced plastics systems the common British units are generally used by the Armed Forces and industry in this country and this system is followed here.

2.01 <u>Thermal Properties</u>. Included under this heading are such properties as degradation, conductivity, expansion, specific heat, diffusivity, emissivity, ablation, and others.

2.02 <u>Electrical Properties</u>. Included under this heading are such properties as resistivity, conductivity, dielectric, magnetic and other. Because of the wide spread use of reinforced plastics in radome structures, some summary and specification data on dielectric properties are reported in this section. Several detailed reports are available on this property for more definitive information.

2.03 <u>Other Physical Properties</u>. Included under this heading are such properties as density, water absorption and others. The effect of water absorption on various material systems is quite important in considering their sturctural application and, therefore, an effort has been made to cover this property in this section. The effects of water absorption on various mechanical properties are included as appropriate in Section 3.0 of this Manual. Water absorption is reported both in terms of percent change in weight (Δw) and percent change in dimension (Δ dimen.). The effect of exposure time is included also.

2.04 <u>Chemical Properties</u>. Included under this heading are such properties as chemical resistance, fire resistance, and environmental resistance.

2.041 Chemical Resistance. This property becomes very important when considering the application of structural reinforced plastic material systems. Both specified and typical values for chemical resistance to certain test fluids are included here. These values are reported in terms of percent change in weight (Δw) and percent change in thickness (Δt). Little or no information appears available at this time on the chemical resistance of these materials to other than the standard fluids. Resistance to gaseous consituents will be included under environmental properties.

2.042 Fire Resistance. As with chemical resistance, this is an extremely important property to consider in applying these materials to structures, particularly habitable ones. It is apparent that more information in this area is needed. Some terminology should be clarified for this property as follows.

2.042.1 Ignition. "A combustible material will ignite when the atmosphere reaches a temperature high enough to start a self-sustaining exothermic condition of the specimen by the available oxygen". This definition may be further broken down into two terms: (1) flash ignition temperature: the lowest initial temperature of air passing around the specimen at which sufficient combustible gas is evolved to be ignited by a small external pilot flame; and (2) self-ignition temperature: the lowest initial temperature of air passing around the specimen at which, in the absence of an ignition source, ignition will start of itself, as indicated by an explosion, flame, or sustained glow.

2.042.2 Spread. Spread, a particularly important consideration in habitable structures, is defined as "the rate and extent of flame (combustion) progression along the material surface from the point of fire origin".

2.042.3 Flammability. This term generally is used as an alternate to "spread" defined above. It is usually measured in terms of rate of fire spread or inches per minute.

2.042.4 Extinguishment. Extinguishment may be defined as the cessation of combustion (burning) caused by environmental conditions created by an external source or by the characteristics of the fuel itself.

2.042.5 Self extinguishing (S.E.). This term refers to materials which, due to their chemical composition, will not support combustion or burning after ignition. Most specifications establish a limit on either the rate of spread of burning or the distance of spread before cessation of burning.

2.043 Environmental Properties. Structural plastics may be used in unusual environments. Although little reportable data is currently available, this section will cover such environments as a vacuum, various gases, and the like.

2.05 <u>Nuclear Properties</u>. This first edition of Manual ID does not include any data under this heading. However, its importance with respect to future applications of reinforced plastics is clearly recognized and coverage of these properties is definitely planned.

3.0 MECHANICAL PROPERTIES

The properties presented in this section include all mechanical properties on which data are available, including various elastic constants. The section is subdivided into ten logical categories.

All strength quantities are given in ksi, i.e. thousands of pounds (kips) per square inch. Most of the data reported apply to the various forms commercially available and to generally accepted processing conditions. The effects of process variations are reported where feasible and in relation to specific properties. The test methods used to obtain the reported data are cross-referenced to Manual 1G which describes these in some detail.

3.01 Specified Mechanical Properties. Although this Manual is primarily a source of information to support design analysis, an attempt has been made to include specified properties. The primary sources for these are the Military Specifications established by various branches of the Armed Forces. Most of these specifications are general in nature in that they do not deal with specific resin systems but rather with generalized groupings of resins. Some of the specifications give requirements for a variety of reinforcement types. Room temperature mechanical properties are the core of the majority of specifications; however, some list requirements for conditions other than room temperature. In most cases, both dry and wet properties are specified, indicating the importance of the latter. The majority of the specifications encountered in this work cover only tension, compression, flexure and elastic properties.

3.02 Typical Mechanical Properties. The primary purpose of this section is to present summary information in a manner which will facilitate comparison of different basic variables. Also included are data which are not readily plotted or presented in other than tabular form. The general variables considered are types or weaves of reinforcement, processing procedure, resin contents, defects and the like.

Some data from quality control or process control reports are included in this section. As these represent actual production values for various properties, they are considered particularly pertinent to this type of handbook. It is planned that future editions will contain more of this type of information.

3.03 thru 3.10 These remaining sections under the heading of Mechanical Properties cover individual properties in detail. Reported here are data resulting from concentrated research efforts, carefully controlled test programs or thorough studies of pertinent variables. The general intent is to give as complete a picture as possible on each property and the factors which may influence it.

3.03 Tension Properties

3.031 Stress Strain Relationships. Included here are basic stress strain data determined by accurate testing procedures. The attempt has been made to isolate the effects of test direction, various reinforcements and test temperature.

3.032 Physical Effects. A variety of physical effects have a major effect on mechanical properties of reinforced plastics. Included in this section are data illustrating the effects of thickness, voids, surface preparation, reinforcement orientation, stress raisers and others on yield and ultimate strengths when information is available.

3.033 Processing Effects. This heading includes data which illustrate the influence of process variables on the property involved. Such variations as process type, pressure, time, temperature and additives are involved in this.

3.034 Environmental Effects. As greater interest is evinced in the use of reinforced plastics under conditions other than standard (room temperature and normal relative humidity, etc.), the properties of these materials under other environmental aspects become more important. Included in this section are available data illustrating the effects of temperature, exposure time, weathering, immersion and other environments on the property involved. As more information in this area becomes available, this section will be considerably expanded.

3.035 Other Effects. Included under this heading are data indicating the effects of other variables not included in previous sections above. For example, prestressing a material under various conditions may show considerable effect on the ultimate or yield strength at the same or other conditions. Data on this are included in this section.

3.04 Compression Properties

3.041 thru 3.045 See Sections 3.031 thru 3.035

3.05 Flexure Properties. Because of relative ease of running flexure tests, a large amount of data is apparently determined by this method. It is, perhaps, the most frequent test run in quality or process control programs. There is some evidence that more scatter results from flexure tests and a few industrial and governmental contacts have questioned the usefulness of flexure properties.

3.051 Stress Strain Relationships. For flexure, these properties are best reported in terms of load versus deflection. See also Section 3.031.

3.052 thru 3.055 See Sections 3.032 thru 3.035

3.06 Shear Properties. A number of methods for testing shear have been developed based on various theoretical approaches. Most common in the data available at present are methods arriving at interlaminar shear or panel shear. If care is taken in designing apparatus to minimize the bending effects, the interlaminar shear test is a practical method of obtaining indications of the shear strength between laminations of a reinforced plastic material. Forest Products Laboratory (1), who confirm this statement, indicate that the angle of loading does not appreciably effect the interlaminar shear strength obtained by this method.

In an attempt to obtain pure shear, Forest Products Laboratory (1), based on previous experience with other materials, have developed a panel shear apparatus. This method attempts to transmit shearing forces directly along the free edge of the panel being tested. Although agreement between the results and theory is not as good as desired, this test is still indicative of pure shear strength of the material. The footnoted report discusses this in more detail.

Preliminary incomplete test programs (1) indicate that the Johnson Shear Test is not apparently reliable for testing laminates reinforced with glass cloth.

3.061 thru 3.065 See Sections 3.031 thru 3.035.

3.07 Bearing Properties. In addition to the influencing factors indicated in the discussion of the foregoing properties, another factor becomes important when considering bearing. This is the consideration of the effects of various edge to hole diameter and end to hole diameter ratios. These effects have been studied in some cases and are presented where available. In reporting bearing properties in this Manual, the bearing area is considered to be equal to the projected hole area or the product of hole diameter times material thickness.

3.071 thru 3.075 See Sections 3.031 thru 3.035.

3.08 Creep and Creep Rupture Properties. These properties are becoming more important because of the continuously increasing interest in developing materials to withstand high temperature environments over a longer period of time as required in newer aerospace applications. It is known that most materials, at elevated temperatures particularly, will generally deform or creep slowly under load and eventually rupture. The more accepted tests maintain constant temperature and load while deformation is measured as a function of time. Common criteria for evaluating materials in regard to their resistance to creep include the stress to obtain a certain total strain (elastic and plastic) at a particular time and temperature, or the stress to obtain certain plastic strain (creep) only.

(1) Forest Products Laboratory Report No. 1803, 1956.

Because of the different nature of this property it is subdivided for reporting purposes in a different manner than the foregoing properties. This breakdown is indicated in the following articles.

3.081 Creep and Creep Rupture

3.081.1 Creep rupture strength (often called stress rupture strength) is, as indicated above, simply the stress, as a function of time and temperature, which causes rupture. The significance of this property is often minimized. Elongation in a creep rupture test is also significant for application considerations; however, measurements of this are seldom recorded or taken during the test.

3.081.2 Notched specimens are often used in creep rupture tests to reveal potential enbrittlement which may occur within a certain range of temperature and time.

3.081.3 The many variables considered for creep and creep rupture have led to the use of different methods of graphical presentation. In this Manual stress is plotted as the ordinate and time as the abscissa, usually with one other variable as a parameter.

3.082 Total Strain

3.082.1 Total strain and creep can be indicated as the parameter on a normal stress vs. time curve. However, these data are usually reported in the form of isochronous stress strain curves. The total strain at a particular time is plotted as the abscissa with the stress necessary to obtain the strain as the ordinate. If the elastic component is deducted, creep is obtained. This is somewhat indefinite because of the uncertainty regarding the modulus of elasticity, indicated by the tangent at the origin of the isochronous curve.

3.082.2 As of this writing, no information on creep or total strain is apparently available. If and when these data become available it will be presented in this section.

3.083 Master Curves

3.083.1 Many attempts have been made, particularly for metals, to assemble creep and creep rupture information in a single master curve. Although it is not yet certain that the effects of temperature and time can be thus substituted for each other, master curves can assist the selection of materials and planning for more specific tests.

3.083.2 When data suitable for presentation in this section become available, it will be included in future editions of this Manual.

3.084 Other. Any creep or creep rupture information which cannot be included under the above headings will be presented in this article.

3.09 <u>Fatigue Properties</u>. These properties not only depend on normal test variables such as condition, temperature, and the like, but also on additional variables as well. These include: type of loading, limiting stresses, number of cycles, and specimen shape. Cycle frequency may also become important under certain conditions. A number of test procedures are available, including rotating beam, reversed bending and axial loading. Usually both smooth and notched specimens are used in test programs. The axial loading fatigue test appears to be most commonly used for testing reinforced plastic laminates.

Because of the different nature of this property, it is subdivided for reporting purposes in a different manner than the foregoing properties. This breakdown is indicated in the following articles.

3.091 S-N Curves

3.091.1 The most common method of presenting fatigue data is by the use of S-N curves. These plot the alternating stress to cause failure (S) as the ordinate vs. the number of cycles to failure (N) as the abscissa (usually a log scale). This method is best if only one stress ratio (see next article) is used.

3.091.2 To define a series of fatigue tests, it is common practice to use a "stress ratio", R, which is defined as:

$$R = \sigma_{max}/\sigma_{min}$$

For example, if the applied stress alternates between 0 and some tension value, $R = \infty$. If $\sigma_{max} = \sigma_{min}$, then $R = -1$.

3.091.3 An alternate definition of the stress ratio is often used:

$$A = \sigma_{alt}/\sigma_{mf}$$

where: $\sigma_{alt(alternating\ stress)} = \frac{1}{2}(\sigma_{max} - \sigma_{min})$

$$\sigma_{mf(mean\ stress)} = \frac{1}{2}(\sigma_{max} + \sigma_{min})$$

For example, in comparing to R above, if $R = \infty$, then $A = 1$ and if $R = -1$, $A = \infty$.

3.091.4 In reporting fatigue data in this Manual, either "R" or "A" or both are indicated as appropriate.

3.092 Stress Range Diagrams

3.092.1 Often a series of fatigue data is developed for more than one stress ratio. Such information is best presented in a stress range diagram which plots alternating stress as the ordinate vs. the mean stress as the abscissa for a given number of cycles to failure. This procure usually requires first plotting individual S-N curves to determine the needed values for a specific number of cycles, usually 10, 10^2, 10^3, etc.

3.092.2 The fatigue strength can be derived from a stress range curve by the following relationship:

$$\sigma_f(max) = \sigma_{mf} + \sigma_{alt}$$

Where: $\sigma_f(max)$ = maximum fatigue strength

σ_{mf} and σ_{alt} as previously defined.

3.093 Other. Other fatigue information which does not fit into the above articles will be included under this heading.

3.10 <u>Elastic Properties</u>. Under this heading not only the classical elastic properties, but also the tangent and/or secant moduli, when available, are reported. This section is organized by the test method involved in obtaining the modulus such as tension, compression, etc. Each of these is then subdivided according to the type of modulus (elastic, tangent, secant, etc.) and the variables influencing same.

3.101 Modulus of Elasticity in Tension

3.101.1 The modulus of elasticity in tension is, perhaps, the most important elastic constant. It is normally determined by the slope at the origin of the static stress strain curve. This slope is often difficult to determine, particularly at elevated temperatures. Therefore, for other materials, at least, the dynamic modulus is growing in acceptance because of increased reliability.

3.101.2 For reinforced plastics, the static stress strain curve often exhibits two distinct portions which are approximately straight lines. Therefore, two moduli, initial and secondary, are frequently determined and reported. In this Manual, the data are understood to be for the initial modulus unless otherwise specified.

3.101.3 The tangent modulus is the slope of the stress strain curve at each stress value considered. It is difficult to accurately determine the slope of any curve and the reported values are therefore subject to variations. Excellent graphical techniques are available to minimize these difficulties, however.

3.101.4 The secant modulus is the slope of the straight line from the origin to the stress value considered. This value is quite easily determined graphically and can be mathematically calculated readily for any particular known stress and corresponding strain.

3.102 Modulus of Elasticity in Compression

3.102.1 The static compression modulus is theoretically equal to the tension modulus. However, considerable differences often exist between these values due to many factors such as residual stresses, specimen variations and the like.

3.102.2 The compression tangent modulus is often preferred for reporting purposes to the compression elastic modulus.

3.102.3 See also Sections 3.101.1 thru 3.101.4.

3.103 Modulus of Elasticity in Flexure

3.103.1 Due to the prevalent use of the flexure test for reinforced plastics, a large amount of elastic modulus data has been developed from this method. The same comments found in section 3.05 pertain here.

3.103.2 See also Sections 3.101.1 thru 3.101.4.

3.104 Modulus of Elasticity in Shear. See Sections 3.101.1 thru 3.101.4.

3.105 Other Elastic Constants. As data become available on other elastic constants, such as Poisson's ratio for example, they will be included in this section. Poisson's ratio can, however, be calculated readily from the moduli of elasticity in tension and shear and, therefore, is not often measured directly.

4. FABRICATION

Although no information is presented under this title in this first edition of Manual ID, it is definitely anticipated that future additions will add data in this section. The purpose of this section will be two fold. First to present a general picture of the fabricability of the material system. Second, to pinpoint the areas in which properties may be adversely affected by fabrication techniques. Included will be such headings as Forming, Machining, Bonding and Fastening, Surface Treating, and the like.

1. GENERAL

1.01 Designations

1.011 Handbook Code Designation: PolGc. This code refers to a general purpose polyester-glass cloth laminate system; the resin being 100% reactive and composed of unsaturated alkyd resins dissolved in styrene monomer.

1.012 Commercial Designations.

1.012.1 Commercial designations are as indicated in data reported in this section.

1.012.2 Typical commercial designations include: Selectron 5003/181, Paraplex P-43/181, Stanpreg V-P/181, Polylite 8000/181, etc.

1.013 Alternate Designations.

1.02 Specifications, Table 1.02.

1.03 Composition

1.031 Materials included in this section are systems of resin and reinforcement combined into laminates by various processes. The system composition includes general purpose polyester resins and standard glass cloth reinforcements.

1.032 For normal structural applications a resin content of 30 to 40 per cent appears to be standard.

1.033 Due to wide spread acceptance and use, 181 weave glass cloth is used as a basic reinforcement for data reporting.

1.034 Other material systems utilizing different resins or reinforcements will be found elsewhere in this Manual. Individual primary materials are described in Manual IC.

1.04 Forms and Conditions Available

1.041 PolGc can be produced in shop by utilizing individual resins, powder or liquid, and glass cloth in the wet lay-up process.

1.042 Prepreg, B-Stage, material can also be readily secured with a variety of compositions.

1.043 PolGc can be secured in a variety of fabricated shapes such as: flat, curved or corrugated sheets; tubes; rods; or structural shapes including Zees, Tees, and Channels. Only properties of material in sheet form are reported herein.

1.044 Due to inherent properties of this material, it can be formed and produced in almost any shape or size.

1.05 Special Considerations

1.051 Careful consideration should be given to the recommendations and experience of material supplier with respect to handling, storage, processing and curing.

2. PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Thermal Degredation

2.011.1 Weight loss due to exposure to elevated temperatures, Fig. 2.011.1.

2.012 Conductivity

2.013 Expansion

2.014 Specific Heat

2.015 Diffusivity

2.016 Emissivity

2.017 Ablation

2.018 Other

TABLE 1.02

Source	No.	Title
Military	MIL-P-8013C	Plastic, Materials, Polyester Resin, Glass Fiber Base Low Pressure Laminates
Military	MIL-P 17549C (SHIPS)	Plastic, Laminates, Fibrous Glass Reinforced, Marine Structural
Military	MIL-R-7575B	Resin, Polyester, Low Pressure Laminates
Military	MIL-R-21607 (SHIPS)	Resins, Polyester, Low Pressure Laminating, Fire Resistant
ASTM	D709-55T	*Laminated Thermosetting Materials-Grade G-3

* This spec does not identify a specific resin.

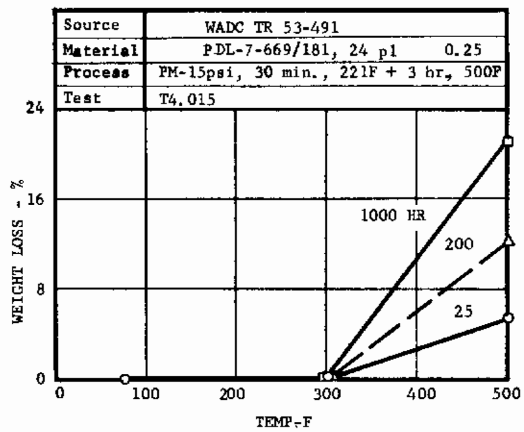

FIG. 2.011.1 WEIGHT LOSS DUE TO EXPOSURE TO ELEVATED TEMPERATURES

2.02 Electrical Properties

2.021 Resistivity

2.022 Conductivity

2.023 Dielectric Properties

2.023.1 Specified dielectric constants and loss tangents, Table 2.023.1.

2.023.2 Typical dielectric constants and loss tangents for various PolGc laminates, Table 2.023.2.

2.024 Magnetic Properties

2.025 Other

2.03 Other Physical Properties

2.031 Density

2.031.1 Typical specific gravity for various materials, Table 2.031.1.

2.032 Water Absorption

2.032.1 MIL-R-7575 specified water absorption after 24 hr. immersion is 0.5% max increase in weight.

2.032.2 Typical water absorption for various materials, Table 2.032.2.

2.032.3 Effect of exposure time on water absorption, Fig. 2.032.3.

2.032.4 Effect of immersion time and prestress on water absorption, Fig. 2.032.4.

2.033 Other

2.04 Chemical Properties

2.041 Chemical Resistance

2.041.1 Specified chemical resistance to certain fluids, Table 2.041.1.

2.041.2 Typical chemical resistance to certain fluids, Table 2.041.2.

2.042 Fire Resistance Properties

2.042.1 Combustion Rate. MIL-R-7575B specifies a maximum of 1.0 inch per minute as tested by T3.013 LP.

2.042.2 MIL-R-21607 specified flame resistance, Table 2.042.2.

2.042.3 Typical fire resistance properties of various materials, Table 2.042.3.

2.043 Environmental Properties

2.05 Nuclear Properties

TABLE 2.023.1

Source	MIL-P-8013C			MIL-R-7575B
Test	T5.032LP			Avg of 4
Specified Type	I	II (1)	III (2)	Grade A
Dielectric Constant				
Dry-Max	-	4.4	4.2	-
Wet-Max	-	4.6	4.4	-
Loss Tangent				
Dry-Max	-	0.045	0.020	-
Wet-Max	-	0.055	0.025	-

(1) 1 MC
(2) 8500 to 10,000 MC

TABLE 2.023.2

Source	Standard 1957		1961	Republic 1958	1960
Material	Stanpreg V-P/ 181-V	V-P4/ 181-V	V-72/ 181-V	Sun CFR 321a/ 150-181-V 0.12, 12 pl (1)	Hetron 92 (2)
	0.125, 12 pl				
Test	T5.032 LP				
Dielectric Constant					
Dry	4.10	4.23	4.2	3.99	4.07
Wet	4.10	4.37	4.227	3.98	4.02
Loss Tangent					
Dry	0.020	0.012	0.0104	0.00222	0.0148
Wet	0.020	0.013	0.0117	0.00273	0.0318

(1) Avg of 4
(2) Avg of 20

TABLE 2.031.1

Source	Standard 1957			1961	Repulic 1958	Convair, SD, 1956		
Material	Stanpreg V-P/ 181-V	V-P3/ 181-V	V-P4/ 181-V	V-P72/ 181-V	Sun CFR 321A 150-181-V 0.125 12 pl	Polylite 8000 181-V 0.125 15 pl (1)	120-V 0.125 30 pl (1)	Selectron 5016 181-V 0.125 12 pl (1)
Test	T2.052 LP							
rc	39.0	31.6	38.2	40.3	42.0	37.88	39.13	35.90
sp g	1.99	1.90	1.82	1.75	1.86	1.88	1.75	1.79

(1) Avg of 3

TABLE 2.032.2

Source	Standard					Convair		Fabricon	
	1957	1962	1957		1961	1956			
Material	Stanpreg V-P/ 181-V	V-P1/ 181-V	V-P3/ 181-V	V-P4/ 181-V	V-P72 181-V	Polylite 8000 181-V 0.125 15 pl (1)	120-V 0.125 30 pl (1)	Phenapreg L-P 5002 181-V 0.125	
	0.125, 12 pl								
Test	T2.072 LP								
rc	39.0	37.8	31.6	38.2	40.3	37.88	39.13	40 to 42	34 to 35
Δw 24 Hr % max	0.09		0.26	0.116	0.05			0.24	0.24
% avg		0.1							
30 day % avg						0.33	0.28		
Δ dimen 30 day % avg						0.01	0.0		

(1) Avg of 3

Source	FPL 1819, 1956
Material	Selectron 5003/181-114, 12 pl 0.125
Process	PM, 14 psi, 220 - 250F
Test	T2.073

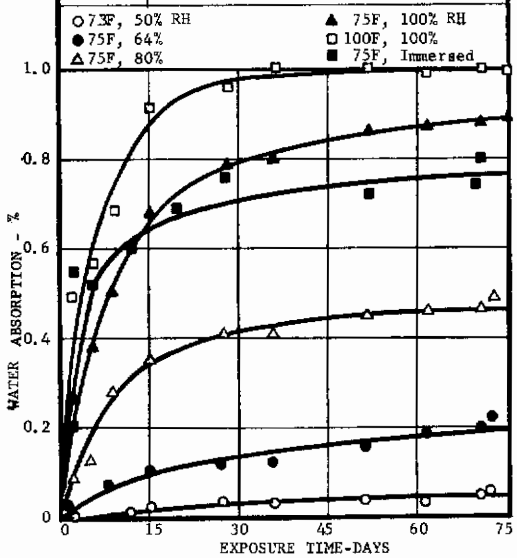

FIG. 2.032.3 EFFECT OF EXPOSURE TIME ON WATER ABSORPTION

Source	FPL 1856, 1956
Material	Selectron 5003/181 Volan A, 12 pl 0.125
Process	PM 14 psi, 90 min , 220 - 250F
Test	T2.073

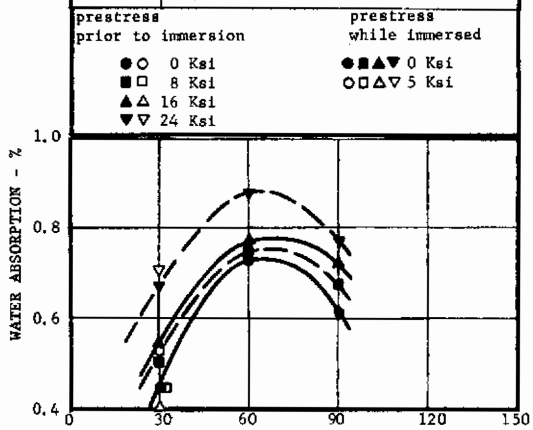

FIG. 2.032.4 EFFECT OF IMMERSION TIME AND PRESTRESS ON WATER ABSORPTION

TABLE 2.041.1

Source	MIL-R-7575B		
Immersion in Chemical fluid (1)	MIL-H-5606 Hydraulic fluid petroleum base	MIL-F-5566 Anti-icing fluid isopropyl alcohol	MIL-S-3136 Test fluids hydrocarbon & iso-octane
Test	T3.042 LP		
Δw % max	0.2	0.1	0.1
Δt % max	0.2	0.1	0.1

(1) σ_{fu} after immersion shall be reported.

TABLE 2.041.2

Source	Standard 1957						1961	
Material	V-P/181V		V-P3/181V		V-P4/181V		V-P72/181V	
	Stanpreg, 0.125, 12 pl							
Test	T3.0421P							
rc	39.0		31.6		38.2		40.3	
24 hr immersion	Δw %	Δt %	Δw %	Δt %	Δw %	Δt %	Δw %	Δt %
Hydraulic oil	0.11	0.00	0.01	0.04	+ 0.006	0.00	+ 0.02	+
Anit-icing fluid	0.02	0.00	0.04	0.02	- 0.011	0.00	- 0.02	+ 0.01
Ethylene glycol	0.47	0.00	0.04	0.09	+ 0.121	0.00	-	-
Hydrocarbon fluid	0.01	0.00	0.00	0.04	+ 0.064	0.00	- 0.05	+ 0.01

TABLE 2.042.2

Source	MIL-R-21607 (SHIPS)	
Material	Polyester (MIL-R-7575, type 1) glass cloth (MIL-Y-1140, style 1000) 0.5, 40 plies, Volan A	
Process	PM-S, 15 psi, 15 min, 212F + 24 hr, 212 F	
Test	T3.015LP	
Class	A - Translucent	B - Opaque
Ignition time-sec	55 min	70 min
Burning time-sec	125 max	65 max

TABLE 2.042.3

Source	Douglas 1957	Standard 1957				1961
Material	Vibrin 144/181 0.125	V-P/181-V		V-P3/ 181-V	V-P4/ 181-V	V-P72/ 181-V
		Stanpreg, 0.125, 12 plies				
Property and Method Flammability T3.013 LP T3.011 ASTM Flame resistance T3.015 LP	S.E.(3)	S.E.	S.E (1)	S.E.	(2)	S.E.

(1) No ignition after 600 sec
(2) 0.46 inch per minute
(3) S.E. - self extinguishing

TABLE 3.011

Source	MIL-P-8013C											
Material	Polyester/glass cloth - 0.125 ± 0.010											
Property (1)	Test	Specimen	Glass cloth designation 112 or 120	116	128 or 128-150	143 or 143-150	162	164 or 164-150	181 or 181-150	182 or 182-150	183	184 or 184-150
σ_{tu}, min -ksi wet (2) -ksi	T6.013LP	Type II	40 38	40 38	40 38	80 75	40 38	33 30	40 38	43 40	43 40	43 40
σ_{cu}, min -ksi wet (2) -ksi	T6.022LP		33 30	30 27	23 21	48 45	16 15	22 20	35 30	32 29	30 27	26 23
σ_{fu}, min -ksi wet (2) -ksi	T6.032LP		50 45	45 40	45 39	90 78	35 30	35 30	50 45	50 45	45 40	45 40
E_f, min-1000 ksi wet (2)-1000 ksi	T6.032LP		2.6 2.5	2.6 2.5	2.6 2.5	4.7 4.5	2.2 2.1	2.2 2.1	2.7 2.5	2.6 2.5	2.6 2.5	2.6 2.5

(1) All values minimum for average of 5
(2) 2 hr in boiling distilled water or, if results are questionable, 30 day soak in RT distilled water

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 MIL-P-8013C Specified Mechanical Properties, Table 3.011.

3.012 MIL-P-17549C Specified Mechanical Properties, Table 3.012.

3.013 MIL-P-7575B Specified Mechanclal Properties, Table 3.013.

3.02 Typical Mechanical Properties

3.021 Typical mechanical properties of PolGc Laminates with various cloth reinforcements, Table 3.021.

3.022 Typical Mechanical Properties of PolGc Laminates, Table 3.022a and 3.022b.

3.023 Typical Mechanical Properties of Cross Laminated and Combination Laminated PolGc Laminates, Table 3.023.

3.024 Typical Mechanical Properties of PolGc Laminates Produced by Various Processes, Table 3.024.

3.025 Typical Effects of Resin Contents on Mechanical Properties of PolGc Laminates, Table 3.025.

3.026 Typical Effects of Outdoor Weathering under Different Conditions on Mechanical Properties of PolGc Laminates, Table 3.026.

3.027 Typical Effects of Defects on Mechanical Properties of PolGc Laminates. Table 3.027.

TABLE 3.012

Source	MIL-P-17549C (SHIPS)			
Material	Polyester/glass cloth			
Property (1)	Test	Grade 1 181 or =	Grade 2 1000 or =	Grade 3 1044 or =
σ_{tu}, min -ksi	T6.013LP Type I	37	28	20
σ_{cu}, min -ksi wet(2) -ksi	T6.022LP	33 28	25 23	21 19
σ_{fu}, min -ksi wet(2) -ksi	T6.032LP	50 45	37 33	31 27
E_f, min-1000 -ksi wet(2)-1000 -ksi	T6.032LP	2.50 2.30	2.00 1.80	1.45 1.25
rc, range %	T2.042LP	35 to 43	42 to 52	49 to 59
vc, max %	T2.081	1.5	2	3

(1) Mechanical properties avg. of 5, rc & vc avg of 3
(2) 2 hr in boiling distilled water

Table 3.013

Source	MIL-R-7575B				
Material	Polyester/181 - 0.125				
Process	PM, 10-30 psi				
Property (1)	Test	Test Conditions Standard	160F after 1/2 hr	Outdoor Weathered(3) 90 days	1 year
σ_{tu}, min -ksi wet(2) -ksi	T6.013LP Type 2	40 38	- -	- -	- -
σ_{cu}, min -ksi wet(2) -ksi	T6.022LP	35 30	- -	- -	- -
σ_{fu}, min -ksi wet(2) -ksi	T6.032LP	50 45	40 -	45 -	45 -
E_f, min - 1000-ksi wet(2)-1000 -ksi	T6.032LP	2.5 2.5	2.3 -	2.5 -	2.5 -
Hardness BHN	T6.063	55	-	-	-
rc %	T2.042LP	to be			
Sp g	T2.052LP	reported			

(1) Avg of 5
(2) 30 days in water
(3) Samples shall show no cracking, crazing delamination, nor any other visible deterioration after exposure.
(4) σ_{fu} after immersion in chemical fluids shall be reported, See Table 2.041.1

TABLE 3.021

Source		FPL 1820A 1960		FPL 1821,1961			FPL 1821A 1959	FPL 1820A 1960				FPL 1823 1958	FPL 1803 1956	FPL 1820A 1960			
Material		Selectron 5003/Gc-114 81 0.230-0.233 23pl		112 84pl	116 70pl	143 26pl	162 0.257 16pl	164 0.257-0.244 16pl		181 0.261-0.265 23pl		181 0.25 23pl	181 0.250 25pl	183 0.244-0.246 14pl		57x 0.241-0.243 36pl	
Process		PM, 14 psi, 100 min., 220-250F BZP, 0.8%										PM, 13 psi, 120 min 220-250F (2)	265F (1)	PM, 14 psi, 100 min, 220-250F			
Test		FPL (3)															
Property	θ	Dry	Wet	Dry	Dry	Dry	Dry	Dry	Wet	Dry	Wet	Dry	Dry	Dry	Wet	Dry	Wet
rc -%	-	33.4-34.4		44.9	36	31.3	41	37.3-37.8		37.4-38.1		2.74	36	36.4-37		38.3	
Sp g	-	1.85		1.70	1.83	1.85	1.72	1.8-1.79		1.77		1.75	1.82	1.85		1.77	
σ_{tu} -ksi	0 45 90	50.16 21.04 49.8	42.2 13.38 38.3	42.70 20.6 38.7	47.0 22.8 46.7	89.85 14.0 10.75	37.6 16.35 20.6	35.13 18.96 31.30	29.27 13.86 24.5	43.17 19.08 38.8	36.91 14.12 30.98	42.94 20.76	45.46 19.77 46.16	51.83 21.120 48.2	44.580 14.06 40.94	72.04 15.06 14.69	62.21 10.69 11.31
σ_{tp}(i) -ksi	0 45 90	8.09 8.04	8.09 7.7	11.8 9.8	6.82 8.20	 2.65	7.94 4.56	7.21 5.66	5.4 4.74	8.22 6.70	8.17 6.52	11.92 4.61	8.47 3.34 8.69	8.61 6.79	8.64 7.05	32.09 3.0	25.47 2.56
σ_{tp}(s) -ksi	0 45 90	29.0 2.67 28.94	24.81 2.39 23.95	29.5 3.76 27.0	29.3 3.74 33.1	61.70 3.89 8.46	19.75 3.46 10.20	17.0 2.59 14.61	11.08 2.67 9.22	31.66 3.01 25.15	23.96 2.33 19.86	31.04 7.12	31.16 4.92 31.56	28.02 3.03 25.98	24.73 2.09 21.16	58.11 2.88 10.68	48.34 1.96 8.97
σ_{cu} -ksi 9 yr storage	0 45 90 0	41.31 37.71 42.3	25.93 22.69	36.85 32.9	28.9 26.45	52.00 21.9	19.10 18.30	24.26 21.81 24.0	13.39 12.79	44.52 39.38 46.3	21.97 22.49	43.22 22,15	43.96 20.29 41.54	37.11 35.15 40.4	20.42 20.37	60.58 23.5 58.9	37.06 16.7
σ_{cp} -ksi 9yr storage	0 45 90 0	29.35 29.44 19.0	22.56 17.84	23.25 21.6	17.95 17.65	36.7 11.45	11.25 10.20	13.84 13.53 12.25	7.18 6.91	26.59 23.58 21.35	15.61 13.26	32.43 5.03	31.39 6.83 30.88	27.28 23.05 21.7	15.18 13.12	40.1 12.4 33.9	33.9 4.01
σ_{cy}(0.2%) -ksi	0 45 90	41.31 37.71	25.93 22.69	36.85 32.9	28.9 26.45	52.00 20.65	19.10 18.30	24.26 21.81	13.13 12.57	44.52 38.66	21.97 22.49	43.22 11.42	43.96 13.25 41.54	37.11 35.15	20.42 20.37	60.58 22.97	37.06 14.69
σ_{fu} -ksi	0 90	53.35 47.9	35.48 31.85	58.25 48.35	43.8 38.80	93.55 18.10	35.0 26.9	37.54 34.0	25.44 22.92	56.49 31.85	35.28 50.58			53.44 51.23	34.93 34.79	87.21 21.51	57.02 18.68
σ_{fp} -ksi	0 90	42.50 41.22	19.27 22.43	31.0 26.45	28.65 26.30	83.30 5.62	17.2 11.3	18.38 16.52	10.02 9.14	39.41 26.28	25.91 22.88			31.53 24.58	19.12 17.76	76.02 7.97	49.12 5.38
σ_{fy}(0.2%)-ksi	0 90	53.35 47.49	35.48 31.85	58.25 48.35	43.80 38.55	93.55 10.30	32.55 22.85	34.65 30.86	21.26 18.96	56.10 50.32	35.28 32.29			52.12 50.7	34.93 34.63	87.21 16.48	57.02 11.8
σ_{su} -ksi	0	12.44		13.6	11.45	12.15	11.7	11.37								10.41	
σ_{sp} -ksi	0	2.0		1.92	1.66	2.52	2.22	2.18								1.95	
σ_{sy}(0.2%)-ksi	0	4.15		4.07	3.42	4.6	4.81	4.96								4.13	
E_t(i)-1000ksi	0 45 90	3.28 3.17	2.88 3.02	2.69 2.64	3.57 2.95	 1.69		2.74 2.48	2.59 2.24	2.83 2.77	2.73 2.44		3.42 1.91 3.2	3.11 3.11	3.0 2.73	4.06 1.42	3.84 1.16
E_t(s)-1000ksi	0 45 90	2.63 2.08 2.6	2.18 1.2 2.61	2.39 1.54 2.24	3.01 1.83 2.64	5.69 1.66 0.44		2.3 1.81 1.95	2.15 1.11 1.85	2.18 1.87 2.07	2.26 1.28 1.94		2.46 1.69 2.35	2.56 1.28 2.30	2.63 2.08 2.6	3.75 1.36 0.61	3.56 0.92 0.58
E_c -1000-ksi 9yr storage	0 45 90 0	3.53 3.32 3.62	3.0 2.67	2.82 2.63	3.20 3.12	5.18 1.59	2.82 2.10	2.85 2.59 2.87	2.38 2.26	3.10 2.82 3.14	2.78 2.58	3.074 1.77	3.16 1.99 3.39	3.24 2.95	3.53 3.32 3.62	4.24 1.65 4.34	4.12 1.37
E_f -1000-ksi	0 90	3.04 2.69	3.04 2.66	2.59 2.4	2.86 2.69	4.75 1.44	2.47 1.720	2.42 2.16	2.42 2.08	2.58 2.59	2.37 2.17			2.99 2.69	3.04 2.69	4.12 1.42	3.79 1.26
G -1000-ksi	0 45 90	0.689 to 0.693		0.66	0.570	0.76	0.580	0.566 to 0.623		0.679 to 0.726			1.62 0.607 1.16	0.672 to 0.687		0.54 to 0.584	
Hardness Barcol		68		69	71	70	63	66-69		67		69		66-69		67-69	

(1) 1.6% 50/50 Tricreoyl phosphate and BZP (2) Same as (1) + 3.3% O_2 (3) Avg of 3 or more

MATERIAL SYSTEMS

TABLE 3.022a

Source	Douglas 1957				Standard 1957		Standard 1962				Standard 1957				Standard 1961	
Material	V-P/181-V 0.125-0.131, 12 pl						V-P1/181-V 12 pl		Stanpreg V-P1A/82-V 0.123, 7 pl		V-P3/181-V 0.125, 12 pl		V-P4/181-V 0.125, 12 pl		P-72/181-V 0.125, 12 pl	
Process	VB, 1.5 hr, 270F		PM-S, 1 hr, 275F		PM, 30 psi, 60 min, 275F		VB, 30 min 280F		VB, 30 min, 275F		PM, 30 psi, 30 min, 150F		PM, 30 psi, 30 min, 270F		PM, 5-60 min, 260F	
Test	AIA (2)				LP-406 (2)											
Property	Dry	Wet(1)	Dry	Wet(1)	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
rc -%	37.5		44.5		39.0		37.8		37.7		31.6	3	38.2		40.3	
Sp g -					1.99		1.82		1.85		1.9		1.82		1.75	
σ_{tu} -ksi					51.9	50.1	50.7	47.4			50.1	52.4	45.1	43.0	54.2	51.4
σ_{cu} -ksi					52.3	38.2	36.64	36.12			45.8	17.1	41.6	34.9	44.1	42.9
σ_{fu} -ksi	67.9	59.1	64.1	54	73.4	66.5	54.33	52.35	60.07	52.61	75.1	66.2	58.5	55.8	60.2	60.9
σ_{fu}-(3)-ksi					69.1						73.2		61.3		47.4	
σ_{fu}, 160F -ksi	31.1 (2)		29.3 (2)		48.6						44.4		52.6		55.2	
σ_{fu}, 200F -ksi	31.1		29.3													
E_{fs}, 200F -ksi	2.94	2.68	3.01	2.71												
σ_{fp} -ksi					47.0						48.3		58.5		39.5	
E_t(i) -1000 ksi							2.9	2.8								
E_f-1000 ksi					3.23	3.05					3.3	3.20	2.64	2.23	3.2	3.1
E_f-(3)-1000 ksi					2.8						4.0		2.49		2.66	
E_f, 160F -1000 ksi					2.7						4.0		2.51		2.8	
E_{fs}-1000ksi	2.94 (2)	2.68 (2)	3.01 (2)	2.71 (2)												
Hardness Barcol					68.5				60		68		68		68	

(1) 5 hr boil

(2) 200F

(3) 3 mos outdoor weathering

(4) Avg of 3 or more

TABLE 3.022b

Source	Douglas 1957		Fabricon		WADC TR 53-491	FPL 1823, 1958
Material	Vibrin 144/ 181-V 0.122-0.125		Phenopreg LP6002/ 181-V 0.125		Plaskon 911-11/ 181-114 23 pl 0.25	Plaskon 911-11/ 181-114 23 pl, 0.25
Process	PM-S, 1 hr, 275F 0.2% BZP		PM, 15-200psi or VB, 10-15 min, 275-300F		PM, 15 psi 30 min, 220F + 3 hr, 500F 1% Luberco ATC	PM, 14 psi, 90 min, 220F
Test	AIA-ARTC(1)		LP-406 (1)			FPL (1)
Property	Dry	Wet(2)	Dry	Wet	Dry	Dry
rc -%	38.8	--	40-42	--	35.8	40.6
Sp g -	--	--	--	--	--	1.76
σ_{tu} -Ksi	--	--	51.2	53.1	36	42.55
σ_{cu} -Ksi	--	--	--	---	35.45	31.83
σ_{fu} -Ksi	66.1	59.8	73.2	65.7	41.1	--
σ_{fu}(200F)-ksi	28.9	--	--	---	---	--
(500F)-Ksi	--	--	--	---	32.9	--
E_f -1000Ksi	--	--	3.2	3.2	2.48	--
E_f(200F)-1000 Ksi	--	--	2.9	---	---	--
(500F)-1000 Ksi	--	--	--	---	2.71	--
Hardness Barcol	--	--	70	---	---	71

(1) Avg of 3 or more (2) 2 hr boil

TABLE 3.023

Source		FPL 1821, 1961		FPL 1848 1960		FPL 1823 1958	FPL 1821 1961	FPL 1821-A, 1959			FPL, 1821, 1961
Material		Selectron 5003									
		112-114 84 pl XL	116-114 70 pl XL	117-V 0.247 XL		143-114 26 pl XL		112-114 facing + 162-114 core 0.262 1-16-1pl	0.264 6-14-6pl	0.260 11-12-11pl	112-114 + 143-114 Alternate 21-20 pl
Process		PM, 14psi, 100min 220-250F BZP, 0.8%		PM, 7psi, 90 min 220-250F BZP, 0.8%		PM, 13psi, 120 min 220-250F (3)		PM, 14 psi, 100 min, 220-250F BZP, 0.8%			
Test		FPL (1)									
Property	θ	Dry	Dry	Dry	Wet (2)	Dry	Dry	Dry	Dry	Dry	Dry
rc -%	-	44.9	36	28.2		33	31.3	41.1	42	42	34.6
Sp g -	-	1.7	1.83	1.88		1.81	1.85	1.71	1.71	1.71	1.84
σ_{tu} -ksi	0	39.15	45.3	54.7	53.32	48.3	51.2	35.6	36.05	37.9	79.95
	45	21.05	22.35				18.8	16.0	16.4	16.2	16.5
	90	39.5	44.75				51.05	19.9	22.4	24.3	18.65
σ_{tp}(i) -ksi	0	10.7	7.11			12.72	7.11	6.4	8.12	8.4	
	45										
	90	9.5	7.25				7.25	4.33	4.66	5.52	3.13
σ_{tp}(S) -ksi	0	23.7	30.2			37.75	30.2	18.5	20.95	24.5	59.6
	45	3.25	3.8				3.85	2.58	2.58	2.38	3.56
	90	25.05	27.35				27.35	11.75	12.85	14.75	14.35
σ_{cu} -ksi	0	38.6	28.9	46.84	37.24	37.58	34.05	23.9	22.10	23.40	50.1
	90	37.05	28.9				41.05	21.75	21.45	23.25	24.45
9yr storage -ksi	0							21.0	24	23.4	
σ_{cp} -ksi	0	23.35	14.55			20.85	19.5	16.95	16.45	16.75	39.00
	90	18.25	19.30				21.8	15.7	17.3	17.80	14.30
9yr storage	0							13.2	14.4	13.00	
σ_{cy}(0.2%) -ksi	0	38.6	28.9			37.58	33.25	23.90	22.10	23.40	38.6
	90	37.05	29.2				40.85	21.75	21.45	23.25	37.05
σ_{fu} -ksi	0	51.45	43.20				54.65	38.8	43.75	55.05	86.40
	90	51.5	41.15				61.10	28.8	33.75	27.8	28.00
σ_{fp} -ksi	0	29.95	31.10				32.45	24.55	24.05	28.2	75.2
	90	27.30	27.65				34.00	12.2	15.25	14.95	8.34
σ_{fy}(0.2%) -ksi	0	51.45	43.20				51.4	38.6	43.75	54.65	86.4
	90	51.45	41.15				60.4	26.25	33.75	36.8	17.15
σ_{su} -ksi	0	14.45	11.30	4.32	4.09		14.1	10.3	10.85	10.9	11.7
Interlaminar -ksi	45			5.11	4.86						
σ_{sp} -ksi	0	2.38	1.64				2.57	2.24	2.16	2.54	2.38
σ_{sy}(0.2%) -ksi	0	4.52	3.55				4.9	4.93	4.58	4.85	4.74
E_t(i) -1000 -ksi	0	2.45	3.06			2.63	3.1	2.76	2.67	2.69	
	90	2.66	3.17				3.0	2.04	1.96	2.10	2.19
E_t(s) -1000 -ksi	0	2.12	2.76			2.24	2.82	2.37	2.25	2.24	5.07
	90	2.25	2.78				2.75	1.38	1.40	1.49	0.99
9yr storage-1000-ksi	0	1.46	1.69				1.7	1.45	1.35	1.53	1.68
E_f -1000 -ksi	0	2.51	2.86				2.91	2.69	2.68	2.73	4.32
	90	2.53	2.86				3.16	2.0	2.11	2.27	1.76
G -1000 -ksi	0	0.57	0.62				0.63	0.570	0.56	0.51	0.67
Hardness Barcol		69	71	68		65	70	69	69	69	72

(1) All avg of 3 or more
(2) 2 Hr boil
(3) 1.6% 50/50 Tricreoyl phosphate and BZP containing 3.3% oz

TABLE 3.024

Source		Convair, 1956				FPL 1848, 1960								Convair 1957	
Material		Polylite 8000/ 120-V 0.125 30pl		Polylite 8000/ 181-V 0.125 15pl		Selectron 5003/ 112-V 0.250 92pl		Selectron 5003/ 181-V, 23pl 0.244		0.217		0.192		Selectron 5016/181/V 0.125 12pl	
Process		VB, 10-12 psi, 2 hr, 190F (2)		(3)		PM, 10 psi, 90 min, 220-250F 0.8% BZP		PM, 90 min, 220-250F, 0.8% BZP 5 psi		14 psi		50 psi		VB, 12 psi, 1 hr, 170F (4) + 1 hr, 250F	
Test		LP-406(5)						FPL(5)						LP-406(5)	
Property	θ	Dry	Wet	dry	Wet	Dry	Wet(1)	Dry	Wet(1)	Dry	Wet(1)	Dry	Wet(1)	Dry	Wet
rc -%		39.1		37.8		39.7		37.2		32.2		26.5		35.9	
Sp g		1.75		1.88		1.75		1.79		1.86		1.94		1.79	
σ_{tu} -ksi	0	48.6	45.5	51.8	50.1	46.36	48.49	50.92	47.85	55.70	54.05	58.1	57.99	50.7	42.7
σ_{cu} -ksi	0 45	50.8	40.7	51.4	40.2	49.52	38.96	46.9	41.56	43.44	38.1	44.82	34.06	44.3	38.1
σ_{fu} -ksi	0 45	68.4	63.4	74.4	59.7									68.9	55.8
σ_{su} -ksi	0 45														
Interlaminar	0 45					5.49 5.46	5.08 5.75	4.8 5.26	4.7 4.55	4.78 6.23	4.9 5.6	4.71 6.12	4.16 5.82		
E_f -1000ksi	0	4.3	2.9	4.1	3.2									2.9	2.7
E_f(160F) -1000ksi	0	4.3	2.9	4.1	3.2									2.9	2.7
Hardness Barcol		72		69		69		68		71		73		78	

(1) 2 hr boil (2) 0.25% Cobalt-napthanate + 0.5% MEK peroxide (3) 0.07% Cobalt-napathanate + 1% MEK peroxide
(4) 0.4% Selectron 5923 + 1% cumene Hydroperoxide (5) Avg of 3 or more

TABLE 3.025

Source	Convair, Process Control Report, 1961																
Material	Polylite 8000/181-V 0.125										Poly 2/R/181-V 0.125						
Process	PM							VB			PM					VB	
Test	LP-406, Avg of 5																
rc -%	27.4	35.6	36.7	36.9	39.1	40.1	40.7	35.8	36.3	41.0	27.3	33.1	35.8	36.4	37.9	35.6	38.7
Spg	1.9	1.9	1.9	1.8	1.8	1.8	1.8	1.8	1.9	1.7	1.8	1.8	1.8	1.7	1.9	1.7	1.7
σ_{tu}-Ksi dry	41.2	44.1	48.2	45.1	38.8	42.2	48.8	36.1	50.2	41.7	47.5	49.2	48.1	41.1	42.8	40.4	41.3
wet	37.0	44.9	45.2	44.0	39.5	41.9	44.1	35.8	42.3	39.9	43.1	47.2	47.4	38.1	43.9	34.5	31.9
σ_{cu}-Ksi dry	46.5	----	59.7	57.6	50.6	56.5	----	52.8	35.4	35.5	41.2	49.0	29.7	47.8	43.3	31.3	25.3
wet	40.7	----	59.9	34.9	35.8	49.1	----	32.9	21.1	30.0	32.9	47.8	24.6	44.4	33.3	22.3	16.4
σ_{fu}-Ksi dry	67.3	74.0	63.4	69.5	61.9	64.4	61.3	63.3	65.1	67.0	62.2	76.2	54.2	66.0	64.7	51.4	41.3
wet	60.3	66.6	54.3	57.6	55.2	63.3	44.8	55.2	47.1	58.5	60.8	62.6	56.0	51.4	58.7	33.9	33.6
E 1000Ksi dry	3.4	3.4	3.4	4.1	2.9	4.0	3.4	2.4	2.8	2.3	2.7	4.1	2.8	3.2	3.0	2.4	2.1
wet	3.1	3.2	3.3	4.1	2.7	3.2	3.2	2.4	2.6	2.5	2.7	4.1	2.7	3.0	2.8	2.3	1.5
Hardness Barcol	72.0	70.0	68.0	68.0	60.0	65.0	68.0	62.0	67.0	----	70.0	35.6	58.0	60.0	70.0	47.0	35.6

TABLE 3.026

Source	MIL-Handbook ANC-17 Part 1, 1955							
Material	Selectron 5003 Garan		Selectron 5003 (RT-setting) Garan		Plaskon 911-11 Garan		Dryply 81 Garan	
Test	T6.013 LP and T6.023 LP							
3 yr outdoor weathering conditions	Arid	Salt	Temperate	Salt	Temperate	Salt	Artic	Salt
σ_{tu} -Ksi	41.3	44.1	42.3	46.1	43.0	39.2	45.8	41.1
change from control - %	-12	-6	-4	+5	-1	-10	+20	+8
σ_{cu} -Ksi	40.7	49.7	52.0	53.9	52.2	45.8	54.8	46.7
change from control - %	+7	+31	+48	+54	+6	+21	+64	+39

TABLE 3.027

Source	FPL 1814, 1960							
Material	Selectron 5003/181-114, 12 pl							
Process	PM, pressure indicated, 100 min, 220-250F							
Test	T6.013 LP and T6.023 LP							
Property	DEFECTS: None	Resin Content High 43%	Low 31%	Low 38%	Wrinkle in one surface Shallow	Deep	Butt Joints	Lab Joints
cure press -psi	14	4	14	50	14	14	14	14
t -in	0.129 to 0.128	0.146 to 0.145	0.114 to 0.113	0.104	0.127 to 0.131	0.131	0.126 to 0.128	0.123
No. spec	8	8	8	8	4	4	6	6
σ_{tu} -Ksi	50.05	41.51	53.10	56.18	40.10	34.70	23.81	43.96
σ_{tp}(i)-Ksi	7.65	6.3	6.76	8.11	9.11	7.28	6.25	7.25
σ_{tp}(s)-Ksi	33.31	26.96	33.44	37.05	27.20	26.20	19.33	28.62
σ_{cu} -Ksi	31.93	33.81	29.04	28.2	31.83	23.25	33.79	31.55
σ_{cp} -Ksi	21.66	22.84	23.27	18.88	19.36	19.30	23.97	21.42
E_t(i)-1000 Ksi	3.33	3.09	3.7	4.0	3.14	2.92	3.07	3.39
E_t(s)-1000 Ksi	2.81	2.52	3.14	3.34	3.84	2.68	2.73	2.97
E_c-1000 Ksi	3.29	2.97	3.59	3.79	3.23	3.13	3.11	3.6

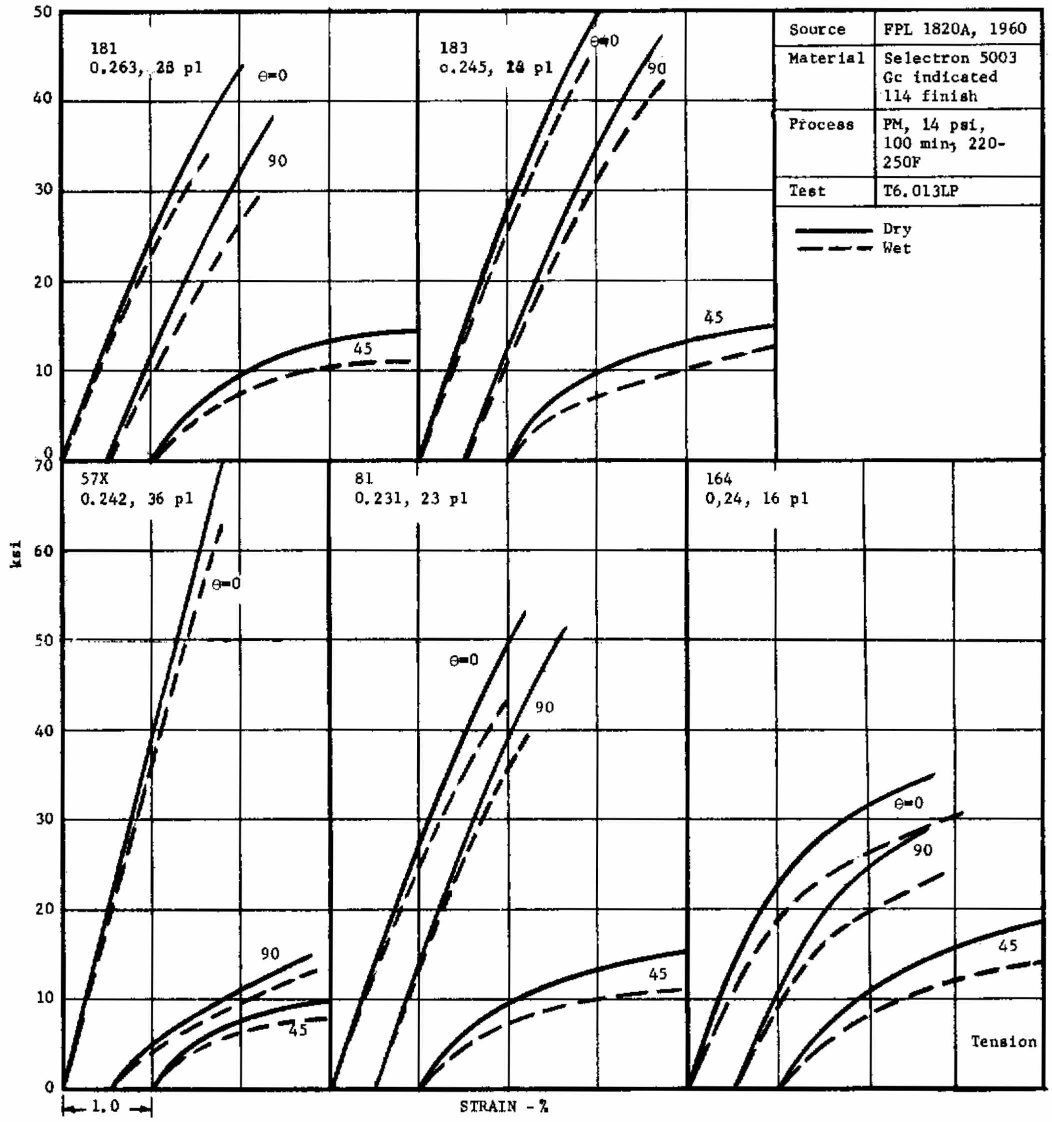

FIG. 3.031.1 AVERAGE STRESS STRAIN CURVES FOR PolGc LAMINATES WITH VARIOUS CLOTH REINFORCEMENTS

3.03 Tension Properties

3.031 Stress Strain Relationships

3.031.1 Average stress strain curves for PolGc laminates with various cloth reinforcements, Fig. 3.031.1.

3.031.2 Average stress strain curves for PolGc laminates at various angles θ, Fig. 3.031.2.

3.031.3 Envelopes of stress strain curves for typical PolGc laminate, Fig. 3.031.3.

3.031.4 Stress strain curves at room and elevated temperatures for typical PolGc laminate, Fig. 3.031.4.

3.032 Physical Effects

3.032.1 Effect of thickness on tension properties of PolGc Laminates, Fig. 3.032.1.

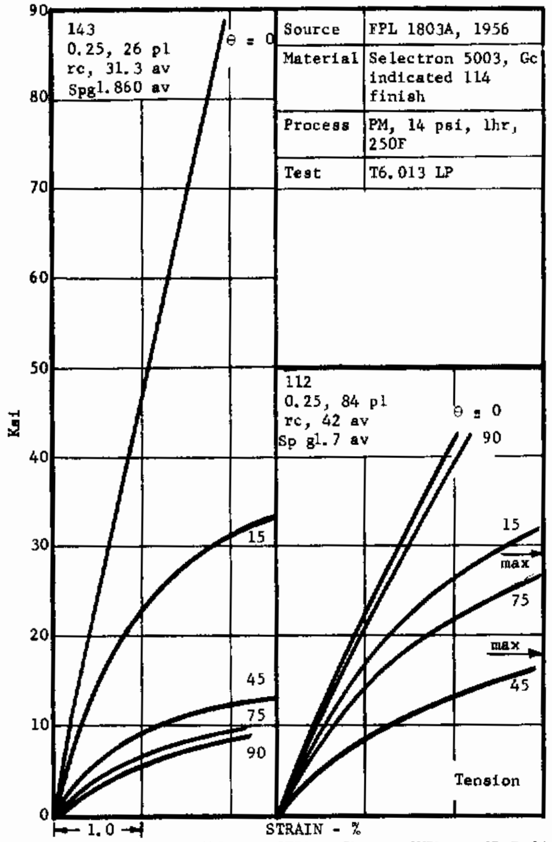

FIG. 3.031.2 AVERAGE STRESS STRAIN CURVES FOR PolGc LAMINATES AT VARIOUS ANGLES θ.

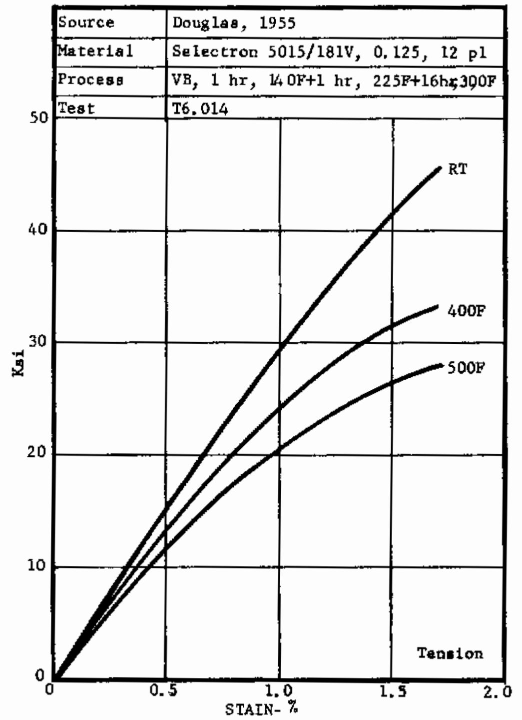

FIG. 3.031.4 STRESS STRAIN CURVES AT ROOM AND ELEVATED TEMPERATURES FOR TYPICAL PolGc LAMINATE

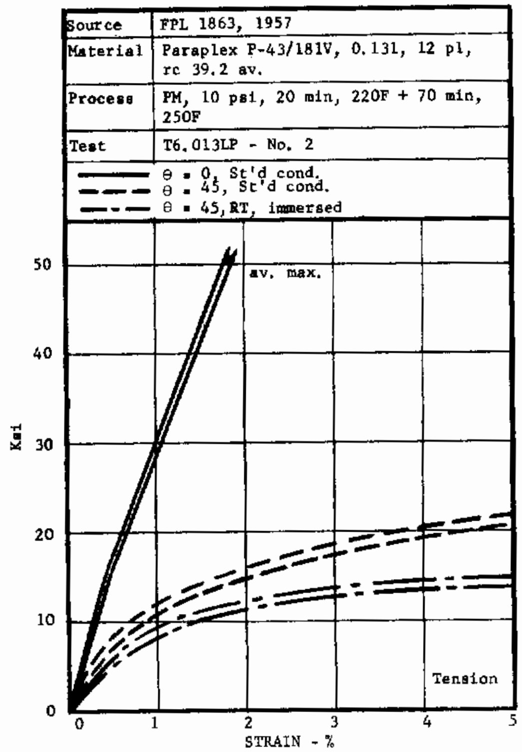

FIG. 3.031.3 ENVELOPES OF STRESS STRAIN CURVES FOR TYPICAL PolGc LAMINATE

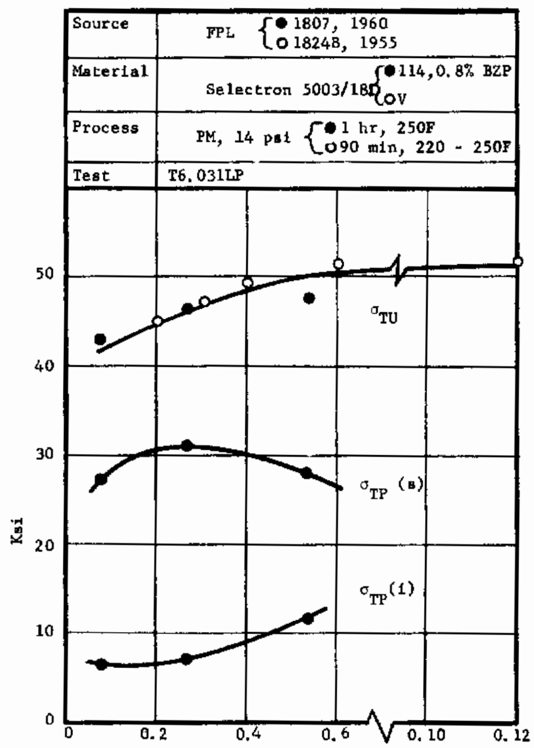

FIG. 3.032.1 EFFECT OF THICKNESS ON TENSION PROPERTIES OF PolGc LAMINATES

3.032.2 Effect of thickness and voids on tension properties of PolGc laminates, Fig. 3.032.2.

3.032.3 Effect of thickness and surface sanding on tension properties of PolGc laminates, Fig. 3.032.3.

3.032.4 Effect of test direction on tension properties of PolGc (112 cloth) laminate, Fig. 3.032.4.

3.032.5 Effect of test direction on tension properties of PolGc (143 cloth) laminate, Fig. 3.032.5.

3.033 Processing Effects. See Section 3.02.

3.034 Environmental Effects

3.034.1 Effect of test temperature on tension strength of PolGc (Selectron) laminate, Fig. 3.034.1.

3.034.2 Effect of test temperature on tension strength of PolGc (PDL-7-669) laminate, Fig. 3.034.2.

3.034.3 Effect of test temperature and test direction on tension strength of PolGc laminate, Fig. 3.034.3.

3.034.4 Effect of exposure and test temperature on tension strength of PolGc laminate, Fig. 3.034.4.

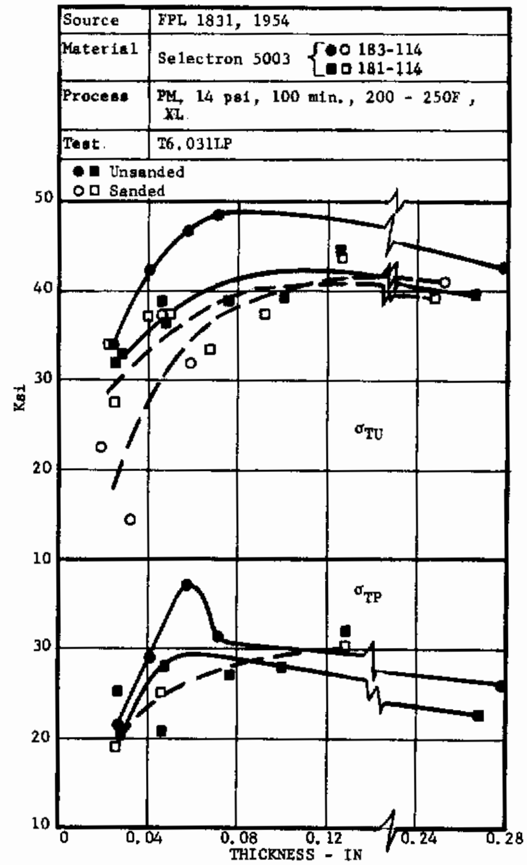

Fig. 3.032.3 EFFECT OF THICKNESS AND SURFACE SANDING ON TENSION PROPERTIES OF PolGc LAMINATES

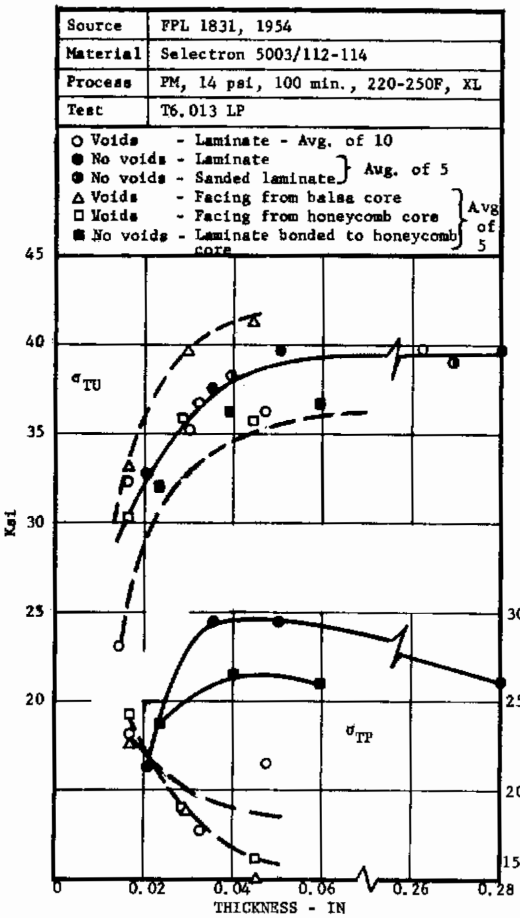

Fig. 3.032.2 EFFECT OF THICKNESS AND VOIDS ON TENSION PROPERTIES OF PolGc LAMINATES

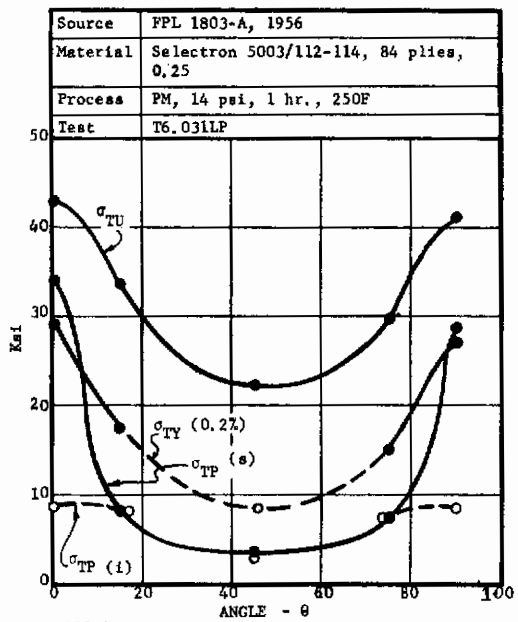

Fig. 3.032.4 EFFECT OF TEST DIRECTION ON TENSION PROPERTIES OF PolGc (112 cloth) LAMINATE

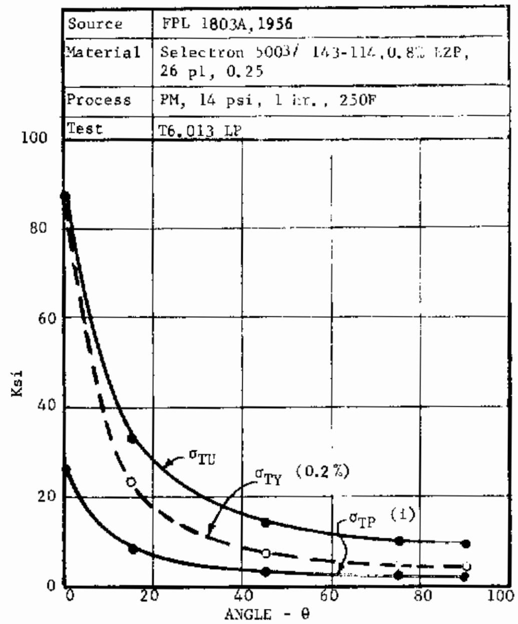

Fig. 3.032.5 EFFECT OF TEST DIRECTION ON TENSION PROPERTIES OF PolGc (143 cloth) LAMINATE

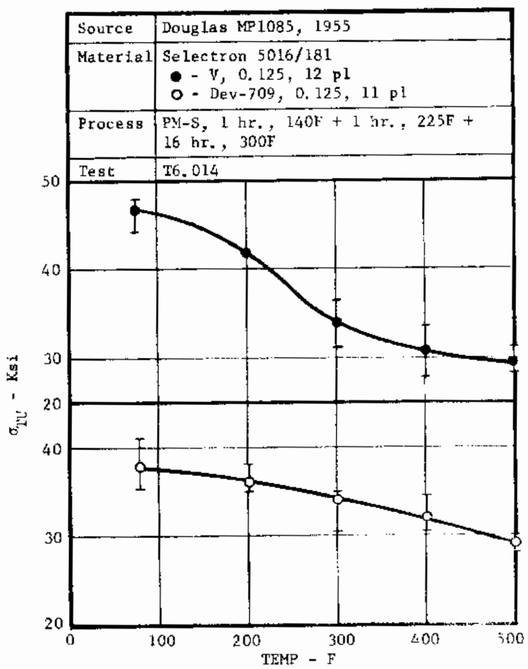

Fig. 3.034.1 EFFECT OF TEST TEMPERATURE ON TENSION STRENGTH OF PolGc (SELECTRON) LAMINATE

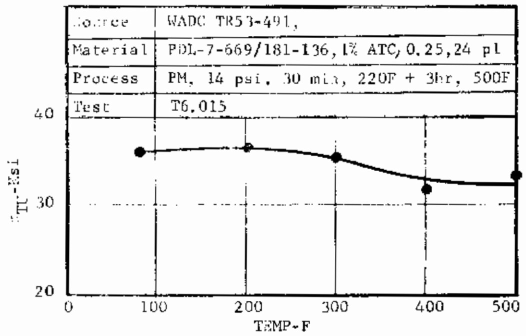

Fig. 3.034.2 EFFECT OF TEST TEMPERATURE ON TENSILE STRENGTH OF PolGc (PDL-7-669) LAMINATE

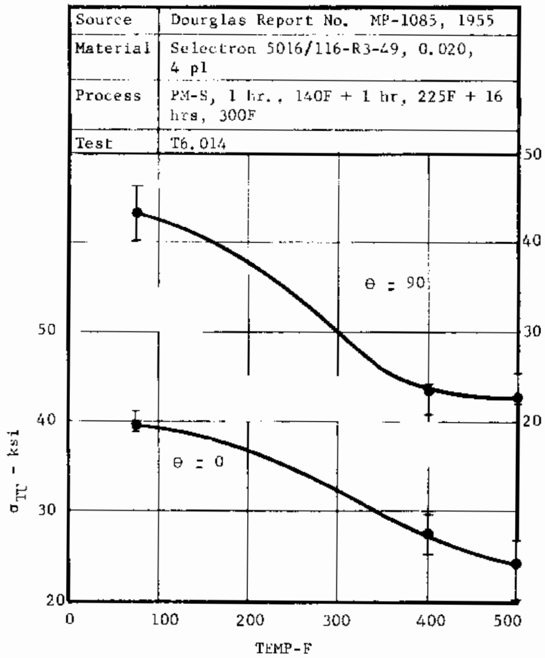

FIG. 3.034.3 EFFECT OF TEST TEMPERATURE AND TEST DIRECTION ON TENSION STRENGTH OF PolGc LAMINATE

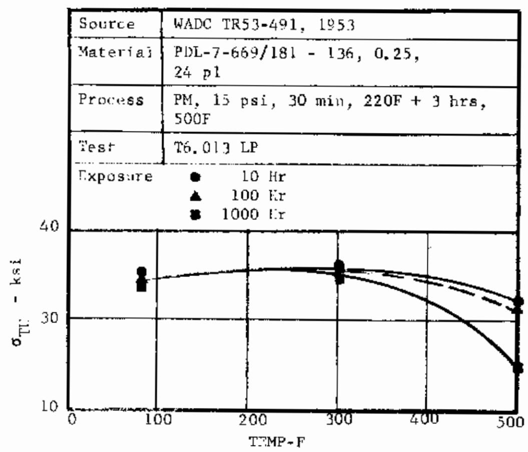

Fig. 3.034.4 EFFECT OF EXPOSURE AND TEST TEMPERATURE ON TENSION STRENGTH OF PolGc LAMINATE

3.035 Other effects

3.035.1 Effect of prestress at room temperature on tension properties of PolGc laminates, Table 3.035.1.

3.04 Compression Properties

3.041 Stress Strain Relationships

3.041.1 Average stress strain curves for PolGc laminates with various cloth reinforcements, Fig. 3.041.1.

3.041.2 Average stress strain curves for PolGc laminates at various angles θ, Fig. 3.041.2.

3.042 Physical Effects

3.042.1 Effect of thickness on compression properties of PolGc laminate, Fig. 3.042.1.

3.042.2 Effect of thickness and specimen type on compression strength of PolGc laminates, Fig. 3.042.2.

3.042.3 Effect of thickness and voids on compression strength of PolGc laminates, Fig. 3.042.3.

3.042.4 Effect of test direction on compression properties of PolGc (112 cloth) laminate, Fig. 3.042.4.

TABLE 3.035.1

Source	FPL 1811, 1957					
Material	Selectron 5003/Gc Indicated					
Process	PM, 14 psi, 100 min., 220-250°F					
Test	T6.013LP					
Prestress				Property after Prestress		
σ_{tp}	σ_t(max)	E_t	No. of Runs	σ_{tp}	σ_{tu}	E_t
Gc = 181-114, 0.125, 12 pl						
-	0	-	6 Avg	6.77	47.60	3.18
6.47	10.7	3.18	3	11.87	50.55	3.10
7.09	18.24	2.97	1	18.24	48.33	2.97
7.51	19.71	3.25	2	19.71	46.14	2.92
5.34	19.58	2.96	1	19.5	44.4	2.67
8.75	24.79	3.10	1	24.79	47.47	2.92
6.7	25.83	2.80	1	25.83	46.50	2.79
7.47	32.02	3.42	3	32.02	52.25	3.07
6.89	35.85	2.92	3	20.22	46.80	2.87
7.01	38.84	3.43	1	30.21	50.71	3.21
8.35	35.17	2.96	1	22.26	44.22	2.64
6.27	41.79	3.13	1	31.34	48.17	2.94
6.82	41.92	2.87	1	30.22	46.02	2.60
Gc = 143-114, 0.125, 13 pl						
-	0	-	6 Avg	69.32	85.98	5.23
-	18.27	4.94	3	52.79	89.34	4.94
-	24.74	5.37	1	59.80	85.16	5.37
-	32.81	5.30	3	65.61	81.4	5.30
-	39.18	5.46	1	63.92	87.23	5.46
-	45.25	5.66	3	62.49	84.03	5.66
-	52.46	5.38	1	60.53	84.34	5.38
-	56.14	5.16	3	72.18	87.02	5.16
54.2	60.23	4.77	1	54.20	87.33	4.77
-	64.97	5.11	1	71.07	85.69	5.11
-	73.72	5.28	1	79.87	87.85	5.28
-	68.98	5.28	1	-	78.62	5.28
62.89	79.66	5.26	1	62.89	86.06	5.26

Source	FPL 1820-A, 1960
Material	Selectron 5003/Gc indicated
Process	PM-14psi, 100 min, 220-250F
Test	T6.022LP

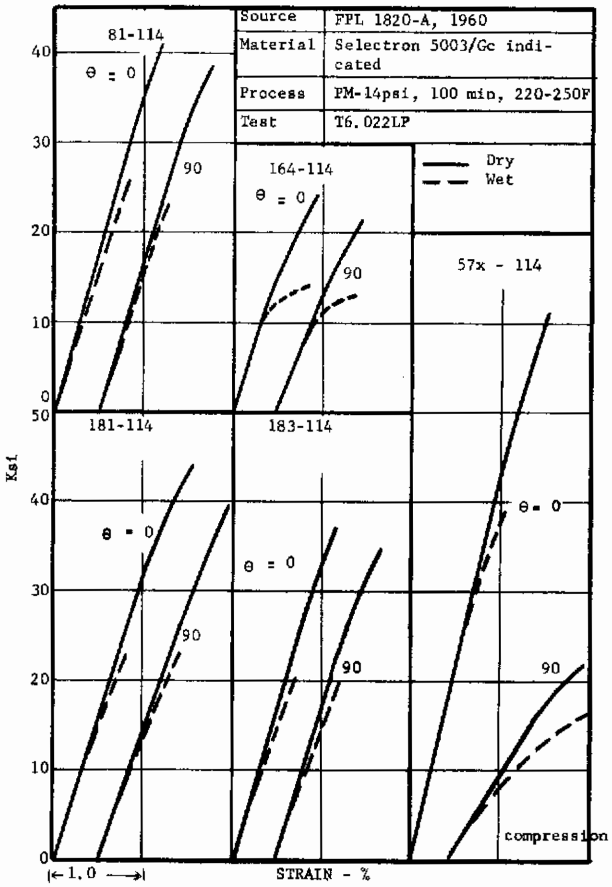

FIG. 3.041.1 AVERAGE STRESS STRAIN CURVES FOR PolGc LAMINATES WITH VARIOUS CLOTH REINFORCEMENTS

Source	FPL 1803-A, 1956
Material	Selectron 5003/Gc indicated
Process	PM-14 psi, 1hr 250F
Test	T6.022LP

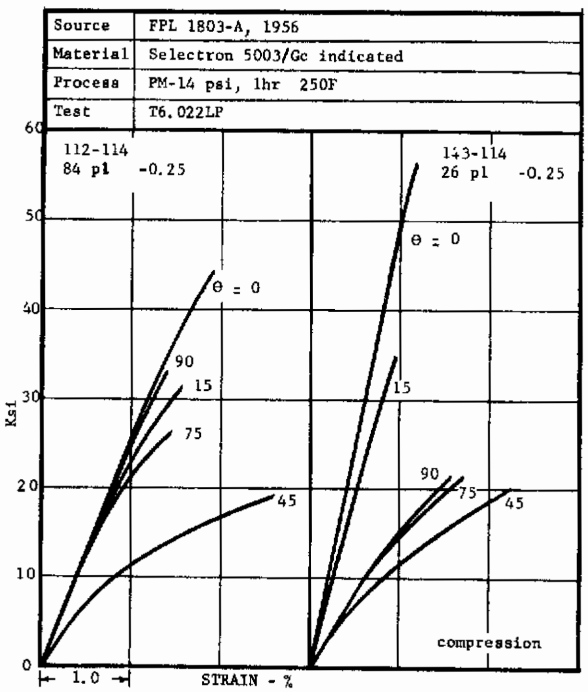

FIG. 3.041.2 AVERAGE STRESS STRAIN CURVES FOR PolGc LAMINATES AT VARIOUS ANGLES θ

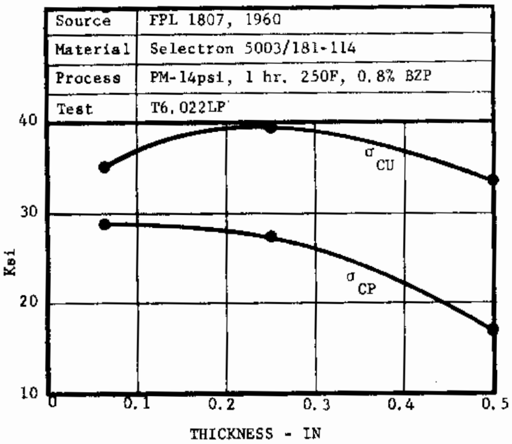

FIG. 3.042.1 EFFECT OF THICKNESS ON COMPRESSION PROPERTIES OF PolGc LAMINATE

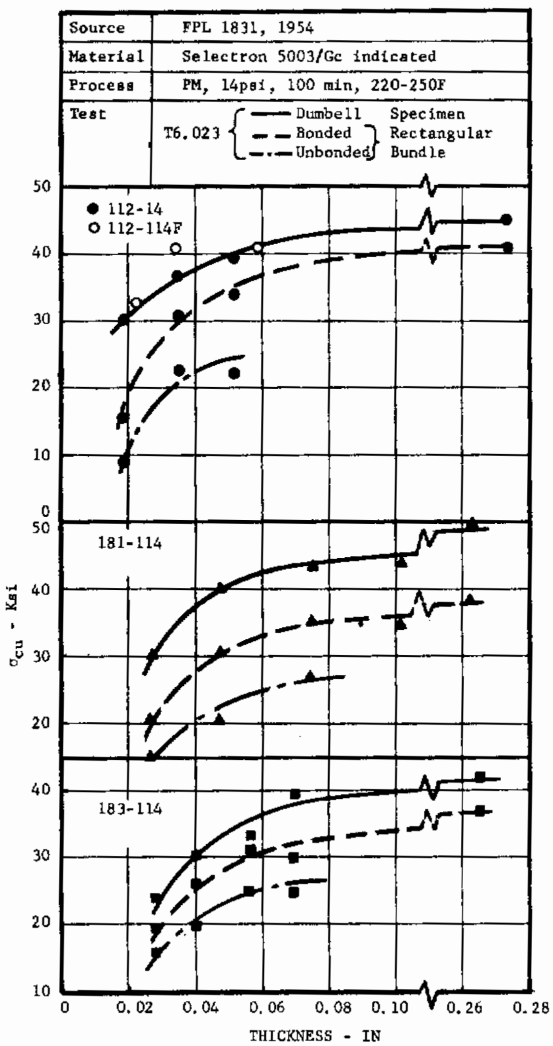

FIG. 3.042.2 EFFECT OF THICKNESS AND SPECIMEN TYPE ON COMPRESSION STRENGTH OF PolGc LAMINATES

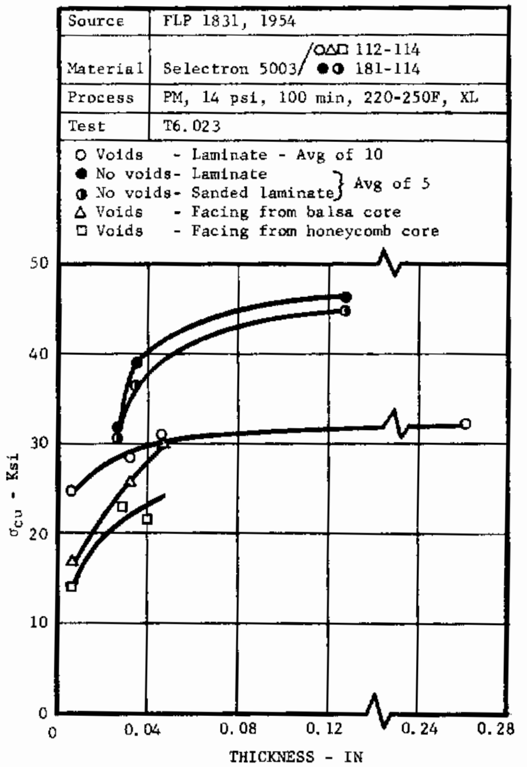

FIG 3.042.3 EFFECT OF THICKNESS AND VOIDS ON COMPRESSION STRENGTH OF PolGc LAMINATES

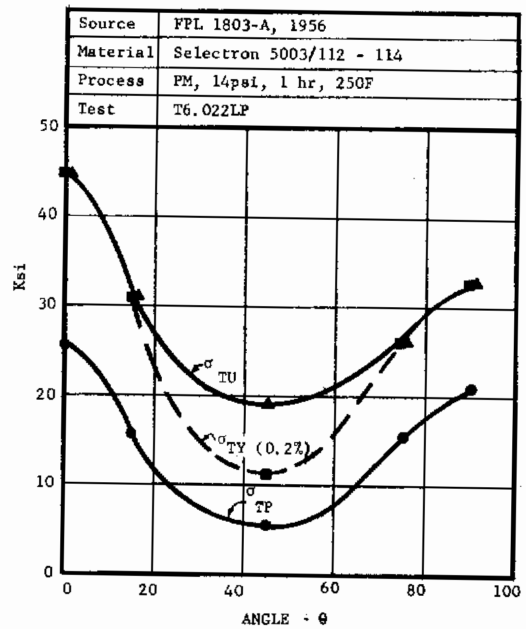

FIG. 3.042.4 EFFECT OF TEST DIRECTION ON COMPRESSION PROPERTIES OF PolGc (112 cloth) LAMINATE

3.042.5 Effect of test direction on compression properties of PolGc (143 cloth) laminate, Fig. 3.042.5.

3.042.6 Effect of test direction on compression properties of PolGc (181 cloth) laminates, Fig. 3.042.6.

3.043 Processing Effects. See Section 3.02.

3.044 Environmental Effects

3.044.1 Effect of exposure and test temperature on compression strength of PolGc laminate, Fig. 3.044.1.

3.045 Other Effects

3.045.1 Effect of prestress at room temperature on compression properties of PolGc laminates, Table 3.045.1.

3.05 Flexure Properties

3.051 Stress Strain Relationships

3.051.1 Average load deflection curves for PolGc laminates with various cloth reinforcements, Fig. 3.051.1.

3.052 Physical Effects

3.052.1 Effect of thickness on flexure strength of PolGc laminate with voids, Fig. 3.052.1.

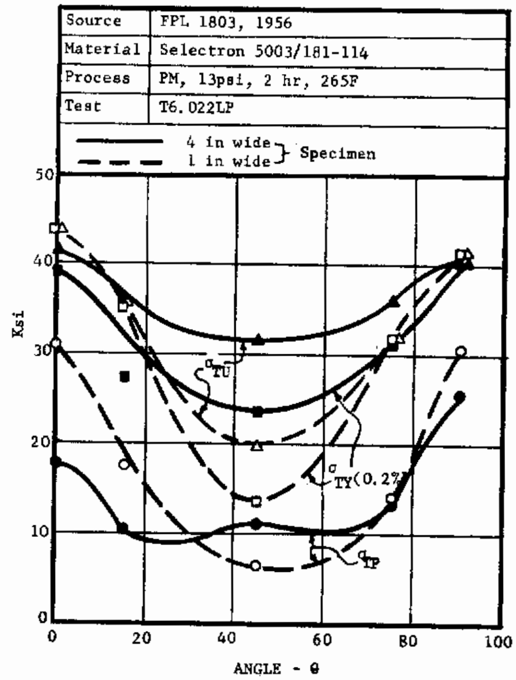

FIG. 3.042.6 EFFECT OF TEST DIRECTION ON COMPRESSION PROPERTIES OF PolGc (181 cloth) LAMINATE

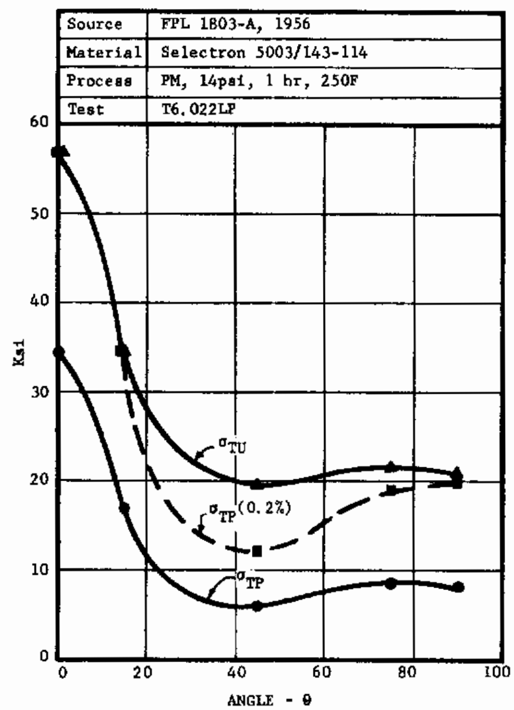

FIG. 3.042.5 EFFECT OF TEST DIRECTION ON COMPRESSION PROPERTIES OF PolGc (143 cloth) LAMINATE

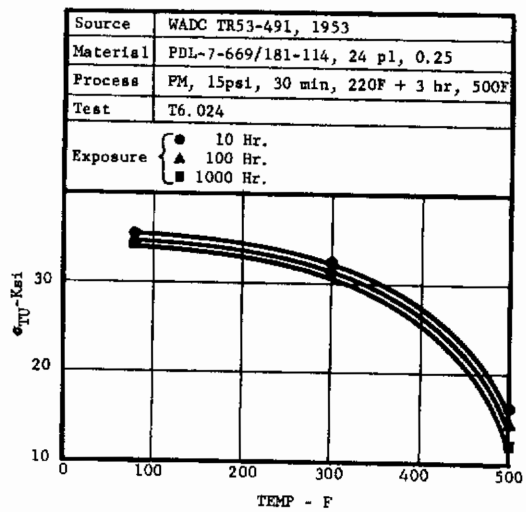

FIG. 3.044.1 EFFECT OF EXPOSURE AND TEST TEMPERATURE ON COMPRESSION STRENGTH OF PolGc LAMINATE

TABLE 3.045.1

Source	FPL 1811, 1957
Material	Selectron 5003/Gc Indicated
Process	PM, 14 psi, 100 min, 220-250F
Test	T6.023LP

Prestress				Property after Prestress		
σ_{cp}	σ_c(max)	E_c	No. of Runs	σ_{cp}	σ_{cu}	E_c
Gc = 181-114, 0.125, 12 pl						
-	0	-	6 Avg	24.77	38.34	3.403
-	6.64	3.37	1	20.74	36.57	3.377
-	9.03	3.01	1	21.06	37.07	3.010
-	10.42	3.127	1	19.36	31.82	3.127
-	13.3	3.358	1	24.94	37.75	3.358
-	14.88	3.379	1	29.76	37.86	3.371
-	14.96	3.169	1	17.96	37.56	3.169
-	21.06	3.381	1	25.92	38.47	3.301
-	19.61	3.333	1	22.06	32.68	3.333
16.06	21.08	3.117	3	21.08	33.50	3.117
17.14	22.36	3.178	1	19.37	33.76	3.178
20.98	26.97	3.078	1	22.42	37.07	3.078
19.24	26.77	3.443	1	24.26	36.48	3.443
33.17	28.14	3.333	1	23.17	37.07	3.333
17.88	28.32	3.190	1	33.85	32.94	3.190
18.07	30.10	3.121	1	22.58	34.18	3.121
Gc = 143-114, 0.125, 13 pl						
-	0	-	6 Avg	28.19	45.88	5.157
-	10.56	5.148	1	25.99	34.96	5.148
-	12.16	5.237	1	17.83	43.28	5.237
-	14.74	5.051	1	16.38	47.08	5.251
15.49	16.31	5.337	1	19.57	44.6	5.337
-	18.91	4.983	1	23.02	40.28	4.983
17.71	22.54	5.337	1	19.32	40.24	5.337
25.28	26.91	5.124	3	30.99	43.63	5.124
24.05	28.06	5.137	1	28.86	43.61	5.137
17.96	24.49	4.986	1	26.12	37.71	4.986
27.75	32.65	5.129	1	31.02	44.24	5.129
25.73	30.55	5.259	1	30.55	40.44	5.259
27.67	36.62	4.949	1	26.04	42.8	4.949
16.16	40.4	5.090	1	29.09	42.67	5.090
22.93	39.3	5.149	1	22.93	40.37	5.149

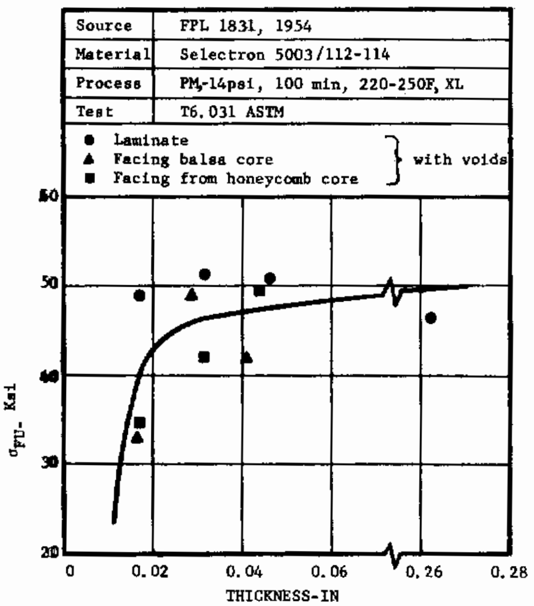

FIG. 3.052.1 EFFECT OF THICKNESS ON FLEXURE STRENGTH OF PolGc LAMINATE WITH VOIDS

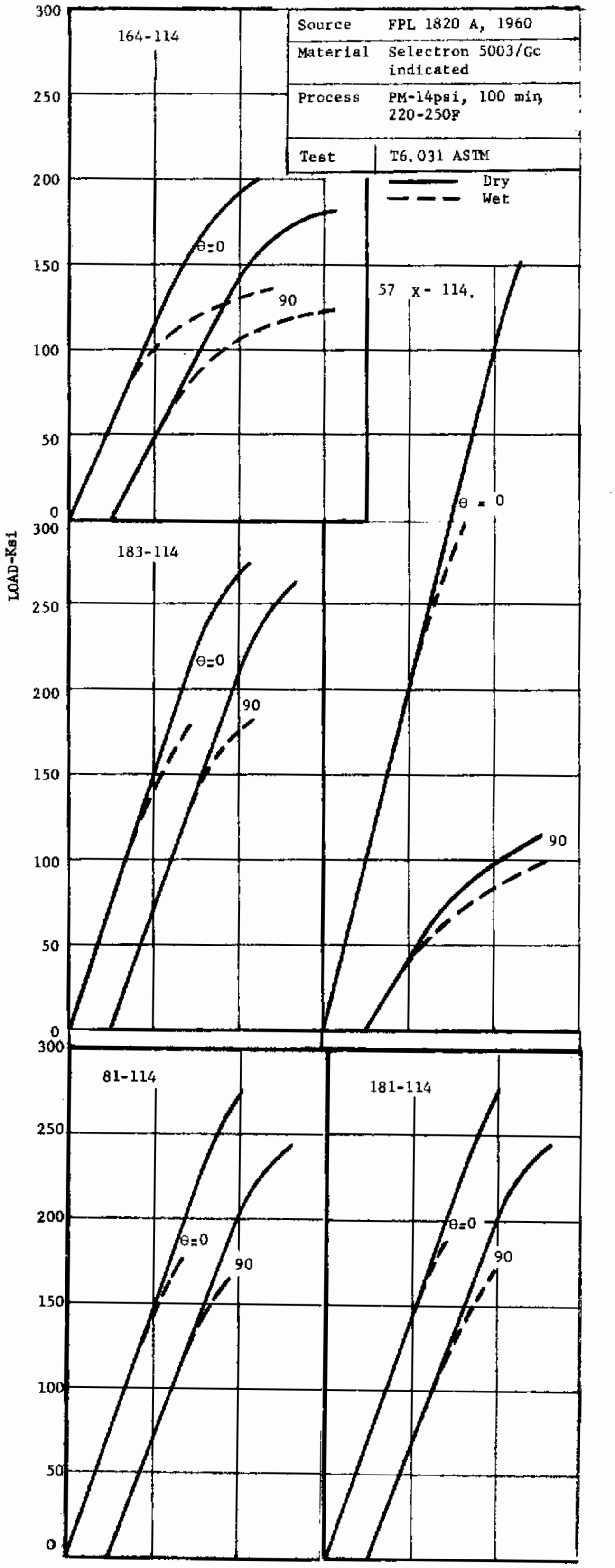

FIG. 3.051.1 AVERAGE LOAD DEFLECTION CURVES FOR PolGc LAMINATES WITH VARIOUS CLOTH REINFORCEMENTS

3.052.2 Effect of span/depth ratio on flexure properties of PolGc laminate, Fig. 3.052.2.

3.053 Processing Effects

3.053.1 Effect of PM, VB and MMD processes on flexure properties of PolGc laminates, Table 3.053.1.

3.054 Environmental Effects

3.054.1 Effect of test temperature on flexure strength of typical PolGc laminate, Fig. 3.054.1

3.054.2 Effect of exposure and test temperature on flexure properties of typical PolGc laminates, Table 3.054.2.

3.054.3 Effect of weathering on flexure properties of typical PolGc laminates, Table 3.054.3.

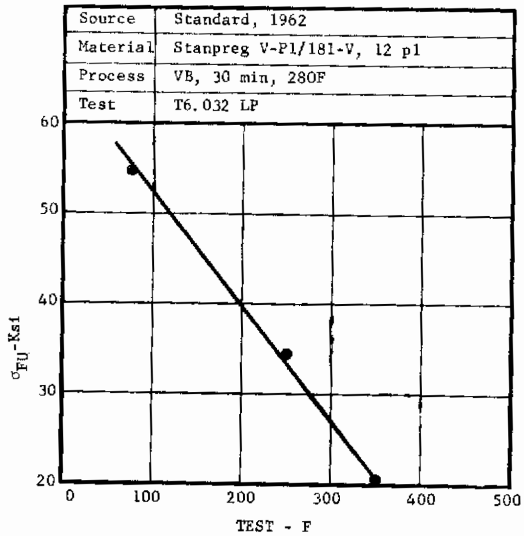

FIG. 3.054.1 EFFECT OF TEST TEMPERATURE ON FLEXURE STRENGTH OF TYPICAL PolGc LAMINATE

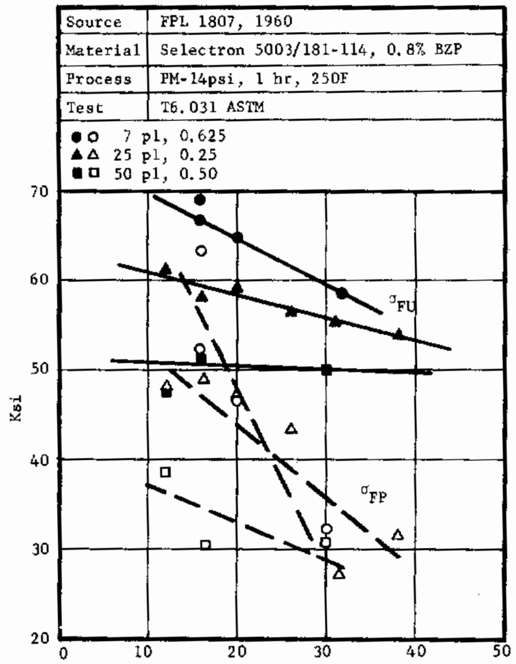

FIG. 3.052.2 EFFECT OF SPAN/DEPTH RATIO ON FLEXURE PROPERTIES OF PolGc LAMINATE

TABLE 3.053.1

Source	Republic, 1958													
Material	Sun CFR - 321A/ 181-V, 12 pl 0.12		0.144		164-V, 6 pl 0.114	0.090	0.090	0.078	Cordo H-165/ 181-V, 12 pl 0.12	0.144	164-V, 6 pl 0.12	0.108
Process	PM-S, 15 min., 250F		VB, 11.7 psi 90 min, 250F		VB, 11.7 psi 90 min, 250F		MMD, 50 psi, 15 min, 250F		PM-S, 15 min, 250F	VB, 11.7 psi, 90 min, 250F	VB, 11.7 psi, 90 min, 250F	MMD, 50 psi, 15 min 250F
Test	T6.032 LP											
Property rc -%	40.0	38.2	43.8	40.1	45.7	37.0	41.6	34.5	35.7	39.8	41.4	41.3
Hardness Barcol	72	73	61	61	69	67	-	-	58	60	59	-
σ_{fu} -Ksi	90.0	79.3	66.5	53.3	35.1	41.7	60.6	57.6	67.0	73.0	38.8	40.5
E_f -Ksi	3.83	3.58	2.83	2.58	2.33	2.66	3.12	3.41	3.44	3.24	2.11	3.52

TABLE 3.054.2

Source	FPL 1825, 1958													
Material	Selectron 5003/181-114 0.127 - 0.136, 12 pl							Resin No. 4/181-114 0.125 - 0.134, 12 pl			Resin No. 3/181-114 0.126 - 0.130, 12 pl			
Process	20 min, 220F + 30 min, 250F			PM, 14 psi 16 hr, 75F		15 min, 160F		16 hr, 75F			20 min, 220F + 30 min, 250F			
Catalyst	BZP-%			BZP, 0.8% Promoter-%		BZP, 0.8% Promoter-%		HCH - % / Promoter-%			Styrene-%			
	0.4	0.8	1.2	2	4	2	4	0.6 / 2.4	1.2 / 4.8	1.8 / 7.2	0	11	22	33
Test	T6.032 LP													
rc -%	37.8	37	37.8	39.4	40.3	40.4	39.8	37.6	36.3	36.1	39.3	38.5	37.5	36.5
Sp g -	1.77	1.78	1.75	1.77	1.76	1.76	1.76	1.82	1.79	1.79	1.81	1.81	1.78	1.78
σ_{fu} -Ksi Dry	53.3	63.2	65.2	57	59.5	59.8	59.3	54	53.8	38.10	58.7	59.24	60.4	61
Wet	38.7	43.6	43.8	38.9	43.1	44	42.2	31.4	33.4	36.2	37.4	39.7	39	40.1
σ_{fp} -Ksi Dry	45.7	54.6	55.1	50.2	53.8	53	52.8	37.6	48.2	54.4	53.8	54.9	54.8	56.1
Wet	21.7	25.5	24.3	24.8	22.8	24.2	24.8	19.2	21.4	24	25.8	20.8	21.4	23.2
E_f -1000Ksi Dry	2.66	2.81	2.82	2.69	2.63	2.56	2.63	2.57	2.57	2.88	2.66	2.74	2.74	2.78
Wet	2.59	2.70	2.73	2.59	2.64	2.58	2.49	2.33	2.48	2.64	2.45	2.59	2.64	2.67
Hardness Barcol	64.6	66.9	66.9	61	61	61	62	61.5	61.4	62	65	65.1	65.1	65.1
Impact IZOD ft lb/in	16	12.1	12.1	15	14.3	15.1	16.5	15.7	15.2	14.9	13.6	14.4	14.4	14.6
1/2 hr at 160F														
σ_{fu}(160F)-Ksi	22.8	37.4	42.6	27.1	27.1	32.9	24.9	26.1	23.4	31.6	18	24.4	27	28.6
σ_{fp}(160F)-Ksi	19.5	27.7	29.0	18.2	15.1	20.2	15.8	13.7	17.0	21.7	8.08	14.2	19.9	20.4
E_f(160F) -1000 Ksi	1.90	2.30	2.48	1.84	1.55	2.10	1.75	2.08	2.24	2.44	1.71	1.99	2.08	2.13
1/2 hr at 350F														
σ_{fu}(350F)-Ksi	5.58	6.45	6.24	3.41	3.7	4.9	4.48	7.41	6.16	6.36	5.86	6.27	6.44	6.3
σ_{fp}(350F)-Ksi	4.5	5.4	5.6	2.7	2.7	3.1	2.8	4.9	5.0	5.6	5.4	5.2	5.4	4.9
E_f(350F) -1000 Ksi	0.89	0.98	0.90	0.57	0.62	0.77	0.73	1.16	1.03	1.05	0.90	1.04	1.02	0.98
192 hr at 350F														
σ_{fu}(350F)-Ksi	5.49	5.39	5.34	4.92	5.64	5.7	6.55	13.48	11.01	11.7	5.83	5.57	5.16	4.53
σ_{fp}(350F)-Ksi	3.0	3.0	3.1	2.9	3.1	2.9	3.3	6.2	6.3	6.5	3.1	3.4	2.7	2.9
E_f(350F) -1000Ksi	0.86	0.89	0.88	0.77	0.80	0.77	0.89	1.61	1.47	1.61	1.07	1.04	1.00	0.88

HCH = 1 - hydroxycyclohexyl hydroperoxide - 1
Promoter = An organo - metallic derivative

MATERIAL SYSTEMS

TABLE 3.054.3

Source	FPL 1825, 1958													
Material	Selectron 5003/181-114 0.127-0.136, 12 pl							Resin No. 4/181-114 0.125 - 0.134, 12 pl			Resin No. 3/181-114 0.126 - 0.130, 12 pl			
Process	PM, 14 psi													
	20 min, 220F and 30 min, 250F			16 hr, 75F		15 min, 160F + RT		16 hr, 75F			20 min, 220F + 30 min, 250F			
Catalyst	BZP-%			BZP, 0.8% Promoter-%		BZP, 0.8% Promoter-%		HCH - % / Promoter-%			BZP, 1.2% Styrene-%			
	0.4	0.8	1.2	2	4	2	4	0.6 / 2.4	1.2 / 4.8	1.8 / 7.2	0	11	22	33
Test	T6.032 LP													
rc -%	37.8	37	37.8	39.4	40.3	40.4	39.8	37.6	36.3	36.1	39.3	38.5	37.5	36.5
Sp g -	1.77	1.78	1.75	1.77	1.76	1.76	1.76	1.82	1.79	1.79	1.81	1.81	1.78	1.78
σ_{fu} -Ksi Dry	53.3	63.2	65.2	57	59.5	59.8	59.3	54	53.8	38.10	58.7	59.24	60.4	61
Wet	38.7	43.6	43.8	38.9	43.1	44	42.2	31.4	33.4	36.2	37.4	39.7	39	40.1
σ_{fp} -Ksi Dry	45.7	54.6	55.1	50.2	53.8	53	52.8	37.6	48.2	54.4	53.8	54.9	54.8	56.1
Wet	21.7	25.5	24.3	24.8	22.8	24.2	24.8	19.2	21.4	24	25.8	20.8	21.4	23.2
E_f-1000Ksi Dry	2.66	2.81	2.82	2.69	2.63	2.56	2.63	2.57	2.57	2.88	2.66	2.74	2.74	2.78
Wet	2.59	2.70	2.73	2.59	2.64	2.58	2.49	2.33	2.48	2.64	2.45	2.59	2.64	2.67
Hardness Barcol	64.6	66.9	66.9	61	61	61	62	61.5	61.4	62	65	65.1	65.1	65.1
Impact IZOD ft lb/in	16	12.1	12.1	15	14.3	15.1	16.5	15.7	15.2	14.9	13.6	14.4	14.4	14.6
3 mos. outdoor														
σ_{fu} -Ksi	48.1	46.9	47.1	58.2	57.7	59.4	59.6	54.3	56.3	53.2	50	49.8	44.3	47
σ_{fp} -Ksi	29.3	35.9	37.0	38.6	34.4	40.9	40.9	29.4	32.1	32.1	28.5	31.5	28.3	29.6
E_f1000-Ksi	2.59	2.56	2.49	2.65	2.61	2.52	2.56	2.62	2.68	2.79	2.39	2.42	2.46	2.45
6 mos. outdoor														
σ_{fu} -Ksi	48.5	44.5	43.4	57.3	59.4	60.4	60.9	57.6	52.3	53.8	48.5	49.5	42	44.4
σ_{fp} -Ksi	39.8	33.5	39.2	30.3	43.2	44.1	44.8	36.4	32.9	31.1	42.7	41.6	36.1	33.2
E_f -1000Ksi	2.64	2.46	2.50	2.79	2.64	2.65	2.68	2.71	2.74	2.87	2.40	2.48	2.46	2.47
12 mos. outdoor														
σ_{fu} -Ksi	50.5	52.4	50.2	56.5	58.8	58.7	61.5	57.2	57.7	58.2	50.8	54.3	50	50
σ_{fp} -Ksi	43.8	43.7	38.1	48.1	48.5	55.3	56.8	39.6	44.5	49.0	44.2	44.4	41.4	40.2
E_f-1000Ksi	2.62	2.57	2.74	2.79	2.63	2.88	2.71	2.76	2.75	2.89	2.55	2.60	2.63	2.64
10 cy wet dry at 75F														
σ_{fu} -Ksi	31.9	37.7	39.7	39.3	42.2	35.4	32.5	38.0	36.7	35.4	35.1	37.2	34.2	36
σ_{fp} -Ksi	24.6	26.1	29.8	31.0	34.2	31.6	25.9	26.8	25.8	21.5	27.8	31.1	28.2	32.0
E_f-1000Ksi	2.48	2.54	2.67	2.71	2.65	2.52	2.40	2.51	2.53	2.65	2.54	2.56	2.53	2.60

HCH = 1 - hydroxycyclohexyl hydroperoxide - 1

Promoter= An organo-metallic derivative

3.054.4 Effect of moisture absorption on flexure properties of PolGc laminate, Fig. 3.054.4.

3.055 Other Effects

3.055.1 Effect of prestress and water absorption on flexure properties of PolGc laminate, Table 3.055.1.

3.055.2 Effect of prestress and weathering on flexure properties of PolGc laminates, Table 3.055.2.

TABLE 3.055.1

Source	FPL 1856, 1956							
Material	Selectron 5003/181-V							
Process	PM, 14 psi, 90 min, 220-250F							
Test	T6.032LP							
Property	Tension Prestress - Ksi							
	Exposed Unstressed				Exposed Stressed			
	0	8	16	24	0	8	16	24
σ_{fu} -ksi	58.0	58.7	58.2	57.3	60.8	59.7	58.7	57.6
σ_{fp} -ksi	35.6	38.5	38.6	39.0	38.8	39.9	40.7	43.4
E_f -1000 ksi	2.81	2.84	2.74	2.76	2.75	2.81	2.71	2.87
30 day water immersion Absorption-%	0.45	.51	.55	.67	0.53	.45	.41	.71
σ_{fu} -ksi	49.8	50.7	48.7	47.2	47.4	47.8	47.5	46.5
σ_{fp} -ksi	21.7	26.6	25.3	26.1	28.3	26.8	28.8	28.8
E_f -1000 ksi	2.86	2.80	2.77	2.72	2.82	2.87	2.76	2.76
60 day water immersion Absorption-%	0.74	.75	.78	.88	---	---	---	---
σ_{fu} -ksi	50.2	48.3	47.9	50.6	---	---	---	---
σ_{fp} -ksi	28.7	26.3	32.3	34.3	---	---	---	---
E_f -1000 ksi	2.85	2.88	2.74	2.71	---	---	---	---
90 day water immersion Absorption-%	0.62	.68	.73	.77	---	---	---	---
σ_{fu} -ksi	47.6	47.4	46.8	46.8	---	---	---	---
σ_{fp} -ksi	24.8	25.5	26.6	27.9	---	---	---	---
E_f -1000 ksi	2.86	2.86	2.79	2.76	---	---	---	---

Source	FPL 1819, 1956
Material	Selectron 5003/181-114
Process	PM-14psi, 100 min, 220-250F
Test	T6.031 ASTM

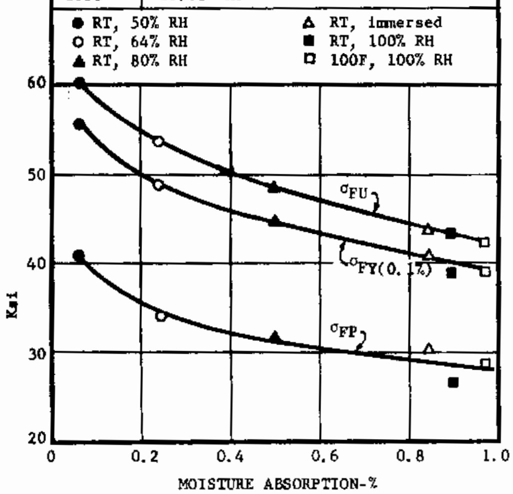

FIG. 3.054.4 EFFECT OF MOISTURE ABSORPTION ON FLEXURE PROPERTIES OF PolGc LAMINATE

TABLE 3.055.2

Source	FPL 1856-A, 1957			
Material	Selectron 5003/181-V			
Process	PM, 14psi, 90min, 220-250F			
Test	T6.032LP			
Property	Tension Prestress - Ksi Exposed Unstressed			
	0	8	16	24
σ_{fu} -ksi	58.0	58.7	58.2	57.3
σ_{fp} -ksi	35.6	38.5	38.6	39.0
E_f -1000 ksi	2.81	2.84	2.74	2.76
3 mos. out-doors				
σ_{fu} -ksi	60.0	58.0	59.0	57.0
σ_{fp} -ksi	35.7	37.8	40.0	40.8
E_f -1000 ksi	2.88	2.89	2.83	2.80
12 mos. out-door				
σ_{fu} -ksi	57.6	57.7	56.3	55.4
σ_{fp} -ksi	39.0	35.7	35.7	33.4
E_f -1000 ksi	2.84	2.88	2.79	2.83

3.06 Shear Properties

3.061 Stress Strain Relationships

3.061.1 Average stress strain curves in panel shear for PolGc laminates at various angles θ, Fig. 3.061.1.

3.061.2 Average stress strain curves in panel shear for PolGc laminates with various cloth reinforcements, Fig. 3.061.2.

3.061.3 Average stress strain curves in panel shear for PolGc laminates in wet and dry conditions, Fig. 3.061.3.

3.062 Physical Effects

3.062.1 Effect of test direction on interlaminar shear strength of typical PolGc laminate, Fig. 3.062.1.

3.062.2 Effect of test direction on panel shear properties of typical PolGc laminates, Fig. 3.062.2.

3.063 Processing Effects

3.064 Environmental Effects

3.065 Other Effects

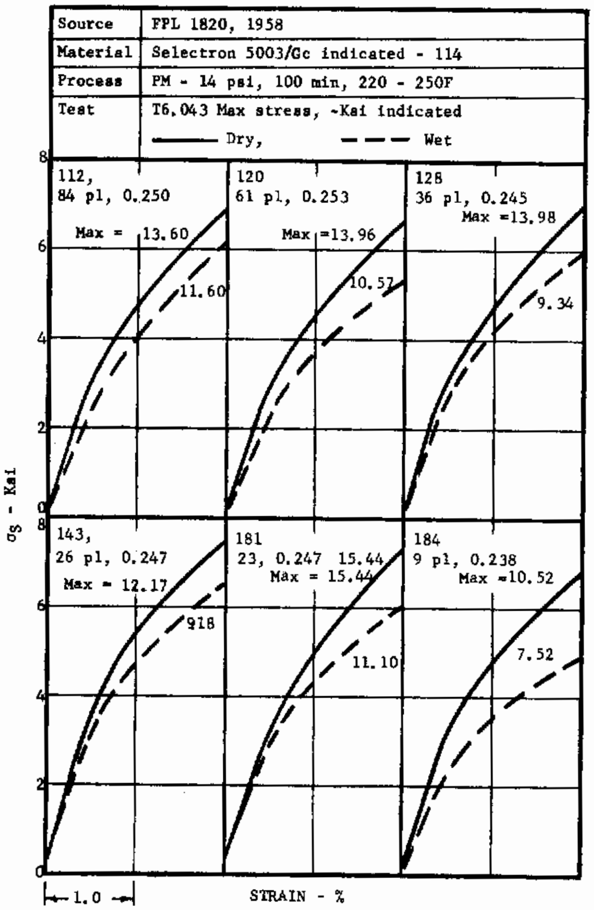

FIG. 3.061.3 AVERAGE STRESS STRAIN CURVES IN PANEL SHEAR FOR PolGc LAMINATES IN WET AND DRY CONDITIONS

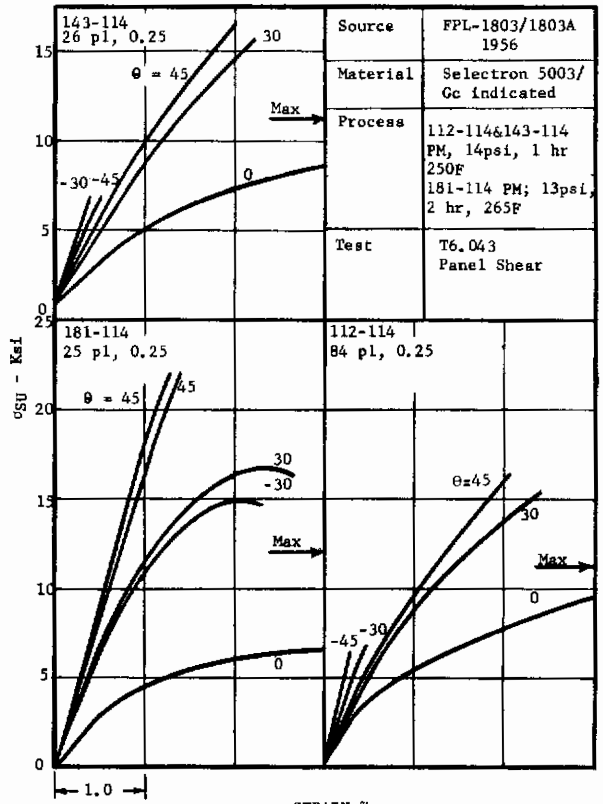

FIG. 3.061.1 AVERAGE STRESS-STRAIN CURVES IN PANEL SHEAR FOR PolGc LAMINATES AT VARIOUS ANGLES θ

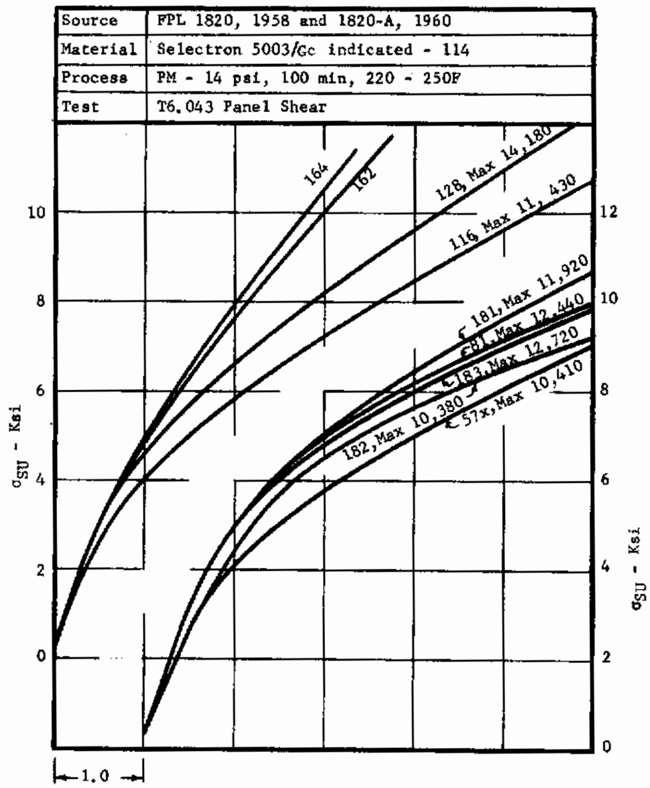

FIG. 3.061.2 AVERAGE STRESS-STRAIN CURVES IN PANEL SHEAR FOR PolGc LAMINATES WITH VARIOUS CLOTH REINFORCEMENTS

Source	FPL 1803 and 1803A
Material	Selectron 5003/Gc indicated-114
Process	Gc 112 and 143-PM, 14 psi, 1 hr, 250F Gc 181-PM, 13 psi, 2 hr, 265F
Test	T6.043 Panel Shear

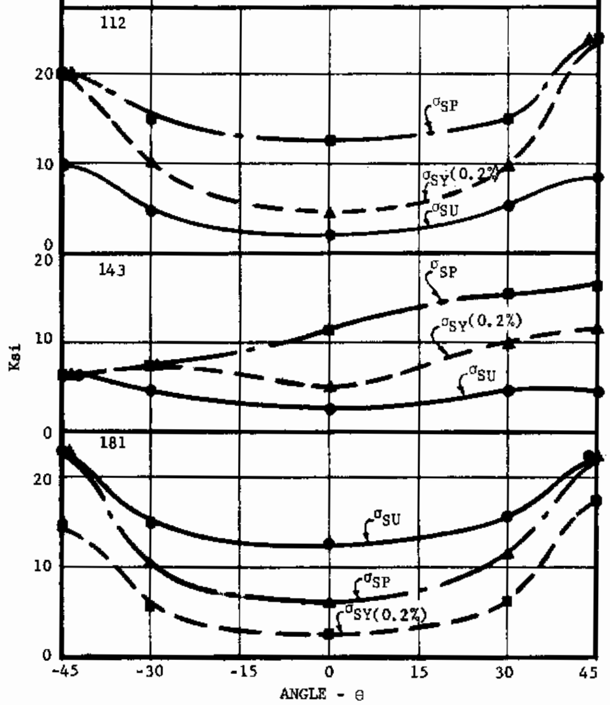

FIG. 3.062.2 EFFECT OF TEST DIRECTION ON PANEL SHEAR PROPERTIES OF TYPICAL PolGc LAMINATES

Source	FPL 1803, 1956
Material	Selectron 5003/181-114
Process	PM, 13 psi, 2 hr., 265F
Test	T6.044 Interlaminar Shear

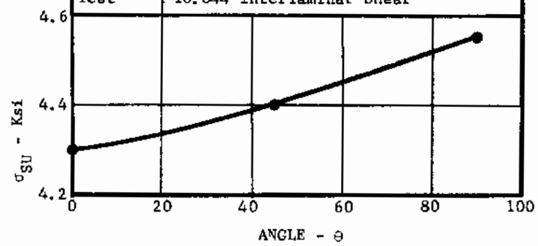

FIG. 3.062.1 EFFECT OF TEST DIRECTION ON INTERLAMINAR SHEAR STRENGTH OF TYPICAL PolGc LAMINATE

3.07 Bearing Properties

3.071 Stress Strain Relationships

3.072 Physical Effects

3.072.1 Bearing strength of PolGc (112 cloth) laminate for various e (end)/D ratios and of various angles θ, Fig. 3.072.1.

3.072.2 Bearing strength of PolGc (112 cloth) laminate for various e (edge)/D ratios and at various angles θ, Fig. 3.072.2.

3.072.3 Bearing strength of PolGc (120 cloth) laminate for various e (end)/D ratios and at various angles θ, Fig. 3.072.3.

3.072.4 Bearing strength of PolGc (120 cloth) laminate for various e (edge)/D ratios and at various angles θ, Fig. 3.072.4.

Source	FPL 1824, 1958
Material	Selectron 5003/112-114, 0.87% BZP
Process	PM-14 psi, 100 min, 220-250F
Test	T6.053

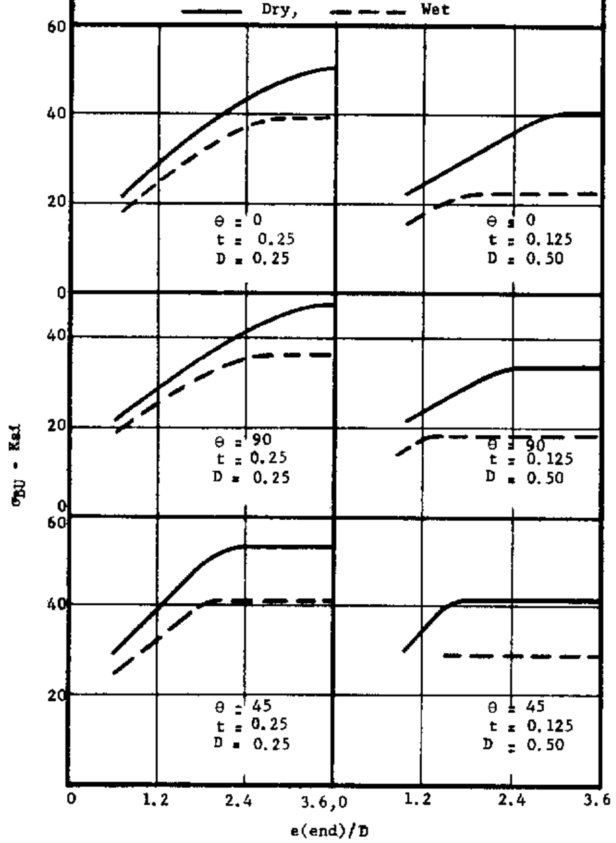

FIG. 3.072.1 BEARING STRENGTH OF PolGc (112 CLOTH) LAMINATE FOR VARIOUS e(END)/D RATIOS AND AT VARIOUS ANGLES θ

Source	FPL 1824, 1958
Material	Selectron 5003/112-114, 0.8% BZP
Process	PM-14 psi, 100 min, 220-250F
Test	T6.053

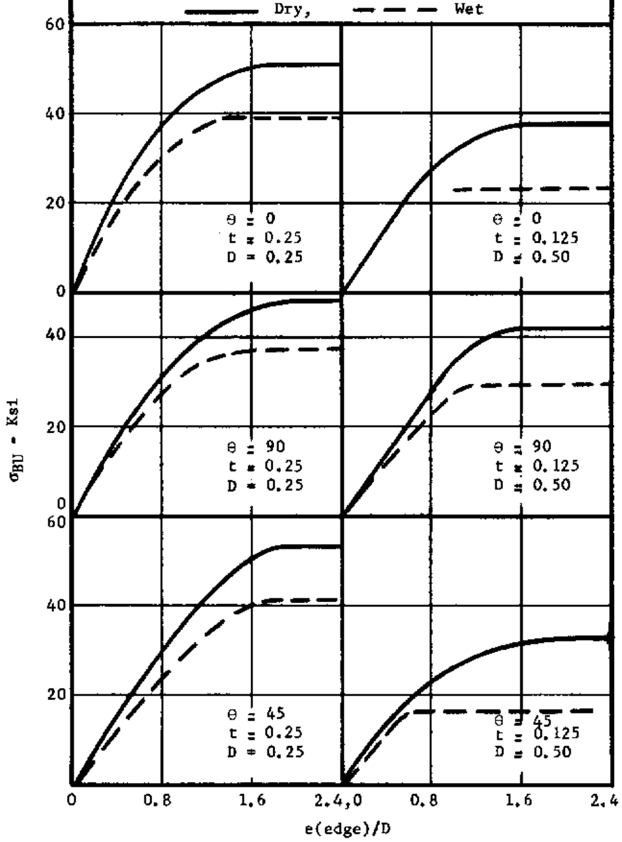

FIG. 3.072.2 BEARING STRENGTH OF PolGc (112 cloth) LAMINATE FOR VARIOUS e (EDGE)/D RATIOS AND AT VARIOUS ANGLES θ

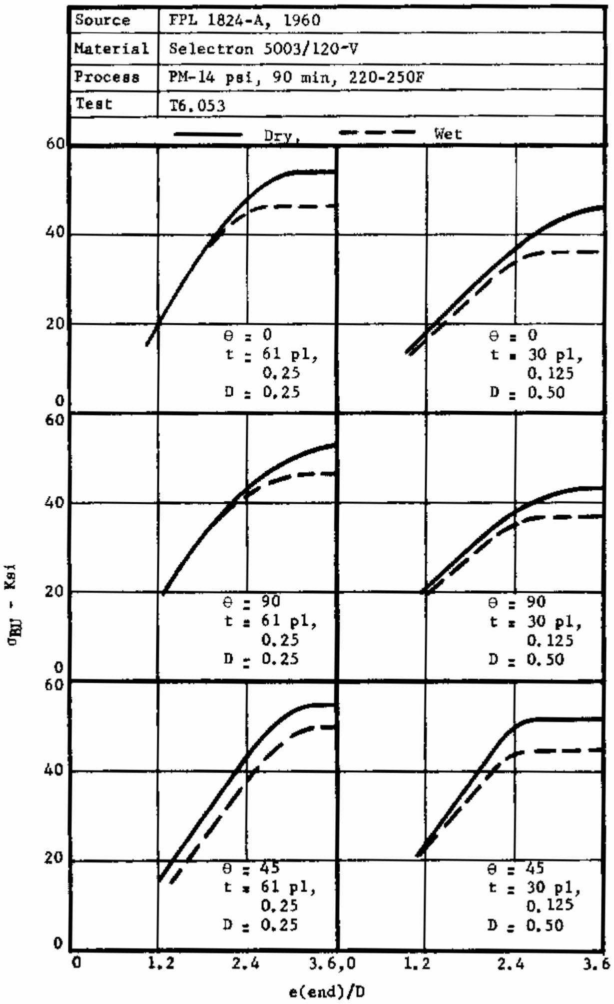

FIG. 3.072.3 BEARING STRENGTH OF PolGc (120 cloth) LAMINATE FOR VARIOUS e (END)/D RATIOS AND AT VARIOUS ANGLES θ

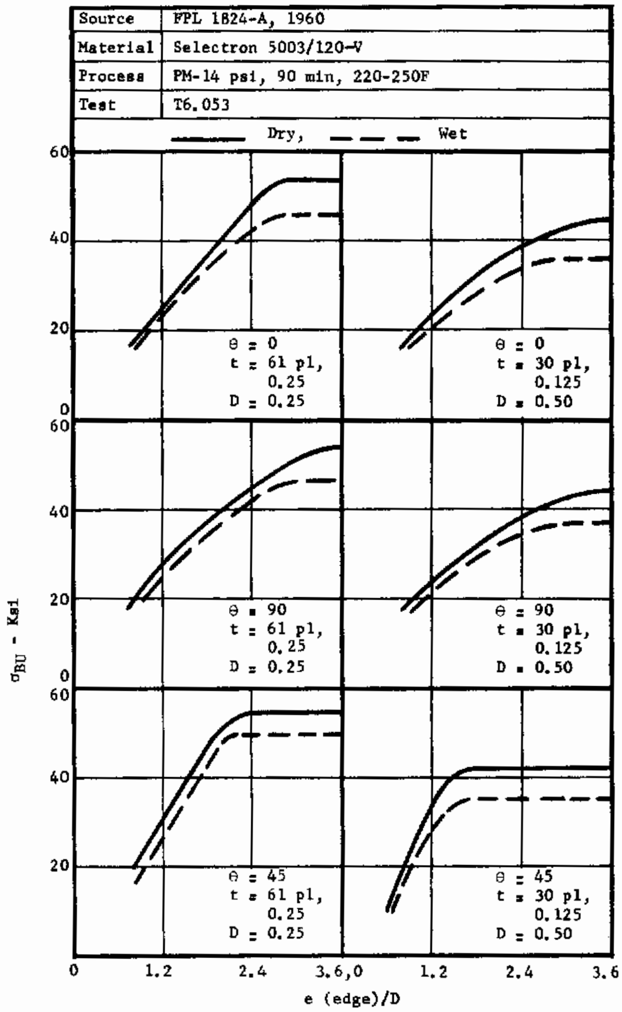

FIG. 3.072.4 BEARING STRENGTH OF PolGc (120 cloth) LAMINATE FOR VARIOUS e (EDGE)/D RATIOS AND AT VARIOUS ANGLES θ

3.072.5 Bearing strength of PolGc (143 cloth) laminate for various e (end)/D ratios and at various angles θ, Fig. 3.072.5.

3.072.6 Bearing strength of PolGc (143 cloth) laminate for various e (edge)/D ratios and at various angles θ, Fig. 3.072.6.

3.072.7 Bearing strength of PolGc (162 cloth) laminate for various e (end & edge)/D ratios and at various angles θ, Fig. 3.072.7.

3.072.8 Bearing strength of PolGc (162 cloth) laminate for various e (end & edge)/D ratios and at various angles θ, Fig. 3.072.8.

3.072.9 Bearing strength of PolGc (181 cloth) laminate for various e (end)/D ratios and at various angles θ, Fig. 3.072.9.

3.072.10 Bearing strength of PolGc (181 cloth) laminate for various e (edge)/D ratios and at various angles θ, Fig. 3.072.10.

3.072.11 Bearing strength of PolGc (184 cloth) laminate for various e (end)/D ratios and at various angles θ, Fig. 3.072.11.

Source	FPL 1824, 1958
Material	Selectron 5003/143-114, 0.8% BZP
Process	PM-14 psi, 100 min, 220-250F
Test	T6.053

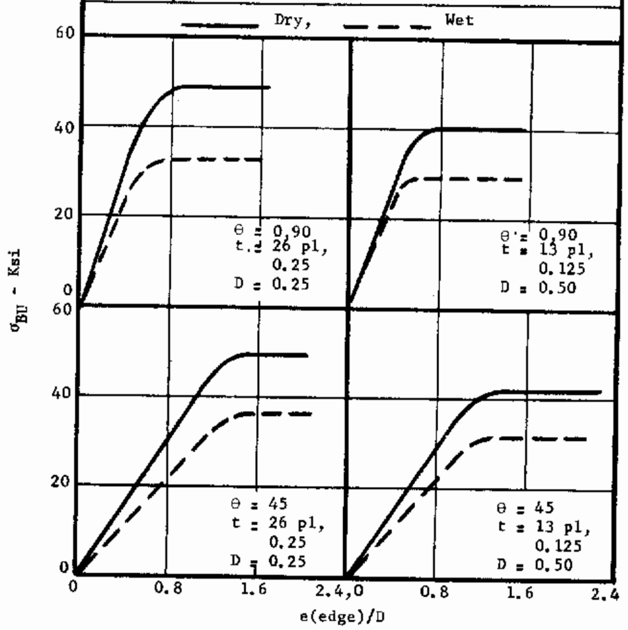

FIG. 3.072.6 BEARING STRENGTH OF PolGc (143 cloth) LAMINATE FOR VARIOUS e(EDGE)/D RATIOS AND AT VARIOUS ANGLES θ

Source	FPL 1824, 1958
Material	Selectron 5003/143-114, 0.8% BZP
Process	PM-14 psi, 100 min, 220-250F
Test	T6.053

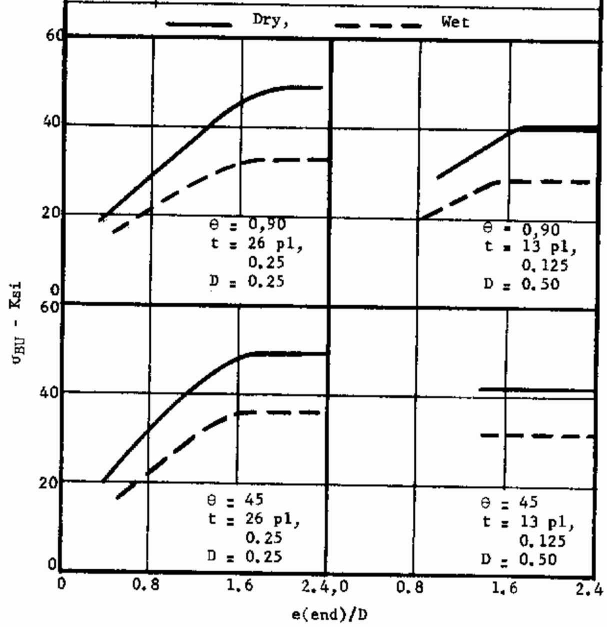

FIG. 3.072.5 BEARING STRENGTH OF PolGc (143 cloth) LAMINATE FOR VARIOUS e(END)/D RATIOS AND AT VARIOUS ANGLES θ

Source	FPL 1824-A, 1960
Material	Selectron 5003/162-V, 0.8% BZP
Process	PM-14 psi, 90 min, 220-250F
Test	T6.053

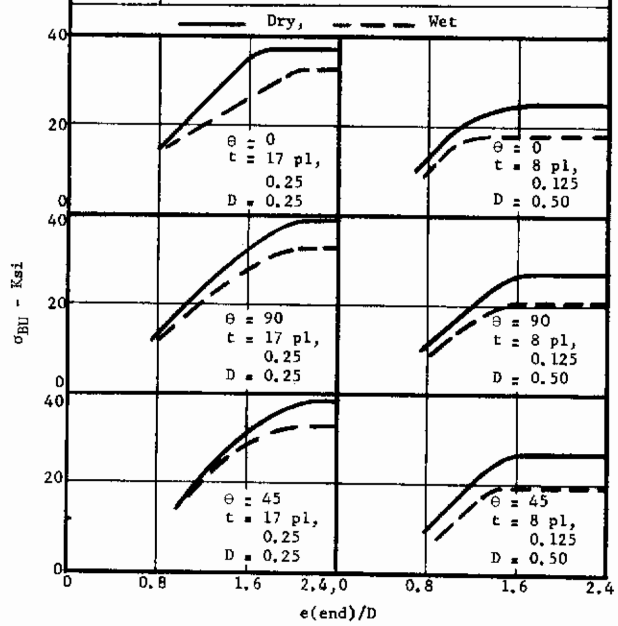

FIG. 3.072.7 BEARING STRENGTH OF PolGc (162 cloth) LAMINATE FOR VARIOUS e(END)/D RATIOS AT VARIOUS ANGLES θ

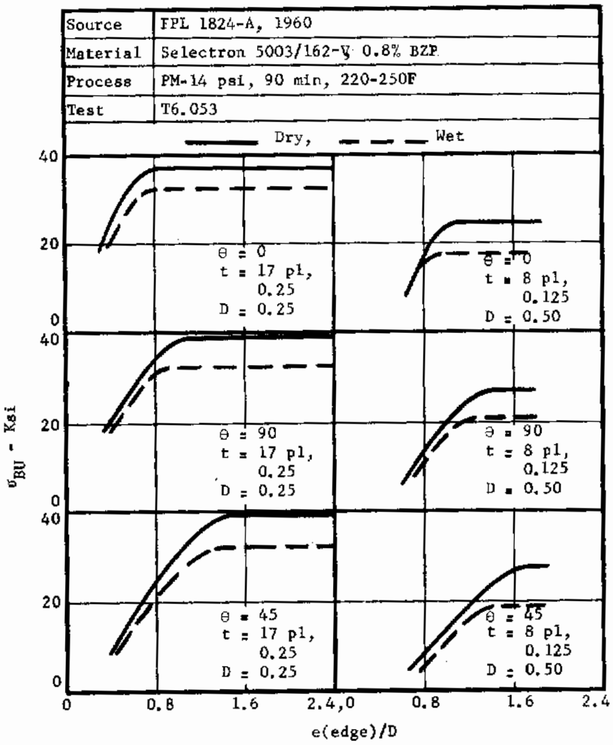

FIG. 3.072.8 BEARING STRENGTH OF PolGc (162 cloth) LAMINATE FOR VARIOUS e (EDGE)/D RATIOS AT VARIOUS ANGLES θ

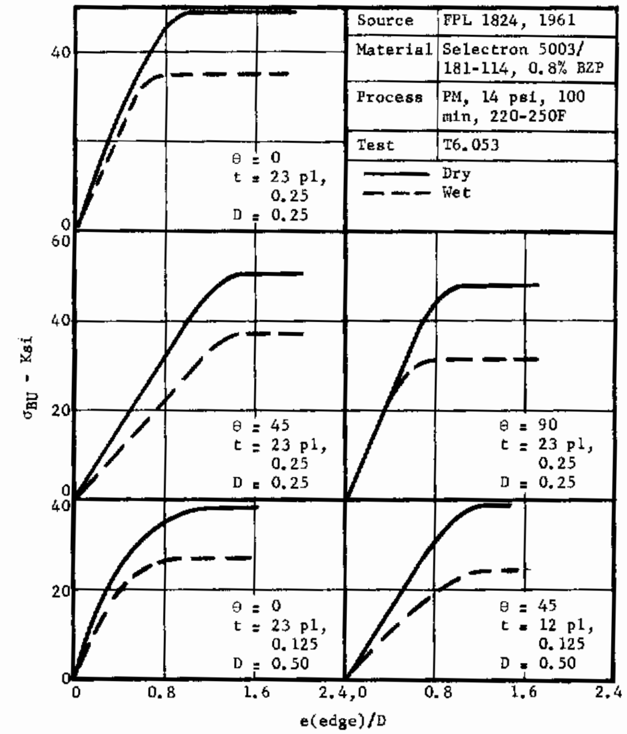

FIG. 3.072.10 BEARING STRENGTH OF PolGc (181 cloth) LAMINATE FOR VARIOUS e(EDGE)/D RATIOS AND AT VARIOUS ANGLES θ

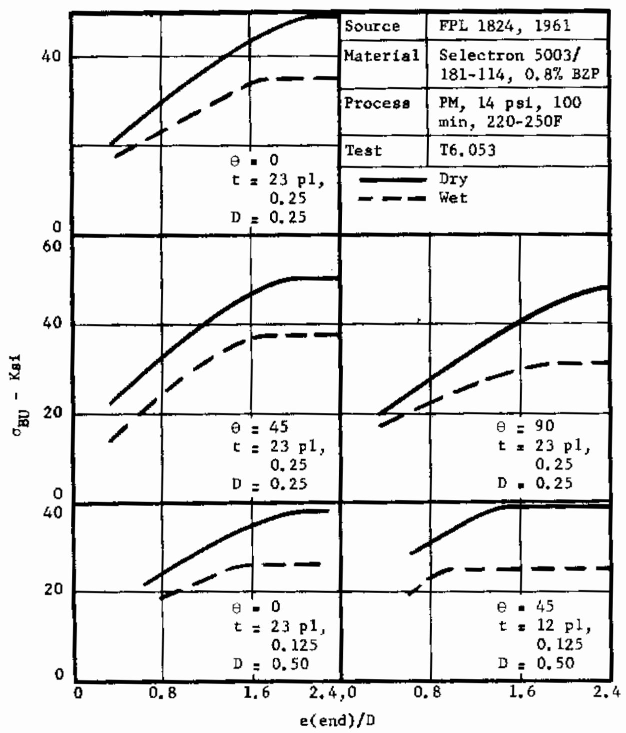

FIG. 3.072.9 BEARING STRENGTH OF PolGc (181 cloth) LAMINATES FOR VARIOUS e(END)/D RATIOS AND AT VARIOUS ANGLES θ

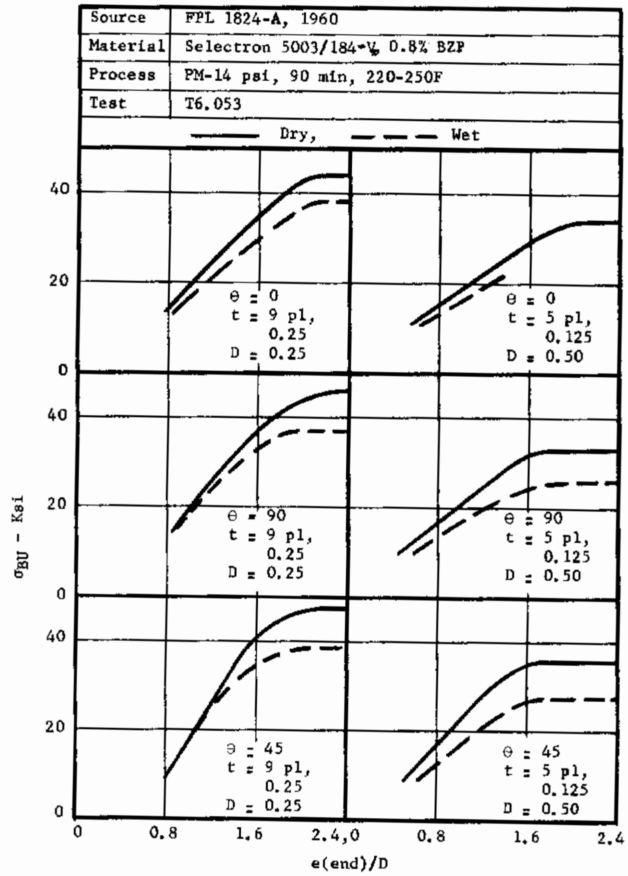

FIG. 3.072.11 BEARING STRENGTH OF PolGc (184 cloth) LAMINATE FOR VARIOUS e(END)/D RATIOS AND AT VARIOUS ANGLES θ

3.072.12 Bearing strength of PolGc (184 cloth) laminate for various e (edge)/D ratios and at various angles θ, Fig. 3.072.12.

3.072.13 Combined effect of e(end)/D and e (edge)/D ratios on bearing strength of typical PolGc laminate, Fig. 3.072.13.

3.072.14 Effect of test direction on bearing properties of typical PolGc laminate, Fig. 3.072.14.

3.073 Processing Effects

3.074 Environmental Effects

3.075 Other Effects

3.08 Creep and Creep Rupture Properties

3.081 Creep and Creep Rupture

3.081.1 Creep rupture curves for typical PolGc laminate at various angles θ, Fig. 3.081.1.

3.081.2 Creep rupture curves for typical PolGc laminate at RT to 500F, Fig. 3.081.2.

3.081.3 Creep rupture curves for notched and unnotched typical PolGc laminate, Fig. 3.081.3.

3.082 Total Strain

3.083 Master Curves

3.084 Other

Source	FPL 1824, 1961
Material	Selectron 5003/112-114, 42 pl, 0.125
Process	PM-14 psi, 100 min, 220-250F
Test	T6.053

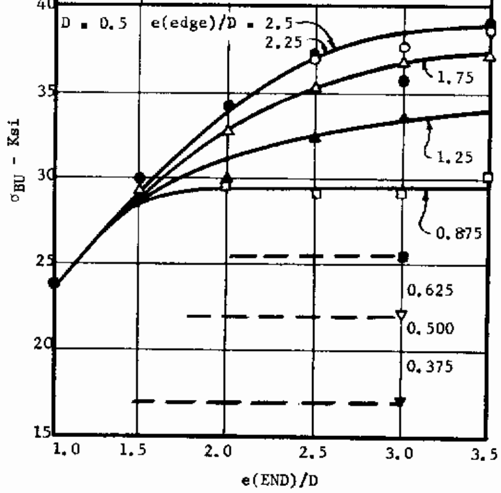

FIG. 3.072.13 COMBINED EFFECT OF e(END)/D AND e(EDGE)/D RATIOS BEARING STRENGTH OF TYPICAL PolGc LAMINATE

Source	FPL 1824-A, 1960
Material	Selectron 5003/184-V , 0.8% BZP
Process	PM-14 psi, 90 min, 220-250F
Test	T6.053

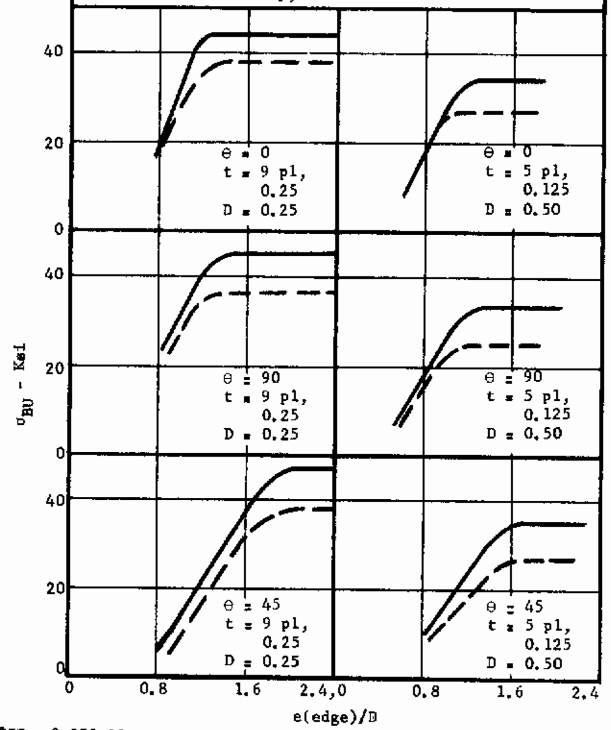

FIG. 3.072.12 BEARING STRENGTH OF PolGc (184 cloth) LAMINATE FOR VARIOUS e(EDGE)/D RATIOS AT VARIOUS ANGLES θ

Source	FPL 1803, 1956
Material	Selectron 5003/181-114, 25 pl, 0.25
Process	PM-13 psi, 2 hr, 265F
Test	T6.053 D = 1/4

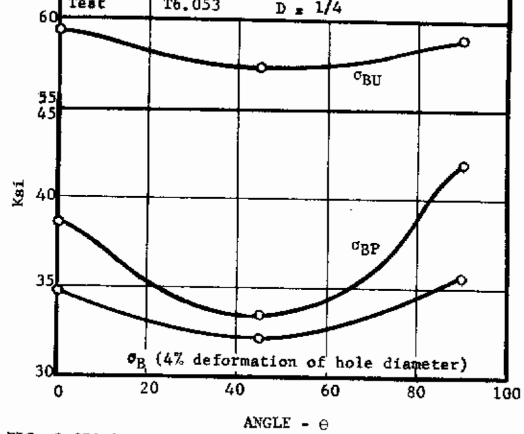

FIG. 3.072.14 EFFECT OF TEST DIRECTION ON BEARING PROPERTIES OF TYPICAL PolGc LAMINATE

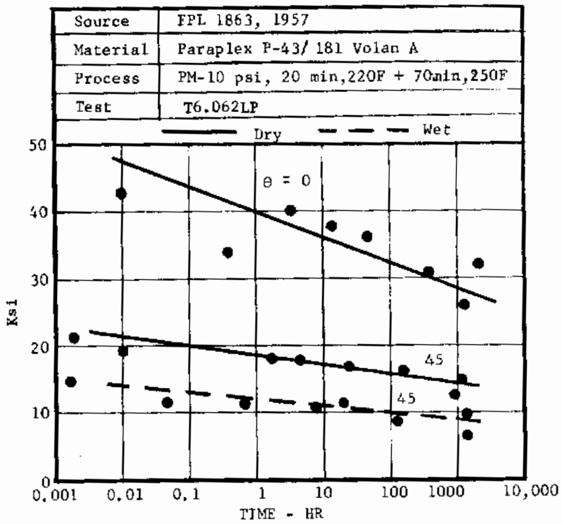

FIG: 3.081.1 CREEP RUPTURE CURVES FOR TYPICAL PolGc LAMINATE AT VARIOUS ANGLES θ

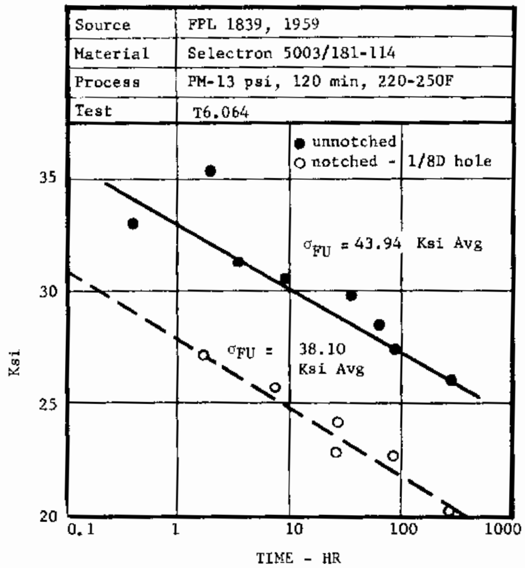

FIG. 3.081.3 CREEP RUPTURE CURVES FOR NOTCHED AND UNNOTCHED TYPICAL PolGc LAMINATE

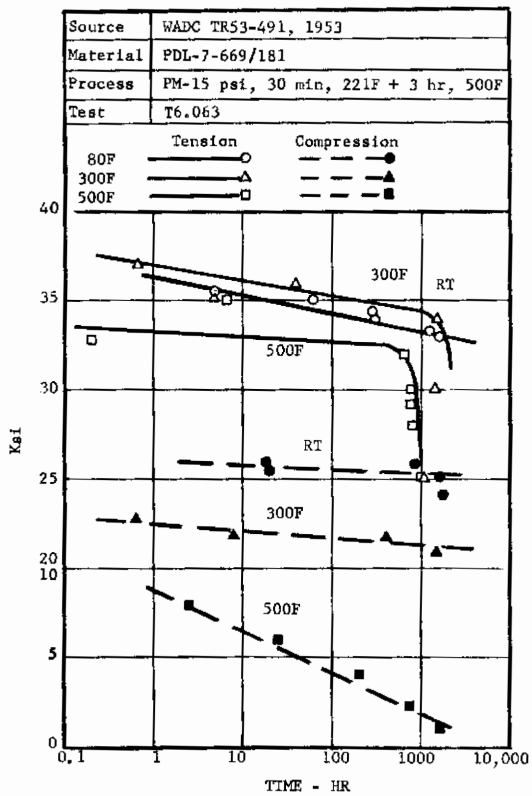

FIG. 3.081.2 CREEP RUPTURE CURVES FOR TYPICAL PolGc LAMINATE AT RT TO 500F

3.09 Fatique Properties

3.091 S-N Curves

3.091.1 S-N curves for unnotched and notched specimens of PolGc (143 cloth) laminate, Fig. 3.091.1.

3.091.2 S-N curves for unnotched and notched specimens of PolGc (181 cloth) laminate, Fig. 3.091.2.

3.091.3 S-N curves for unnotched and notched specimens of PolGc (181 cloth) laminate at θ = 0 and 45, Fig. 3.091.3.

3.091.4 S-N curves for unnotched and notched specimens of PolGc (181 cloth) laminate showing effects of cooling during test, Fig. 3.091.4.

3.091.5 S-N curves in bolt bearing for PolGc laminate, Fig. 3.091.5.

3.092 Stress Range Diagrams

3.092.1 Stress range diagram for typical PolGc (181 cloth) laminate, Fig. 3.092.1.

3.093 Other

Source	FPL 1823, 1958
Material	Plaskon 911-11/181-114, 23 pl, 0.25
Process	PM-14 psi, 90 min, 220F
Test	T6.073 - Axial

● Unnotched ——— Dry
O Notched – – – Dry, uncooled

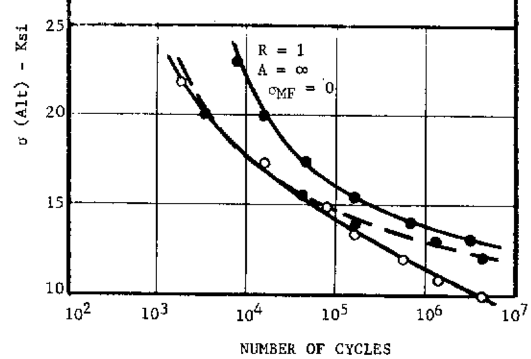

FIG. 3.091.2 S-N CURVES FOR UNNOTCHED AND NOTCHED SPECIMENS OF PolGc (181 cloth) LAMINATE

Source	FPL 1823, 1958
Material	Selectron 5003/143-114, 26 pl, 0.25
Process	PM-13 psi, 120 min, 220-250F
Test	T6.073 - Axial

● Unnotched
O Notched-1/8D hole

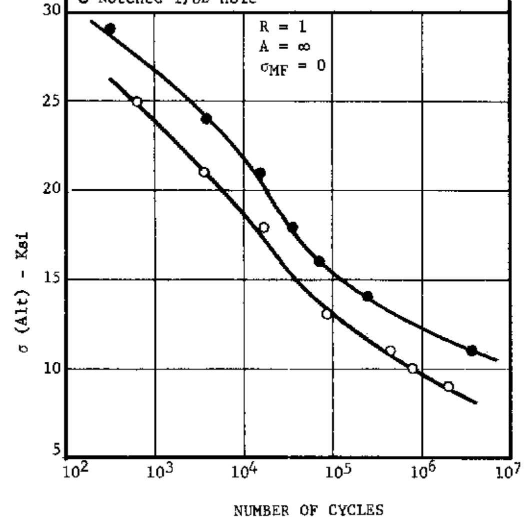

FIG. 3.091.1 S-N CURVES FOR UNNOTCHED AND NOTCHED SPECIMENS OF PolGc (143 cloth) LAMINATE

Source	FPL 1823, 1958
Material	Selectron 5003/181-114
Process	PM-13 psi, 120 min, 220-250F
Test	T6.073 - Axial

● Unnotched ——— Dry
O Notched-1/8D hole – – – Wet

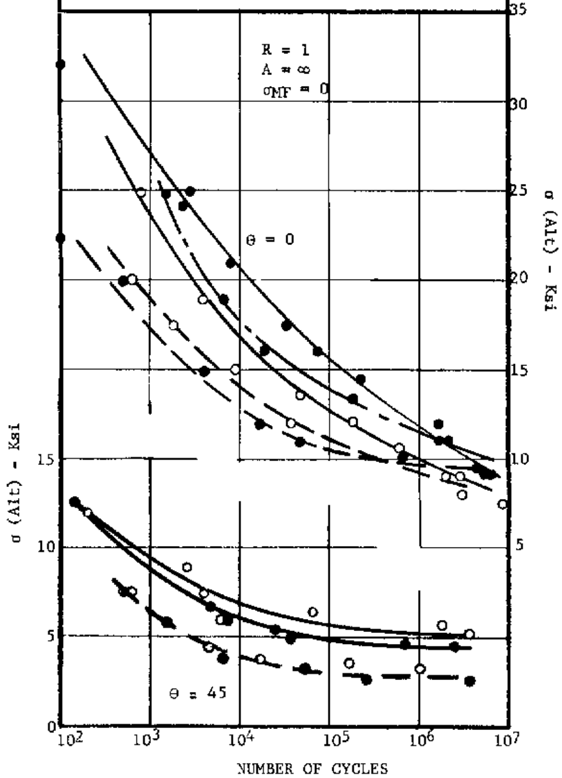

FIG. 3.091.3 S-N CURVES FOR UNNOTCHED AND NOTCHED SPECIMENS OF PolGc (181 CLOTH) LAMINATE AT θ = 0 & 45

Source	FPL 1823, 1958
Material	Selectron 5003/181-114, 23 pl, 0.25
Process	PM-14 psi, 120 min, 220-250F
Test	T6.073

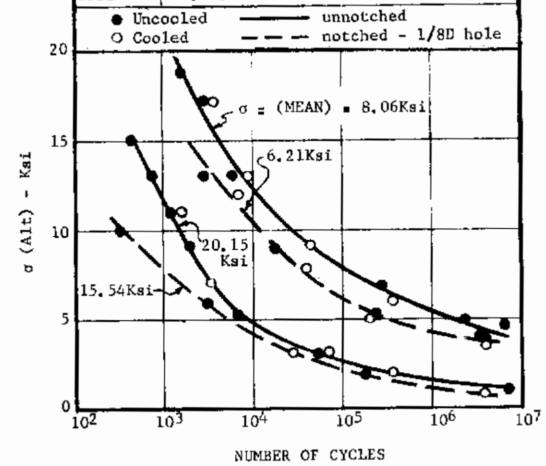

FIG. 3.091.4 S-N CURVES FOR UNNOTCHED AND NOTCHED SPECIMENS OF PolGc (181 cloth) LAMINATE SHOWING EFFECTS OF COOLING DURING TEST

Source	FPL 1823, 1958
Material	Selectron 5003/181-114
Process	PM-13 psi, 120 min, 220-250F
Test	T6.073 - Axial
Bolt bearing thru 1/4 D bolt.	

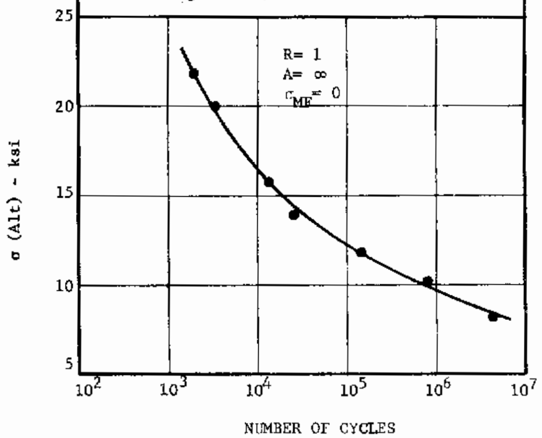

FIG. 3.091.5 S-N CURVES IN BOLT BEARING FOR PolGc LAMINATE

Source	FPL 1823-A, 1960
Material	Selectron 5003/181-114, 26 pl, 0.25
Process	PM-13 psi, 120 min, 220-250F
Test	T6.073 - Axial

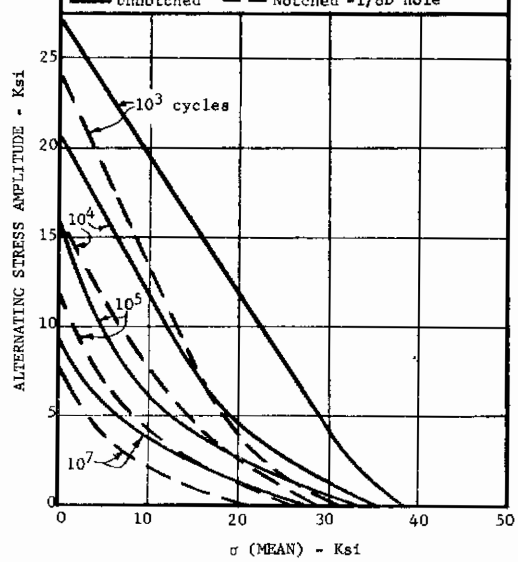

FIG. 3.092.1 STRESS RANGE DIAGRAM FOR TYPICAL PolGc (181 CLOTH) LAMINATE

3.10 Elastic Properties

3.101 Modulus of Elasticity In Tension

3.101.1 Modulus of elasticity in tension for PolGc laminates with various cloth reinforcements and at various angles θ, Fig. 3.101.1.

3.101.2 Effect of thickness on modulus of elasticity in tension for PolGc laminate, Fig. 3.101.2.

3.101.3 Effect of thickness and voids on modulus of elasticity in tension for PolGc laminates, Fig. 3.101.3.

3.101.4 Effect of thickness and surface sanding on modulus of elasticity in tension for PolGc laminate, Fig. 3.101.4.

3.101.5 Effect of test temperature on secant modulus in tension for typical PolGc laminate, Fig. 3.101.5.

3.102 Modulus of Elasticity in Compression

3.102.1 Modulus of elasticity in compression for PolGc laminates with various cloth reinforcements and at various angles θ, Fig. 3.102.1.

3.102.2 Effect of thickness on modulus of elasticity in compression for PolGc laminate, Fig. 3.102.2.

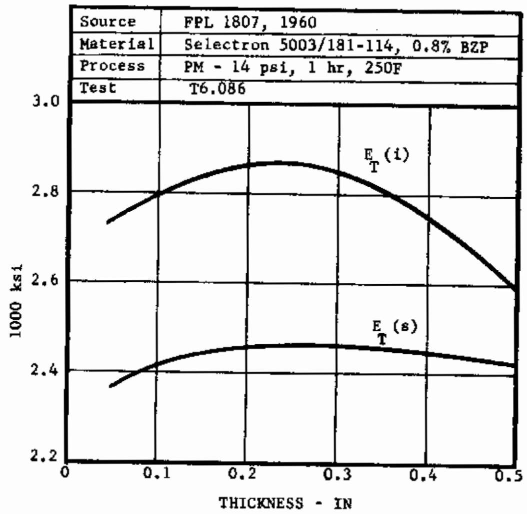

FIG. 3.101.2 EFFECT OF THICKNESS ON MODULUS OF ELASTICITY IN TENSION FOR PolGc LAMINATE

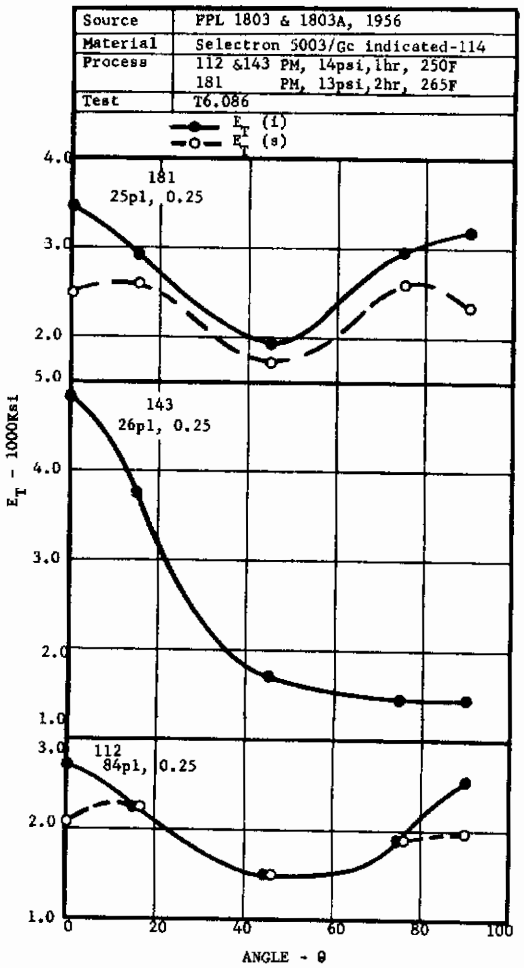

FIG. 3.101.1 MODULUS OF ELASTICITY IN TENSION FOR PolGc LAMINATES WITH VARIOUS CLOTH REINFORCEMENTS AND AT VARIOUS ANGLES θ

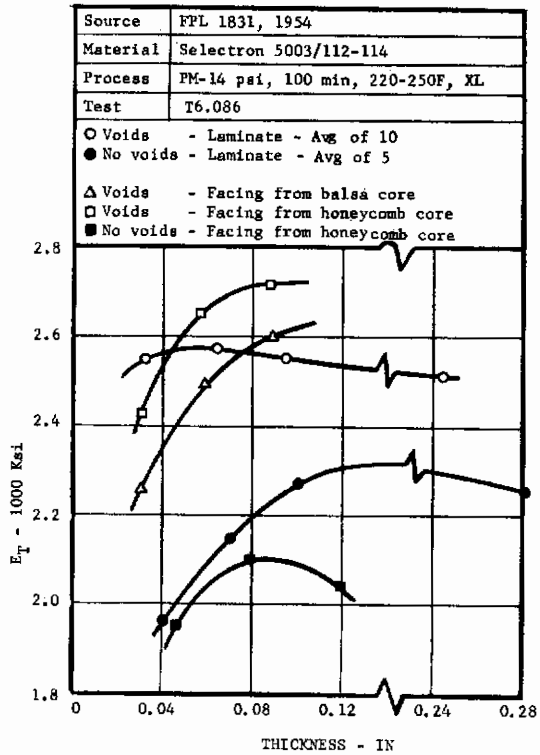

FIG. 3.101.3 EFFECT OF THICKNESS AND VOIDS ON MODULUS OF ELASTICITY IN TENSION FOR PolGc LAMINATES

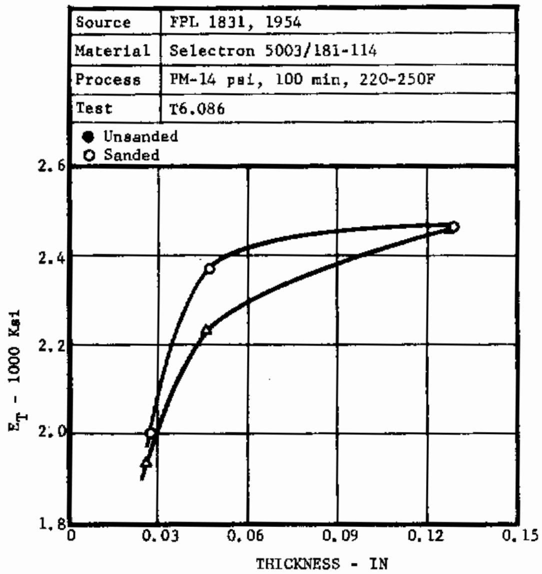

FIG. 3.101.4 EFFECT OF THICKNESS AND SURFACE SANDING ON MODULUS OF ELASTICITY IN TENSION FOR PolGc LAMINATE

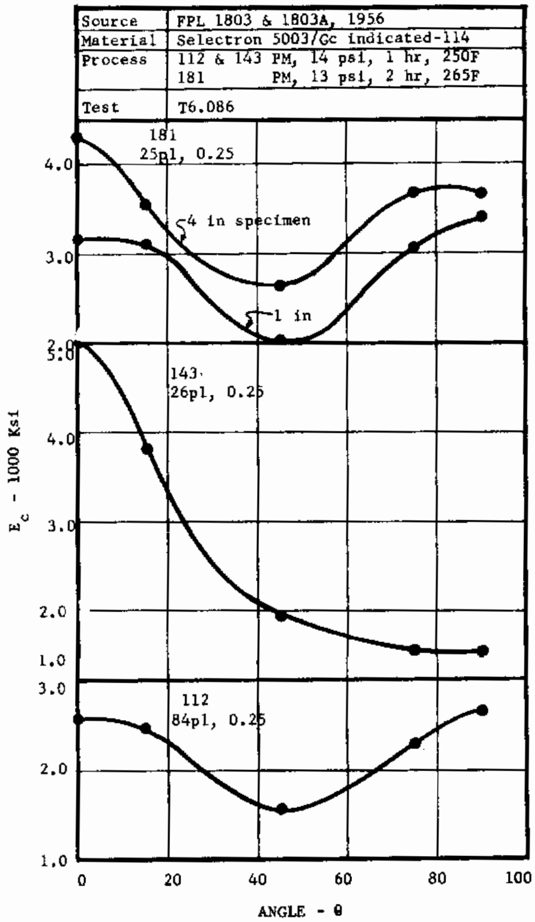

FIG. 3.102.1 MODULUS OF ELASTICITY IN COMPRESSION FOR PolGc LAMINATES WITH VARIOUS CLOTH REINFORCEMENTS AND AT VARIOUS ANGLES θ

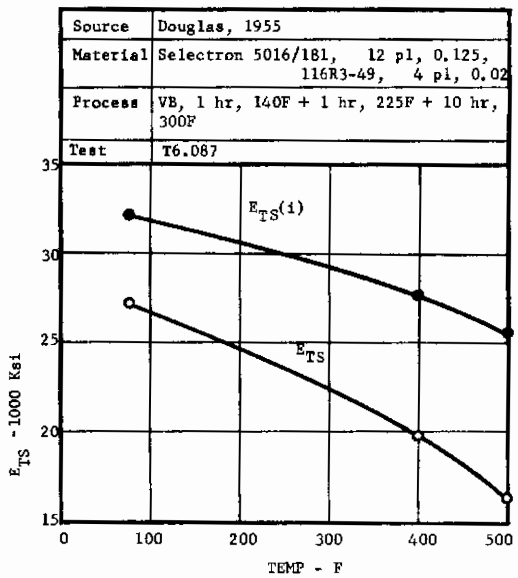

FIG. 3.101.5 EFFECT OF TEST TEMPERATURE ON SECANT MODULUS IN TENSION FOR TYPICAL PolGc LAMINATE

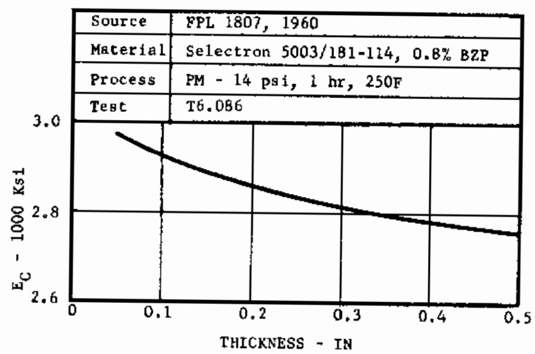

FIG. 3.102.2 EFFECT OF THICKNESS ON MODULUS OF ELASTICITY IN COMPRESSION FOR TYPICAL PolGc LAMINATE

3.102.3 Tangent modulus vs compression strength for PolGc (112 & 143 cloth) laminates at various angles θ, Fig. 3.102.3.

3.102.4 Tangent modulus vs compression strength for PolGc (181 cloth) laminate at various angles θ, Fig. 3.102.4.

3.102.5 Tangent modulus vs compression strength for PolGc laminates, under dry and wet conditions, Fig. 3.102.5.

3.103 Modulus of Elasticity in Flexure

3.103.1 Effect of span depth ratio on modulus of elasticity in flexure for PolGc laminate, Fig. 3.103.1.

3.103.2 Effect of thickness on modulus of elasticity in flexure for PolGc laminate with voids, Fig. 3.103.2.

3.103.3 Effect of moisture absorption on modulus of elasticity in flexure for PolGc laminate, Fig. 3.103.3.

3.103.4 Effect of weathering on modulus of elasticity in flexure for PolGc laminates, see Table 3.054.3.

3.103.5 Effect of prestress and water absorption on modulus of elasticity in flexure for PolGc laminates, See Table 3.055.1.

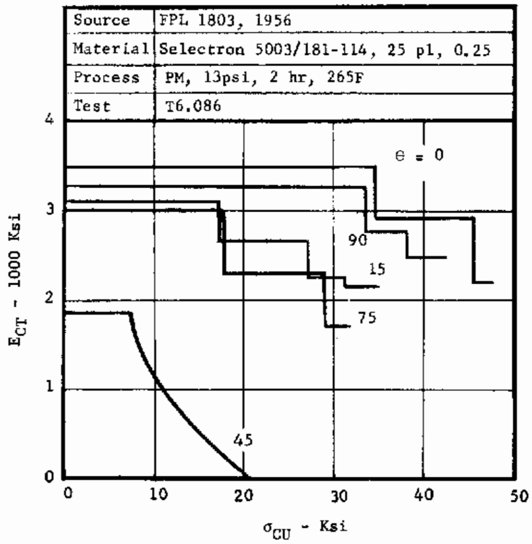

FIG. 3.102.4 TANGENT MODULUS VS COMPRESSION STRENGTH FOR PolGc (181 cloth) LAMINATE AT VARIOUS ANGLES θ

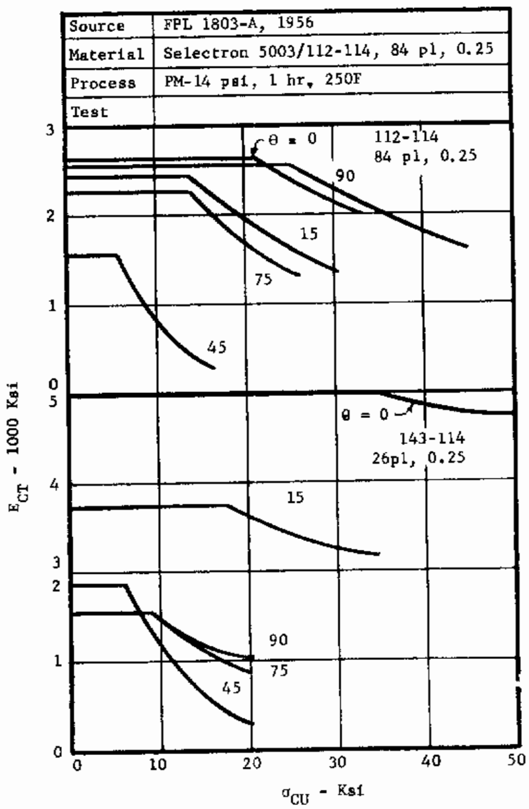

FIG. 3.102.3 TANGENT MODULUS VS COMPRESSION STRENGTH FOR PolGc (112 & 143 cloth) LAMINATES AT VARIOUS ANGLES θ

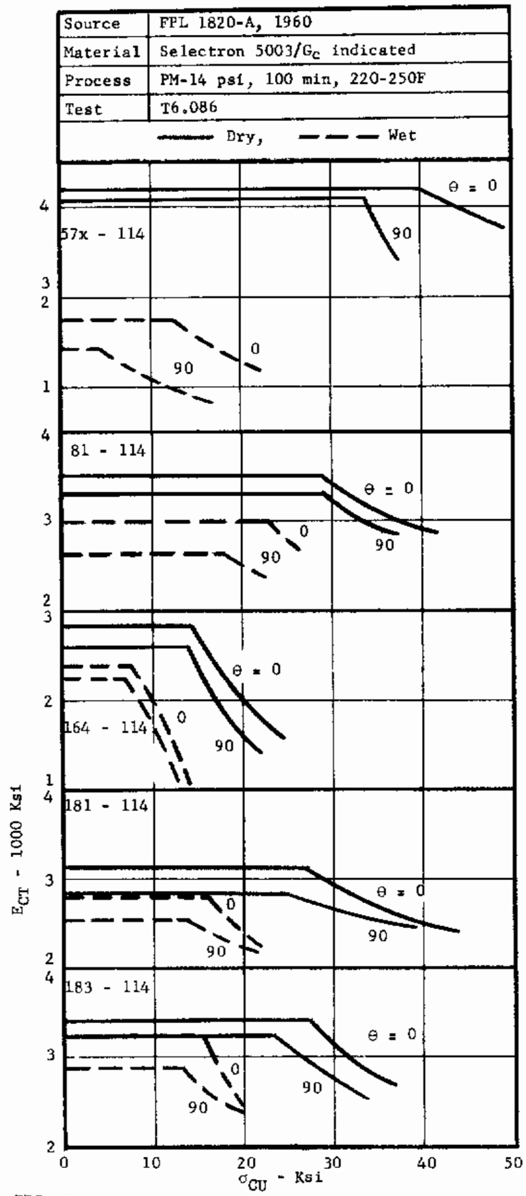

FIG. 3.102.5 TANGENT MODULUS VS COMPRESSION STRENGTH FOR PolGc LAMINATES UNDER DRY AND WET CONDITIONS

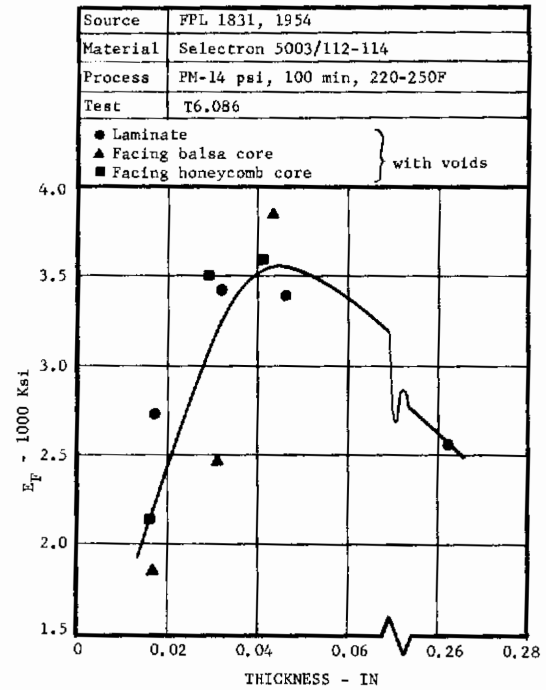

FIG. 3.103.2 EFFECT OF THICKNESS ON MODULUS OF ELASTICITY IN FLEXURE FOR PolGc LAMINATE WITH VOIDS

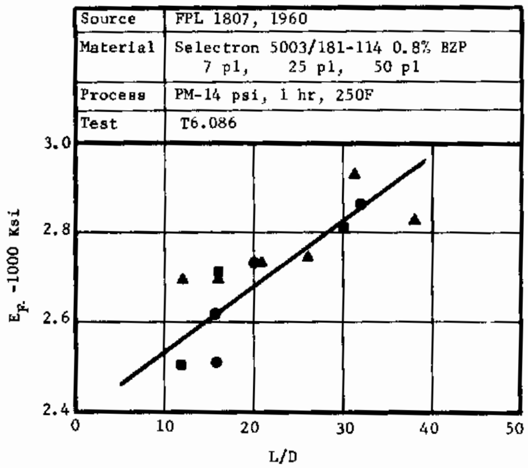

FIG. 3.103.1 EFFECT OF SPAN/DEPTH RATIO ON THE MODULUS OF ELASTICITY IN FLEXURE FOR PolGc LAMINATE

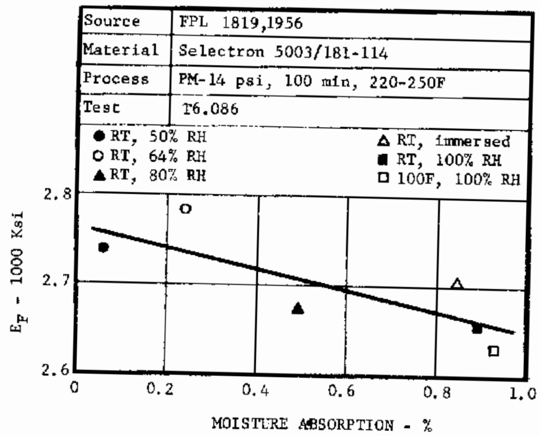

FIG. 3.103.3 EFFECT OF MOISTURE ABSORPTION ON MODULUS OF ELASTICITY IN FLEXURE FOR PolGc LAMINATE

3.104 Modulus of Elasticity In Shear

3.104.1 Modulus of elasticity in shear for PolGc laminates with various cloth reinforcements and at various angles θ, Fig. 3.104.1.

3.104.2. Tangent modulus vs shear strength for PolGc laminates with various cloth reinforcements, Fig. 3.104.2.

3.104.3 Tangent modulus vs shear strength for PolGc (112 and 143 cloth) laminates at various angles θ, Fig. 3.104.3.

3.104.4 Tangent modulus vs shear strength for PolGc (181 cloth laminate at various angles θ, Fig. 3.104.4.

Source	FPL 1807, 1960
Material	Selectron 5003/181-114, 0.8% BZP
Process	PM - 14 psi, 1 hr, 250F
Test	T6.086

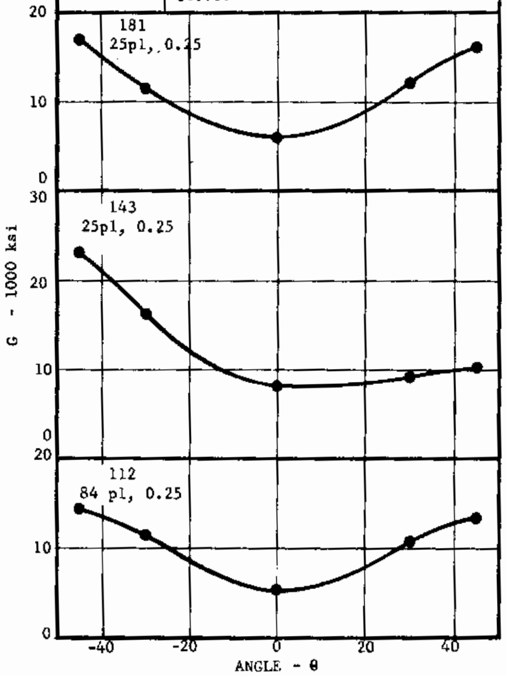

FIG. 3.104.1 MODULUS OF ELASTICITY IN SHEAR FOR PolGc LAMINATE WITH VARIOUS CLOTH REINFORCEMENTS AND AT VARIOUS ANGLES θ

Source	FPL 1820-A, 1960
Material	Selectron 5003/Gc indicated
Process	PM-14 psi, 100 min, 220-250F
Test	T6.086

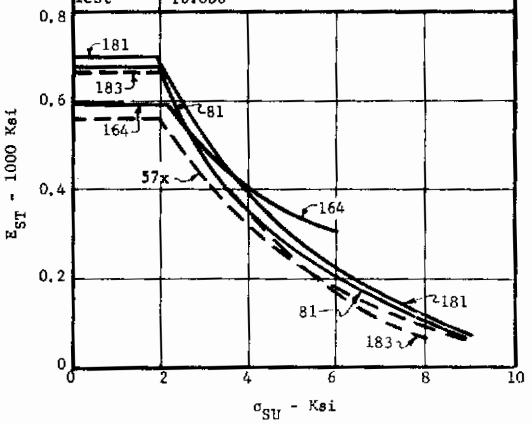

FIG. 3.104.2 TANGENT MODULUS VS SHEAR STRENGTH FOR PolGc LAMINATES WITH VARIOUS CLOTH REINFORCEMENTS

Source	FPL 1803-A, 1956
Material	Selectron 5003/143-114, 26 pl, 0.25
Process	PM-14 psi, 1 hr, 250F
Test	T6.086

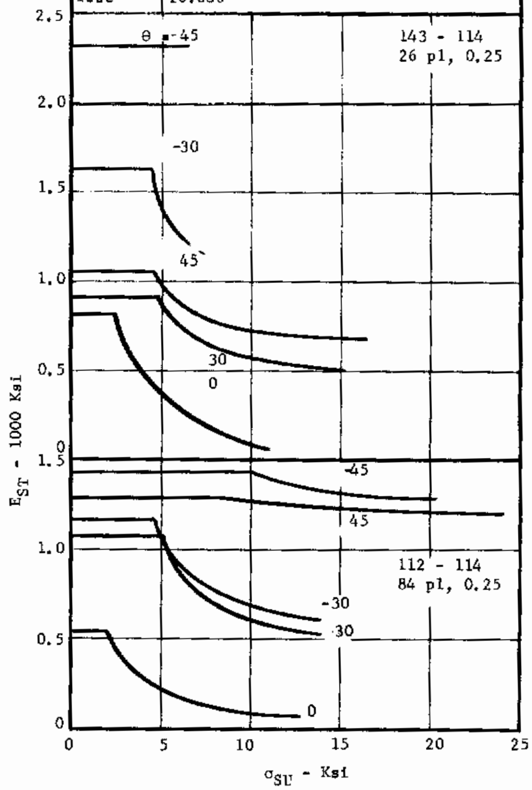

FIG. 3.104.3 TANGENT MODULUS VS SHEAR STRENGTH FOR PolGc (112 & 143 cloth) LAMINATES AT VARIOUS ANGLES θ

Source	FPL 1803, 1956
Material	Selectron 5003/181-114, 25 pl, 0.25
Process	PM-13 psi, 2 hr, 265F
Test	T6.086

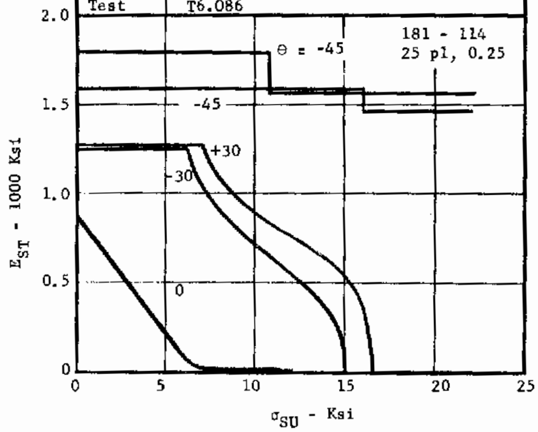

FIG. 3.104.4 TANGENT MODULUS VS SHEAR STRENGTH FOR PolGc (181 cloth) LAMINATE AT VARIOUS ANGLES θ

1. GENERAL

1.01 Designations

1.011 Handbook Code Designation: P02Gc. This code refers to a polyester-glass cloth laminate system having improved mechanical properties and thermal resistance compared to Po1Gc. The resin is 100% reactive and composed of unsaturated alkyd resins disolved in styrene monomer.

1.012 Commercial Designations

1.012.1 Commercial designations are as indicated in data reported in this section.

1.012.2 Typical commercial designations include: Vibrin X-1047, Laminac 4232, etc.

1.013 Alternate Designations

1.02 Specifications, Table 1.02.

1.03 Composition

1.031 Materials included in this section are systems of resin and reinforcement combined into laminates by various processes. The system composition includes special purpose, to improve mechanical properties, polyester resins and standard glass cloth reinforcements.

1.032 For normal structural applications a resin content of 30 to 40 percent appears to be standard.

1.033 Due to wide spread acceptance and use, 181 weave glass cloth is used as a basic reinforcement for data reporting.

1.034 Additional information on polyester-glass cloth laminates will be found in Section Po1Gc which describes the general purpose polyester systems.

1.035 Other material systems utilizing different resins or reinforcements will be found elsewhere in this Manual. Individual primary materials are described in Manual IC.

1.04 Forms and Conditions Available

1.041 Po2Gc can be produced in shop by utilizing individual resins, powder or liquid, and glass cloth in the wet lay-up process.

1.042 Prepreg, B-Stage, material can also be readily secured with a variety of compositions.

1.043 Po2Gc can be secured in a variety of fabricated shapes, but only properties of the material in sheet form are reported herein.

1.044 Due to inherent properties of this material, it can be formed and produced in almost any shape or size.

1.05 Special Considerations

1.051 Careful consideration should be given to the recommendations and experience of material supplier with respect to handling, storage, processing and curing.

2 PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Thermal Degredation

2.012 Conductivity

2.013 Expansion

2.014 Specific Heat

2.015 Diffusivity

2.016 Emissivity

2.017 Ablation

2.018 Other

TABLE 1.02

Source	No.	Title
Military	MIL-P-25395 (USAF)	Plastic Materials, Heat Resistance, Low Pressure Laminated, Glass Fabric Base, Polyester Resin
Military	MIL-R-7575	Resin, Polyester, Low Pressure Laminates
Military	MIL-R-25042A	Resin, Polyester, High Temperature Resistance, Low Pressure Laminating

2.02 Electrical Properties

2.021 Resistivity

2.022 Conductivity

2.023 Dielectric Properties

2.023.1 Specified dielectric constants and loss tangents, Table 2.023.1.

TABLE 2.023.1

Source	MIL-R-25042A	MIL-R-7575			
Test	T5.032LP	(8500 to 10,000 MC)			
Specified Type or Class	III Avg of 3	Grade B class Avg of 4 1	2	3	4
Dielectric Constant Dry-Max	4.3[1]	3.6 to 4.0	4.0 to 4.2	4.2 to 4.4	4.4 to 4.6
Wet-Max	4.4[1]				
Loss Tangent Dry-Max	0.025[2]				
Wet-Max	0.03[2]				

(1) ± 3% change in value of standard condition over specified.

(2) Temperature range 0.045 over specified temperature range.

2.023.2 Typical dielectric constants and loss tangents for various PO2Gc laminates, Table 2.023.2.

TABLE 2.023.2

Source	WADC-AF-TR-6602 1951
Material	Vibrin X-1047/ 181-114, 14 pl
Process	PM, 90 min, 176 to 248F BZP, 2%
Test	10,000 MC
rc - %	36
Constant Dielectric	
Dry	4.04
Wet	5.24
Loss Tangent	
Dry	0.012
Wet	0.049

2.024 Magnetic Properties

2.025 Other

2.03 Other Physical Properties

2.031 Density

2.032 Water Absorption

2.032.1 MIL-R-25042A specified water absorption after 24 hr immersion is 3.3% max increase in weight.

2.032.2 MIL-R-7575B, Grade B, specified water absorption after 24 hr immersion is 0.5% max increase in weight.

2.033 Other

2.04 Chemical Properties

2.041 Chemical Resistance

2.041.1 Specified chemical resistance to certain fluids, Table 2.041.1.

TABLE 2.041.1

Source	MIL-R-25042A (2)	MIL-R-7575B (1)	MIL-R-25042A (2)	MIL-R-7575B (1)	MIL-R-25042A (2)	MIL-R-7575B (1)
Immersion in Chemical fluid	MIL-H-5606 Hydraulic fluid petroleum base		MIL-F-5566 Anti-icing fluid iso-propyl alcohol		MIL-S-3136 Hydrocarbon Test fluids and iso-octane	
Test	T3.042 LP					
Δw% max	2	0.2	2	0.1	2	0.1
Δt% max	0.2	0.2	0.1	0.1	0.2	0.1

(1) Grade B, σ_{fu} after immersion shall be reported.

(2) σ_{fu} = 43 ksi

2.042 Fire Resistance Properties

2.042.1 Combustion rate. MIL-R-25042A and 7575B, Grade B, specify a maximum of 1.0 inch per minute as tested by T3.0313LP.

2.043 Environmental Properties

2.05 Nuclear Properties

3. MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 MIL-R-25042A Specified Mechanical Properties, Table 3.011.

3.012 MIL-R-25395 (USAF) Specified Mechanical Properties, Table 3.012.

3.013 MIL-R-7575B, Grade B, Specified Mechanical Properties, Table 3.013.

TABLE 3.011

Source	MIL-R-25042A					
Material	Polyester/glass cloth					
Process						
Property	Test	Test Conditions				
	Avg of 5	Standard	500F 1/2 hr	after 192 hr	Outdoor Weathering(2) 90 days	Outdoor Weathering(2) 1 year
σ_{tu}, min - ksi	T6.013LP Type 2	35	18	--	--	--
wet(1)-ksi		33	--	--	--	--
σ_{cu}, min - ksi	T6.022LP	30	15	--	--	--
wet(1)-ksi		28	--	--	--	--
σ_{fu}, min - ksi	T6.032LP	48	30	17	--	--
wet(1)-ksi		43	--	--	--	--
E_f, min-1000 ksi	T6.032LP	2.8	2.0	1.5	2.4	2.4
wet(1)1000-ksi		2.4	--	--	--	--
Hardness - BHN	T6.063LP	55	--	--	--	--
rc %	T2.042LP	to be				
Sp g	T2.052LP	reported				

(1) 30 days in water.
(2) Samples shall show no crackling, crazing, delamination, nor any other visible deterioration after exposure.
(3) σ_{fu} after immersion in chemical fluids = 43 ksi, see also Table 2.041.1.

TABLE 3.013

Source	MIL-7575B, Grade B				
Material	Polyester/181 - 0.125				
Process	PM, 10 - 30 psi				
Property	Test Avg of 5	Test Conditions			
		Standard	160F after 1/2 hr	Outdoor Weathering(2) 90 days	Outdoor Weathering(2) 1 year
σ_{tu}, min -ksi	T6.013LP Type 2	50	--	--	--
wet(1) -ksi		48	--	--	--
σ_{cu}, min -ksi	T6.022LP	45	--	--	--
wet(1) -ksi		40	--	--	--
σ_{fu}, min -ksi	T6.032LP	65	44	50	50
wet(1) -ksi		60	--	--	--
E_f, min - 1000 -ksi	T6.032LP	3.2	2.6	2.7	2.7
wet(1)1000 -ksi		3.1	--	--	--
Hardness BHN	T6.063LP	55	--	--	--
rc %	T2.042LP	to be			
Sp g	T2.052LP	reported			

(1) 30 days in water

(2) Samples shall show no cracking, crazing, delamination, nor any other visible deterioration after exposure.

(3) σ_{fu} after immersion in chemical fluids = 43 ksi, see also Table 2.041.1.

TABLE 3.012

Source	MIL-P-25395 (USAF)									
Material	Polyester/glass cloth - 0.125 ± 0.010									
Property - min.	Glass cloth designation									
	112	116	120	128	143	162	164	181 or 182	183	184
σ_{tu}, dry -ksi	35	35	35	35	70	35	29	35	35	35
wet -ksi	33	33	33	33	66	33	26	33	33	33
500F after 1/2 hr -ksi	13	18	18	18	35.5	18	18	18	18	18
σ_{cu}, dry -ksi	28	26	30	30	42	15	15	30	26	24
wet -ksi	26	24	28	18	38	13	13	28	24	21
500F after 1/2 hr -ksi	15	13.5	15	10.5	21.5	7	7	15	13.5	11.5
σ_{fu}, dry -ksi	48	43	43	43	80	30	30	48	43	43
wet -ksi	43	37	37	37	70	26	26	43	38	38
500F after 1/2 hr -ksi	30	26	30	26	52	19.3	19.3	30	26.7	26.7
500F after 192 hr -1000-ksi	17	14.7	17	14.7	29.5	10.9	10.9	17	15.1	15.1
E_f(i), dry -1000-ksi	2.6	2.6	2.6	2.6	4.8	2.2	2.2	2.8	2.6	2.6
wet -1000-ksi	2.4	2.4	2.4	2.4	4.4	2.0	2.0	2.4	2.4	2.4
500F after 1/2 hr - 1000-ksi	2.0	2.0	2.0	2.0	3.6	1.68	1.68	2.0	2.0	2.0
500F after 192 hr - 1000-ksi	1.5	1.5	1.5	1.5	2.7	1.3	1.3	1.5	1.5	1.5

3.02 Typical Mechanical Properties

3.021 Typical Effects of Outdoor Weathering under Different Conditions on Mechanical Properties of Po2Gc Laminates, Table 3.021.

3.03 Tension Properties

3.031 Stress Strain Relationships

3.032 Physical Effects

3.033 Processing Effects

3.034 Environmental Effects

3.034.1 Effect of exposure and test temperature on tension strength of Po2Gc laminate, Fig. 3.034.1.

3.035 Other Effects

TABLE 3.021

Source	MIL-HANDBOOK ANC-17 Part I - 1955			
Materials	PDL-7-669/181		Vibrin X-1047/181	
Test	T6.013LP and T6.023LP			
3 yr outdoor Weathering Conditions	Salt	Artic	Arid	Artic
σ_{tu} - ksi	23.1	26.5	27.2	30.4
Change from control - %	-33	-24	-33	-25
σ_{cu} - ksi	26.1	36.5	23.9	29.2
Change from control - %	-27	+2	-8	+13

3.04 Compression Properties

3.041 Stress Strain Relationships

3.042 Physical Effects

3.043 Processing Effects

3.043.1 Effect of cure pressure on compression strength of Po2Gc laminates at room and elevated temperature, Fig. 3.043.1.

Source	Mil-Hd bk 17, Part 1, 1955
Material	Laminac 4232/181-136
Process	
Test	

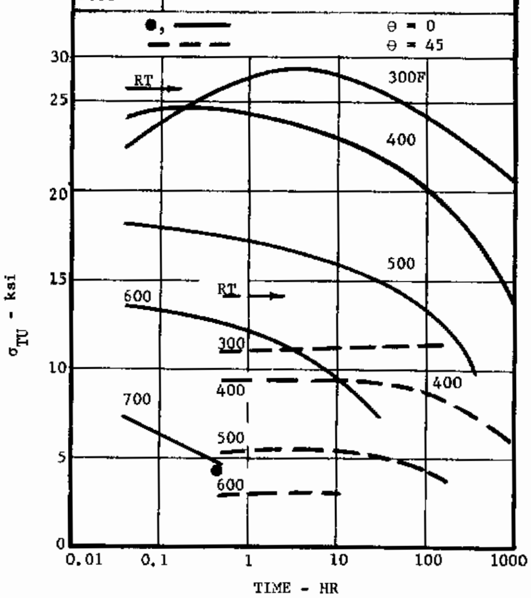

FIG. 3.034.1 EFFECT OF EXPOSURE AND TEST TEMPERATURE ON TENSION STRENGTH OF PO2Gc LAMINATE

Material	Resin indicated/181-114, 2% BZP,14 p
Process	PM, psi indicated, 30 min, 176-248F + post cure 24 hr, 350F
Test	WADC

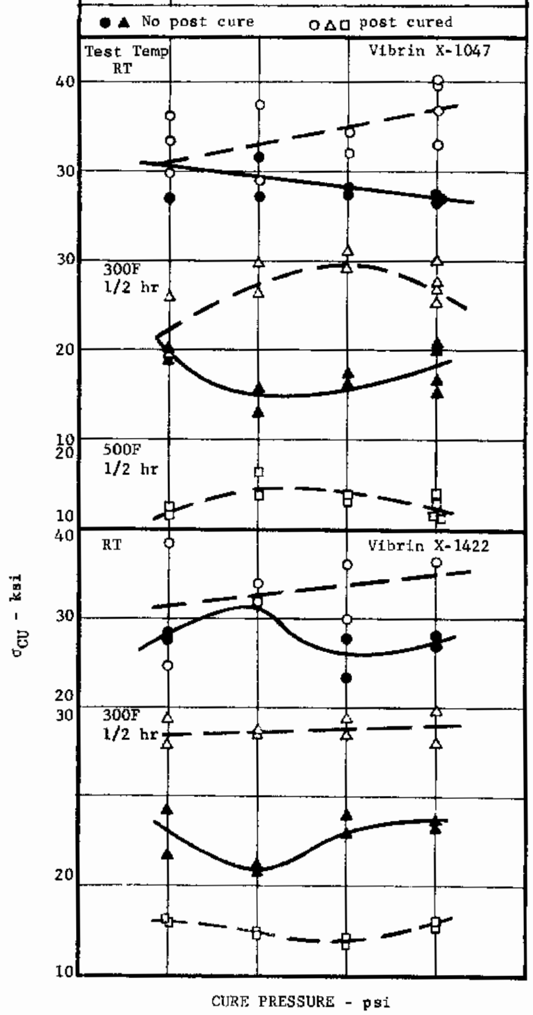

FIG. 3.043.1 EFFECT OF CURE PRESSURE ON COMPRESSION STRENGTH OF PO2Gc LAMINATES AT ROOM AND ELEVATED TEMPERATURES

3.044 Environmental Effects

3.044.1 Effect of exposure and test temperature on compression strength of Po2Gc laminate, Fig. 3.044.1.

3.05 Flexure

3.051 Stress Strain Relationships

3.052 Physical Effects

3.053 Processing Effects

3.053.1 Effect of cure pressure on flexure strength of Po2Gc (Vibrin X-1047) laminates at various exposure and test temperatures, Fig. 3.053.1.

Source	WADC 6602, 1951
Material	Vibrin X-1047/181-114, 2% BZP, 50% Triallyl cyanurate, 14 pl
Process	PM, psi indicated, 30 min, 176-248F
Test	WADC

Cure Pressure psi	rc %	RT σ_{FU} - ksi
● 10	40-42	38.4
○ 15	35-37	43.2
■ 20	33-35	42.2
□ 25	30	42.4

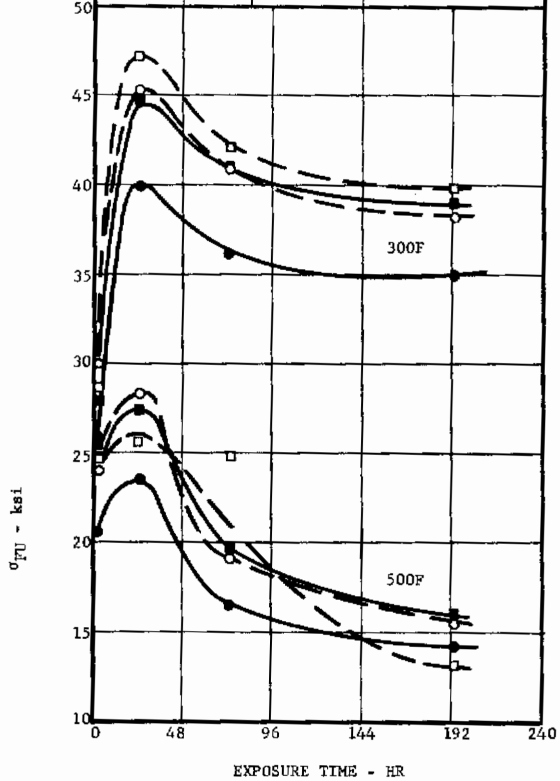

FIG. 3.053.1 EFFECT OF CURE PRESSURE ON FLEXURE STRENGTH OF PO2Gc (VIBRIN X-1047) LAMINATES AT VARIOUS EXPOSURE AND TEST TEMPERATURES

Source	Mil-Hd bk 17, Part 1, 1955
Material	Laminac 4232/181-136
Process	
Test	

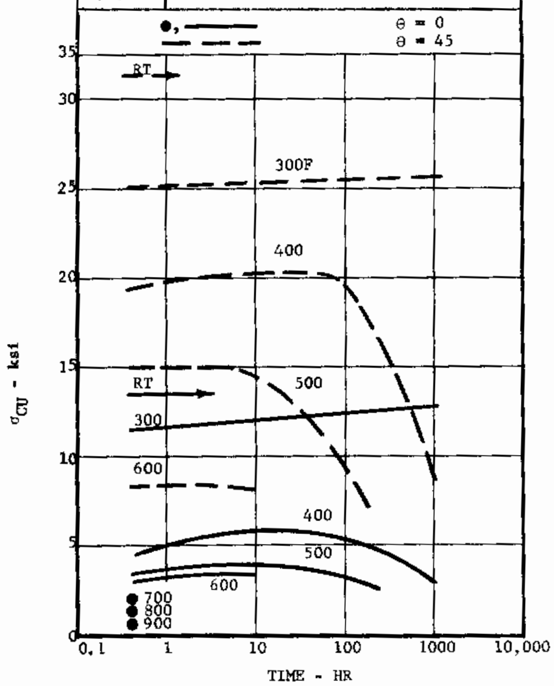

FIG. 3.044.1 EFFECT OF EXPOSURE AND TEST TEMPERATURE ON COMPRESSION STRENGTH OF PO2Gc LAMINATE

3.053.2 Effect of cure pressure on flexure strength of Po2Gc (Vibrin X-1422) laminates at various exposure and test temperatures, Fig. 3.053.2.

Source	WADC 6602, 1951	
Material	Vibrin X-1422/181-114, 2% BZP, 55% triallyl cyanurate, 14 pl	
Process	PM, psi indicated, 30 min, 176-248F	
Test	WADC	
Cure Pressure	rc %	RT σ_{FU}-ksi
● 10	39-42	47.4
○ 15	39-40	46.7
■ 20	35-36	47.0
□ 25	33	44.9

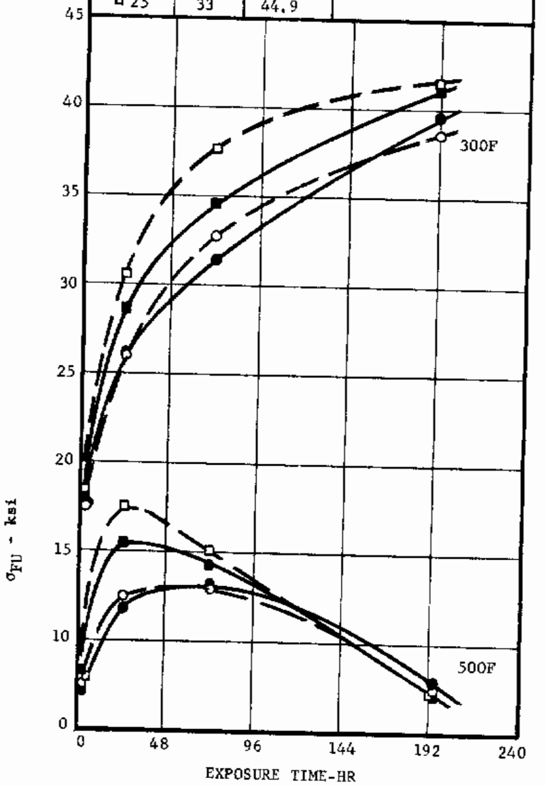

FIG. 3.053.2 EFFECT OF CURE PRESSURE ON FLEXURE STRENGTH OF PO2Gc (VIBRIN X-1422) LAMINATES AT VARIOUS EXPOSURE AND TEST TEMPERATURES

3.053.3 Effect of various post cures on the flexure properties of Po2Gc (Vibrin X-1047) laminates, Table 3.053.3.

3.053.4 Effect of various post cures on the flexure properties of Po2Gc (Vibrin X-1422) laminates, Table 3.053.4.

TABLE 3.053.3

Source	WADC TR 6602, 1951											
Material	Vibrin X-1422/181-114, 14 pl, BZP, 2%											
Process	PM, 15 psi, 20 min + 15 min + 175 - 185F + 248F + Post Cure											
Property Avg of 2	None	24 hr 350F	16 hr 400F	24 hr 400F	5 hr 450F	8 hr 450F	16 hr 450F	24 hr 450F	1 hr 500F	3 hr 500F	5 hr 500F	8 hr 500F
σ_{fu} -ksi	40.6	45.5	47.8	42.5	50.9	47.2	46.2	44.0	46.6	50.1	47.1	44.8
after 1/2 hr at												
300F -ksi	26.0	36.7	40.8	40.2	42.7	44.1	41.9	42.5	37.0	41.4	40.0	40.3
500F -ksi	20.6	21.7	21.9	20.7	23.7	28.3	27.4	27.8	28.8	32.9	31.7	33.5
after 24 hr at												
300F -ksi	34.0	36.2	40.3	40.3	45.2	43.5	40.9	42.9	40.8	45.5	43.1	40.8
500F -ksi	32.7	31.6	30.2	31	32.7	31.9	27.0	28.2	30.8	32.8	32.8	31.4
after 72 hr at												
300F -ksi	34.4	36.8	40.0	41.3	42.2	45.0	41.4	42.4	42.9	43.3	43.3	41.9
500F -ksi	20.3	20.1	20.2	20.9	20.3	24.2	20.9	21.3	21.9	23.3	23.6	20.8
after 192 hr at												
300F -ksi	37.9	29.3	40.7	42.4	46.5	45.2	40.9	43.2	45.6	47.0	47.6	41.3
500F -ksi	11.7	11.0	11.4	11.5	12.7	11.5	11.4	10.4	12.9	13.3	14.9	12.6
E_f -1000 ksi	2.92	2.74	3.58	2.90	3.0	2.5	2.62	2.83	2.46	2.74	2.92	2.45
after 1/2 hr at												
300F - - 1000 ksi	2.54	2.61	2.49	2.30	2.43	2.51	2.59	2.59	2.34	2.34	2.50	2.30
500F - 1000 ksi	1.98	1.83	1.87	1.82	2.14	2.27	1.85	2.03	2.25	2.14	2.03	2.12
after 24 hr at												
300F - 1000 ksi	2.44	2.5	2.5	2.41	2.66	2.42	2.36	2.47	2.66	2.52	2.55	2.78
500F - 1000 ksi	2.21	2.08	2.05	2.21	2.26	2.01	2.03	2.00	2.21	2.32	2.04	2.08
after 72 hr at												
300F - 1000 ksi	2.55	2.77	2.51	2.70	2.57	2.57	2.04	2.71	2.43	2.43	2.58	2.38
500F - 1000 ksi	1.96	1.95	1.84	2.16	2.29	2.58	2.04	2.05	2.28	2.09	2.28	2.05
after 192 hr at												
300F - 1000 ksi	2.21	2.45	2.50	2.66	2.54	2.48	1.61	2.39	2.52	2.85	2.50	2.43
500F - 1000 ksi	1.54	1.50	1.55	1.79	1.77	1.61	1.61	1.71	1.90	1.83	1.79	1.78

TABLE 3.053.4

Source	WADC TR 6602, 1951											
Material	Vibrin X-1422/181-114, 14 pl, BZP, 2%											
Process	PM, 15 psi, 20 min + 15 min + 175 - 185F + 248F + Post Cure											
Property Avg of 2	None	24 hr 350F	16 hr 400F	24 hr 400F	5 hr 450F	8 hr 450F	16 hr 450F	24 hr 450F	1 hr 500F	3 hr 500F	5 hr 500F	8 hr 500F
σ_{fu}	34.8	43.8	43	45.6	42	46.7	43.5	49.5	43	48	48	44.5
after 1/2 hr at												
300F -ksi	22.7	34.2	32.6	39.6	36.7	38.9	39.1	41.8	35	--	27.1	29.2
500F -ksi	12	14.1	11.7	12.4	18.9	15.6	12	9.9	17	13.4	12	12
after 24 hr at												
300F -ksi	27.5	34.2	34.2	40	38.7	38.8	39.8	38.2	37.1	26.4	21.1	18.7
500F -ksi	16.9	19.8	19.1	19.9	21.4	22.6	19.8	19	21.7	21.6	13.8	18.2
after 72 hr at												
300F -ksi	30.2*	35.5*	40.2*	39.1*	38.8	42.8	40.6*	39.7*	20.9	29.1	20.6	15.2
500F -ksi	18.1	18.8	18.4	17.0	18.5	18.4	18.7	18.5	18.5	19.2	19.4	19.6
after 192 hr												
300F -ksi	36.6	39.7	15.6	40.7	40.5	43.5	39.5	39.8	20.6	21.1	22.4	22.5
500F -ksi	11.4	12.8	12.3	12.6	12	11.4	11.5	12	11.8	12.1	12.8	12.8
E_f - 1000 ksi	3.05	2.58	2.54	2.76	3.08	2.83	2.4	2.54	3.06	3.10	3.35	3.4
after 1/2 hr at												
300F -1000 ksi	2.32	2.39	2.32	2.34	2.43	2.4	2.11	2.13	2.35	--	1.32	2.01
500F -1000 ksi	1.49	1.97	1.52	1.44	2.22	1.71	1.25	1.04	1.82	1.3	0.67	1.1
after 24 hr at												
300F -1000 ksi	2.73	2.27	2.33	2.51	2.42	2.32	2.31	2.22	2.29	1.2	1.36	1.04
500F -1000 ksi	1.66	1.75	1.51	1.73	1.78	1.73	1.44	1.52	1.82	1.82	1.14	1.69
after 72 hr at												
300F -1000 ksi	2.42*	2.21*	2.33*	2.29	2.55	2.46	2.19*	2.36*	0.96	1.56	1.44	
500F -1000 ksi	1.8	1.72	1.63	1.69	1.73	1.96	2.23	1.97	1.89	1.94	1.91	1.92
after 192 hr at												
300F -1000 ksi	2.5	2.35	2.08	2.46	2.48	2.61	2.49	2.28	1.19	1.02	1.04	1.61
500F -1000 ksi	1.72	1.67	1.51	1.80	1.62	1.68	---	1.59	2.49	1.85	2.0	1.35

* after 48 hr at temperature

3.053.5 Also see Section 3.055 for effects of additives and glass finish on flexure strengths.

3.054 Environmental Effects

3.054.1 Effect of exposure and test temperature on various Po2Gc laminates, Fig. 3.054.1.

3.054.2 Effect of exposure and test temperature on Po2Gc (Vibrin X-1047) laminate, Fig. 3.054.2.

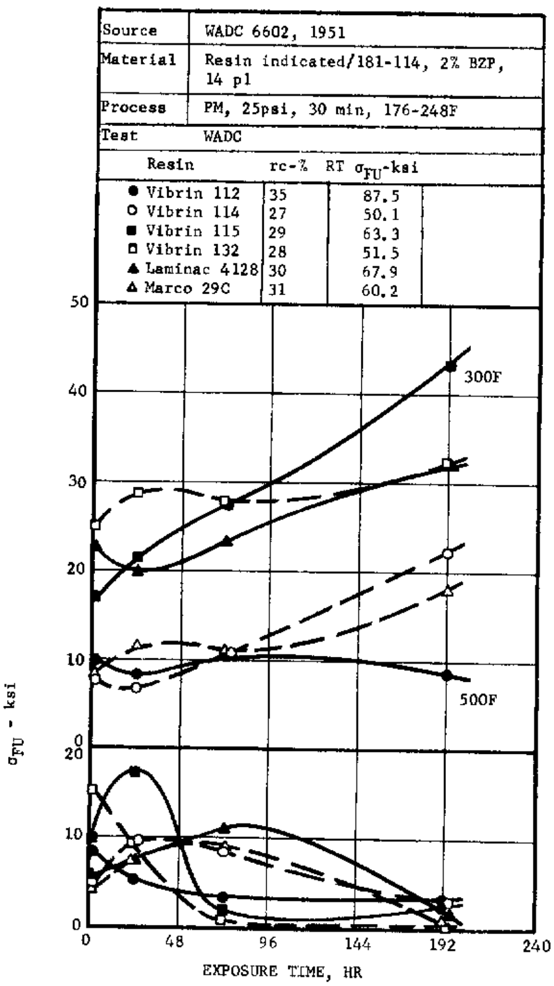

FIG. 3.054.1 EFFECT OF EXPOSURE AND TEST TEMPERATURE ON FLEXURE STRENGTH OF VARIOUS PO2Gc LAMINATES

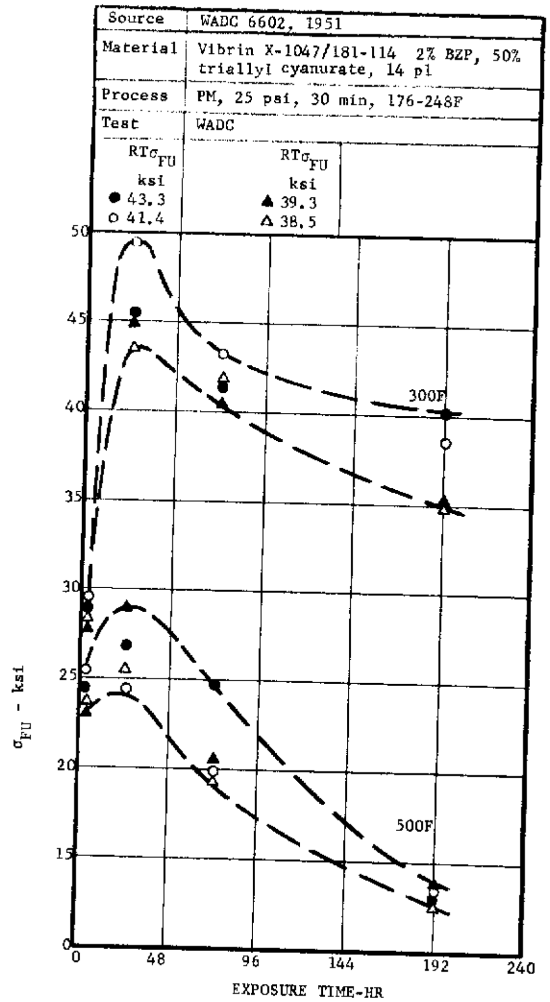

FIG. 3.054.2 EFFECT OF EXPOSURE AND TEST TEMPERATURE STRENGTH OF PO2Gc (Vibrin X-1047) LAMINATE

3.054.3 Effect of exposure and test temperature on Po2Gc (Vibrin X-1422) laminate, Fig. 3.054.3.

3.055 Other Effects

3.055.1 Effect of various additive concentrations on flexure strength of Po2Gc (Vibrin X-1039) laminates at various exposure and test temperatures, Fig. 3.055.1.

Source	WADC 6602, 1951
Material	Vibrin X-1422/181-114, 2% BZP, 55% triallyl cyanurate, 14 pl
Process	PM, 25 psi, 30 min, 176-248F
Test	WADC

$RT\sigma_{FU}$ ksi	$RT\sigma_{FU}$ ksi
● 48.2	▲ 48.0
○ 48.4	△ 48.0

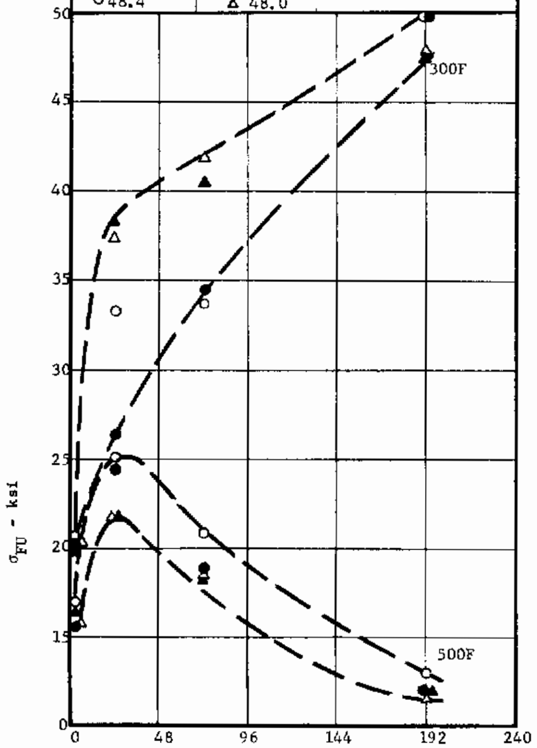

FIG. 3.054.3 EFFECT OF EXPOSURE AND TEST TEMPERATURE STRENGTH OF PO2Gc (Vibrin X-1422) LAMINATE

Source	WADC 6602, 1951
Material	Vibrin X-1039/181-114, 2% BZP, 14 pl
Process	PM, 25 psi, 30 min, 185-248F + Post Cure
Test	WADC

RT rc %	σ_{FU} ksi	triallyl cyanurate pph	Styrene pph	diallyl phthalate pph	Post Cure
36	51.3	75	25	--	None
29	55.9	50	50	--	None
31	46.0	50	--	50	None
32	51.2	50	--	50	24hr, 300F

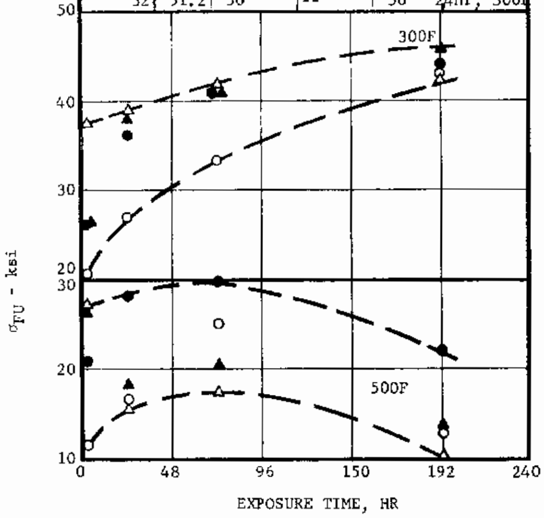

FIG. 3.055.1 EFFECT OF VARIOUS ADDITIVE CONCENTRATIONS ON FLEXURE STRENGTH OF PO2Gc (VIBRIN X-1039) LAMINATES AT VARIOUS EXPOSURE AND TEST TEMPERATURES

3.055.2 Effect of triallyl cyanurate concentration on flexure strength of Po2Gc (Vibrin X-1047) laminates at various exposure and test temperatures, Fig. 3.055.2.

3.055.3 Effect of triallyl cyanurate concentration on flexure strength of Po2Gc (Vibrin X-1422) laminates at various exposure and test temperatures, Fig. 3.055.3.

Source	WADC 6602, 1951
Material	Vibrin X-1422/181-114, 2% BZP, 14 pl
Process	PM, 25 psi, 30 min, 185-248F
Test	WADC

TC %	rc %	RT σ_{FU}-ksi	TC %	rc %	RT σ_{FU}-ksi
□ 60	34	45.3	○ 33	36-39	58.1
■ 65	32-33	43	● 43	35-37	54.8
▽ 70	31-32	39.2	△ 50	29-32	46
▼ 75	28-29	32.4	▲ 55	31-32	45.6

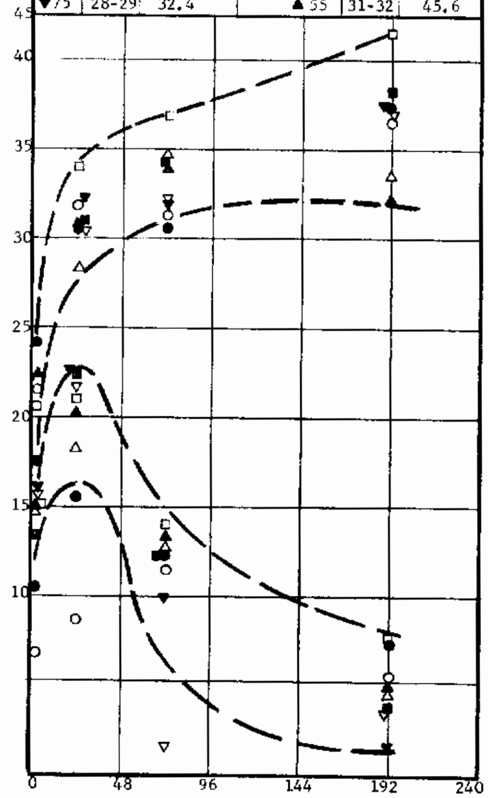

FIG. 3.055.3 EFFECT OF TRIALLYL CYANURATE CONCENTRATION ON FLEXURE STRENGTH OF P02Gc (VIBRIN X-1442) LAMINATES AT VARIOUS EXPOSURE AND TEST TEMPERATURES

Source	WADC 6602, 1951
Material	Vibrin X-1047/181-114, 2% BZP, 14 pl
Process	PM, 25 psi, 30 min, 185-248F
Test	WADC

TC %	rc %	RT σ_{FU}-ksi	TC %	rc %	RT σ_{FU}-ksi
□ 60	31	41.1	○ 50	55	43.8
■ 65	33-35	34.7	● 32	31-33	42.7
▽ 70	30-32	31.5	△ 33	30	50.9
▼ 75	30-31	32.7	▲ 43	35	48.4

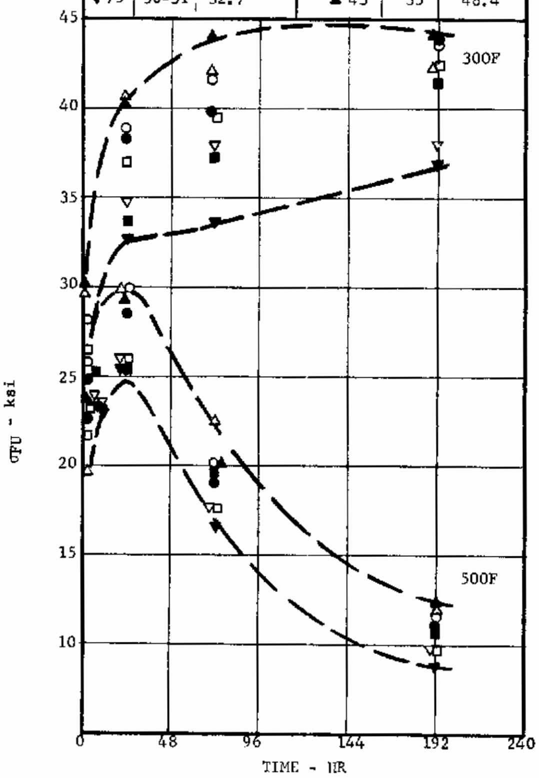

FIG. 3.055.2 EFFECT OF TRIALLYL CYANURATE CONCENTRAION ON FLEXURE STRENGTH OF Po2Gc (VIBRIN X-1047) LAMINATES AT VARIOUS EXPOSURE AND TEST TEMPERATURES

3.055.4 Effect of various glass finishes on flexure strength of Po2Gc laminates at various exposure and test temperatures, Fig. 3.055.4.

3.06 <u>Shear Properties</u>

3.07 <u>Bearing Properties</u>

3.08 <u>Creep and Creep Rupture Properties</u>

3.09 <u>Fatigue Properties</u>

3.10 <u>Elastic Properties</u>

3.101 Modulus of Elasticity in Tension

3.101.1 Effect of exposure and test temperature on modulus of elasticity in tension for typical Po2Gc laminate, Fig. 3.101.1.

3.102 Modulus of Elasticity in Compression

3.103 Modulus of Elasticity in Flexure

3.103.1 See Tables 3.053.3 and 3.053.4.

Source	WADC 6602, 1951
Material	Vibrin X-1047/181-finish indicated, 2% BZP, 14 pl. ● ■ □ 50%, ○ 43% Triallyl cyanurate
Process	PM ● 10 psi, ○ ■ □ 15 psi, 30 min, 176-248F
Test	WADC

finish	rc %	RT σ_{FU}-ksi	
● Bjorksten	30.5	51.95	
○ 114	35	47.4	
■ Garan	38	46.5	
□ Bjorksten	29	42.8	

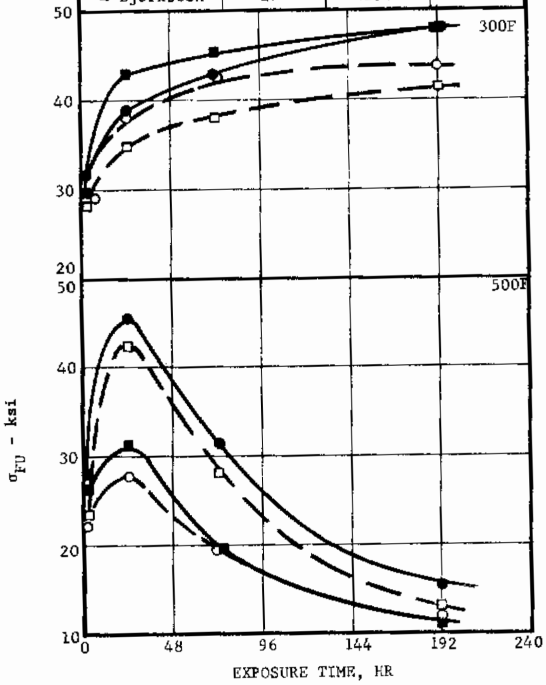

FIG. 3.055.4 EFFECTS OF VARIOUS GLASS FINISHES ON THE FLEXURE STRENGTH OF PO2Gc LAMINATES AT VARIOUS EXPOSURE AND TEST TEMPERATURES

Source	Mil-Hd bk 17, Part 1, 1955
Material	Laminac A232/181-136
Process	
Test	
————	θ = 0
— —	θ = 45

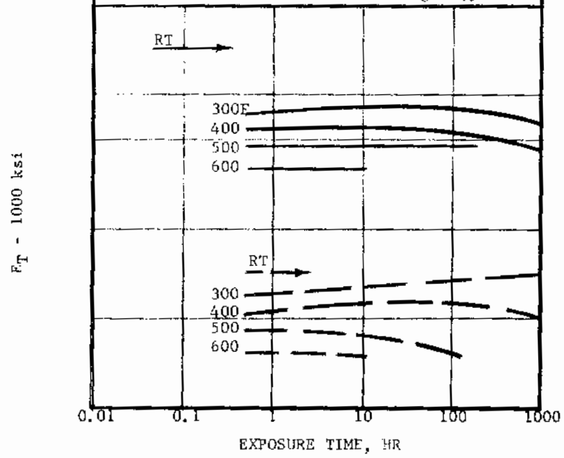

FIG. 3.101.1 EFFECTS OF EXPOSURE AND TEST TEMPERATURE ON MODULUS OF ELASTICITY IN TENSION FOR TYPICAL PO2Gc LAMINATE

0.0 INTRODUCTION

0.01 Purpose of Manual

0.011 The purpose of this Manual is to present various theories as they are particularly applicable to analysis of reinforced plastics as structural materials. Emphasis is placed on those theories which are most commonly accepted and proven by experiment. Each section will develop the theory through to applicable design formulas which are then used in Manual IB, Basic Design, for various structural applications. Charts showing variations in many of the design constants are also presented.

0.012 Included in this first edition of Manual IE are discussions of the more basic analyses of laminated and filament wound materials. In future editions these discussions will be expanded and additional material forms (such as sandwich) will be covered.

0.013 The information included herein has been developed from the results of published work on research programs primarily concerned with analysis and its proof. However, considerable influence of actual design and analysis as practiced within the industry has been allowed where deemed appropriate and worthwhile.

0.014 Where appropriate, alternative approaches to analysis and theory are presented and discussed.

0.015 It is considered unnecessary to detail each step in the development of theoretical expressions. The major steps in derivations are presented, leaving the intermediate mathematical calculations to the reader.

0.02 Identification Code

0.021 For purposes of organization and cross reference the information presented in this Manual is divided into sections as indicated in the table of contents which follows.

0.022 Each section is coded to identify the structural form of the material and the analysis involved. The titles indicated in the table of contents will clarify this procedure.

0.03 Contents of Manual IE

0.031 This Manual is divided into Sections as follows:

Section No.	Subject
1.0	INTRODUCTION
2.0	LAMINATES, Class L I Laminates as Isotropic Materials
3.0	LAMINATES, Class L II Orthotropic Materials in Flat Plates
4.0	LAMINATES, Class L III Buckling of Laminates
5.0	LAMINATES, Class L IV Laminates as Curved Plates
6.0	LAMINATES, Class L V Joining of Laminates
7.0	LAMINATES, Class L VI Openings in Laminates
20.0	FILAMENT WINDING, Class F I Simple Pressure Bottles with and without Integral End Closures
21.0	FILAMENT WINDING, Class F II Bottles with End Ports
22.0	FILAMENT WINDING, Class F III Conventional Structural Applications
23.0	FILAMENT WINDING, Class F IV Contoured Shapes
24.0	FILAMENT WINDING, Class F V Joining of Wound Structures
25.0	FILAMENT WINDING, Class F VI Openings in Wound Structures
30.0	FABRIC WINDING, Class Fb I Shingle Wound Structures
31.0	FABRIC WINDING, Class Fb II Tape Wound Structures
40.0	SANDWICH CONSTRUCTION, Class S I Honeycomb Cores
41.0	SANDWICH CONSTRUCTION, Class S II Foam Cores
42.0	SANDWICH CONSTRUCTION, Class S III Honeycomb plus Foam Cores
43.0	SANDWICH CONSTRUCTION, Class S IV Parallel Cores

0.032 Only the initial sections on Laminates and Filament Winding are included in this first edition. However, the Table of Contents will indicate future expanded coverage.

0.033 Each section of this Manual is sub-divided into major subjects as follows:

Paragraph	Subject
2.0	SECTION TITLE
2.01	Physical Description
2.02	Stress Analysis Discussion
2.03	Fundamental Stress Formulas
2.04	Derivation of Design Formulas
2.05	Helpful Stress Analysis Charts

0.034 It will be noted that for each structural classification one paragraph number will always indicate the same subject. This will facilitate the use of this Manual.

0.035 For complete Table of Contents for the entire Handbook, see Manual IA.

0.04 Abbreviations and Glossary

0.041 A certain procedure for theoretical analysis symbols has been adopted as standard in this Manual. The system involved is adopted from accepted procedures familiar within industry and research.

0.041.1 Standard symbols for analysis are as follows:

A	=	cross sectional area
A	=	constant
E	=	Modulus of elasticity
F	=	Force
G	=	Modulus of rigidity
I	=	Moment of inertia
L	=	Length
m,M	=	Constant
P	=	Axial load
S	=	Failure (ultimate) stress
t	=	Thickness
W_s	=	Energy of distortion
α,β,θ,ϕ	=	Angles
γ	=	Shear strain
δ	=	deformation or deflection
ϵ	=	Direct strain
μ	=	Poisson's Ratio
Σ	=	Sum of or summation
σ	=	Direct stress
τ	=	Shear stress
$\cong$	=	Equivalent

0.041.2 These symbols are modified by subscripts relating the symbol to a set of coordinate axes or other physical considerations. These are clarified in the text where used.

0.041.3 It will be noted that the use of symbols in this Manual differs somewhat from the system adopted in Manual ID. This is due to the necessity of establishing different connotations for stress analysis and for mechanical properties.

0.042 For complete listing of all abbreviations and definitions used throughout the handbook, see Manual IA.

0.05 Information Sources

0.051 Where particularly important, the information source is footnoted directly within the text.

0.052 A general bibliography of pertinent reference works used in compiling this Manual includes the following more important items.

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21. Anonymous, "Bureau of Ships Design Manual for Glass Reinforced Plastics in Naval Applications", (PB 171096), U. S. Department of Commerce, Office of Technical Services (1958).
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0.053 A complete source index is given in Manual IA.

2.0 LAMINATES, CLASS L I

Laminates as isotropic materials

2.01 Physical Description

2.011 Laminates, Class L I, include those laminates composed of resin reinforced with random oriented chopped strands or mats of fiberglass or similar material, which are principally applicable to structural parts.

2.012 Laminates are composed of layers of reinforcing, usually some form of fiber glass, that are impregnated and bonded together with resin. The reinforcement for these Class L I structural laminates takes the form of chopped strands or mats of fiber glass in which the fibers have a random orientation. The bonding of the fibers is accomplished by impregnation with any one of several possible resins, the most common of which are the polyesters, the epoxies, the phenolics, and the polystyrenes. Polystyrene resins are thermoplastic; the others are thermosetting. An almost infinite variety of laminates is possible through the combination of the various reinforcements with various resins. Even further variation can be obtained through the use of combinations of reinforcement in a single laminate.

2.02 Stress Analysis Discussion

2.021 Structural plastic laminates may be divided into three general types:

2.021.1 Those laminates whose strength and other mechanical properties are the same in all directions and, consequently, are said to be isotropic.

2.021.2 Those laminates whose properties vary depending on the orientation of the laminate but are based on the properties in two directions ninety degrees apart, commonly said to be orthotropic*.

2.021.3 Those laminates built up of combinations of either or both of the first two.

2.022 The stress analysis of reinforced laminates is carried out by applying one of two basic approaches to design. The particular approach depends on the mechanical characteristics of the laminate as determined by the type of reinforcement used in its fabrication.

2.023 Since Class L I laminates are reinforced with a mat or chopped strand type of reinforcement, the reinforcing fibers are randomly oriented and they are a material that is essentially isotropic. In other words, the elastic properties are nearly equal in all directions in the plane of the plate. Consequently, in this case, the approach to design and stress analysis is analagous to the engineering approach used with conventional materials. The application of these standard methods to mat reinforced plastics differs from their application to conventional materials only in the values used for the elastic constants. Therefore, it is only necessary to know the strength, modulus of elasticity, shearing modulus, and Poisson's ratio for the combined mat and resin. These values are obtained from the standard tests for these properties which are made on the laminate for which the stress analysis is to be undertaken.

2.024 Theoretical and experimental studies conducted by the Forest Products Laboratory (F.P.L. Report No. 1841) indicate that an isotropic laminate may be created by appropriately combining layers of orthotropic material in a specific orientational relation to each other. The layers must be oriented so that their principal axes are at successive angles determined by the expression:

$$\phi = \pi/n \quad \text{. . . . . Eq. 2.024}$$

where: ϕ = angle between principal axes of two adjacent layers of orthotropic material

n = any integer number greater than 2

The resulting laminate will be isotropic in that its elastic properties are independent of the direction of loading defined by the angle θ.

* During investigations for this work, the term "aeolotropic" was sometimes used synonimously with "orthotropic". Due to definition connotation and accepted usage, orthotropic will be used in this Handbook for the laminate type described. See Glossary of Terms in Manual IA for more complete information on these two terms.

3.0 LAMINATES, CLASS L II

Laminates as orthotropic materials in flat plates.

3.01 Physical Description

3.011 Laminates, Class L II, include those laminates composed of resin reinforced with woven cloth of fiberglass or similar material, which are principally applicable to structural parts.

3.012 Laminates are composed of layers of reinforcing, usually some form of fiber glass, that are impregnated and bonded together with resin. The reinforcement for these Class L II structural laminates takes the form of a woven cloth in which the fibers occur as warp and fill and provide reinforcement in two directions at right angles to each other, or as roving or continuous filaments which provide reinforcement in only one principal direction. The bonding of the fibers is accomplished by impregnation with any one of several possible resins, the most common of which are the polyesters, the epoxies, the phenolics, and the polystyrenes. Polystyrene resins are thermoplastic; the others are thermosetting. An almost infinite variety of laminates is possible through the combination of the various reinforcements with various resins. Even further variation can be obtained through the use of combinations of reinforcement in a single laminate.

3.02 Stress Analysis Discussion

3.021 Structural plastic laminates may be divided into three general types:

3.021.1 Those laminates whose strength and other mechanical properties are the same in all directions and, consequently, are said to be isotropic.

3.021.2 Those laminates whose properties vary depending on the orientation of the laminate but are based on the properties in two directions ninety degrees apart, commonly said to be orthotropic (1).

3.021.3 Those laminates built up of combinations of either or both of the first two.

3.022 The stress analysis of reinforced laminates is carried out by applying one of two basic approaches to design. The particular approach depends on the mechanical characteristics of the laminate as determined by the type of reinforcement used in its fabrication.

3.023 Since Class L II laminates are fabricated using cloth or roving as the reinforcement, the mechanical properties of the resulting combination depend on the direction in which they are measured. These laminates, therefore, are not isotropic; they are orthotropic. Variation of strength and other properties of the material, dependent on the orientation of load to direction of fiber in the reinforcement, results in a significant modification of the conventional design equations, and calls for an approach to design different from the approach used with mat reinforced laminates. Whether the reinforcement consists of cloth woven of yarn fabrics oriented at right angles to each other, rovings with strands parallel to each other, or multi-layers of fabrics or rovings placed parallel or perpendicular to each other, the resultant laminate has two principal directions parallel and perpendicular to the direction of the main reinforcement, and all of these combinations result in an orthotropic material.

3.03 Fundamental Stress Formulas

3.031 The first step in the development of the general stress and strain equations for an orthotropic material is to develop the general equations of stress and strain for the case of plane stress. From consideration of combined stress in strength of materials, the equations of stress transformation are readily obtained.

(1) During investigation for this work the term "aeolotropic was sometimes used synonymously with "orthotropic". Due to definition connotation and accepted usage, orthotropic will be used in this Handbook for the laminate type described. See Glossary of Terms in Manual IA for more complete information on these two terms.

3.031.1 If a unit cube of material (unit thickness) is in equilibrium when subjected to a condition of plane stress composed of the direct tensile stresses, σ_a, σ_b, and shearing stresses, τ_{ab}, as shown in Fig. 3.031.1a, the transformation of stress from coordinate axes a, b to corrdinate axes 1, 2 (making an angle θ with a, b) is accomplished by considering the equilibrium of a wedge, at angle θ, taken from the original element. Fig. 3.031.1b shows the relationship between the axes; Fig. 3.031.1c shows the equilibrium condition of the wedge. The positive directions of the stresses are assumed as shown in Fig. 3.031.1.

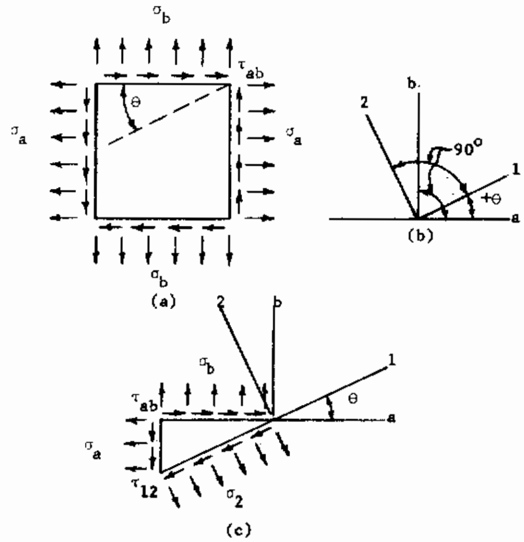


FIG. 3.031.1 ILLUSTRATIONS FOR DERIVATION OF BASIC STRESS TRANSFORMATION EXPRESSIONS

3.031.2 In Fig. 3.031.1c, application of the equations of equilibrium $\Sigma F1 = 0$ and $\Sigma F2 = 0$ results in the transformation equations Eq. 3.031.2.

$$\sigma_1 = \sigma_a \cos^2\theta + \sigma_b \sin^2\theta + \tau_{ab} \sin 2\theta \quad \text{Eq 3.031.2a}$$

$$\sigma_2 = \sigma_a \sin^2\theta + \sigma_b \cos^2\theta - \tau_{ab} \sin 2\theta \quad \text{Eq 3.031.2b}$$

$$\tau_{12} = \frac{1}{2}(\sigma_2 - \sigma_a) \sin^2\theta + \tau_{ab} \cos 2\theta \quad \text{Eq 3.031.2c}$$

3.031.3 To transfer strains between the same two axes, the values of σ_1, σ_2 and τ_{12} from Eq 3.031.2 are substituted in:

$$\epsilon_1 = \frac{\sigma_1}{E} - \frac{\mu\sigma_2}{E}; \quad \epsilon_2 = \frac{\sigma_2}{E} - \frac{\mu\sigma_1}{E}; \quad \text{and } \gamma_{12} = \frac{\tau_{12}}{G}$$

Collection of terms and substitution of

$$\epsilon_a = \sigma_a/E - \mu_{ab}/E; \quad \gamma_{\alpha\beta} = \tau_{ab}/G; \quad \text{and } G = \frac{E}{2(1+\mu)}$$

Results in Eq 3.031.3.

$$\epsilon_1 = \epsilon_a \cos^2\theta + \epsilon_b \sin^2\theta + \gamma_{ab} \sin\theta \cos\theta \quad \text{Eq 3.031.3a}$$

$$\epsilon_2 = \epsilon_a \sin^2\theta + \epsilon_b \cos^2\theta - \gamma_{ab} \cos^2\theta \quad \text{Eq 3.031.3b}$$

$$\gamma_{12} = (\epsilon_b - \epsilon_a) \sin 2\theta + \gamma_{ab} \cos 2\theta \quad \text{Eq 3.031.3c}$$

3.04 Derivation of Design Formulas

3.041 The equations, Eq 3.031.2 and 3.031.3, may now be used to develop the relations necessary to understand and to design laminates as orthotropic materials. This section considers laminates consisting of one type of reinforcing only "parallel" laminated, i.e., the warp or principal axis of the reinforcing is laid parallel in each layer.

3.041.1 For this type of material, a different system of coordinate axes is taken to avoid confusion with the system used to develop the equations for the transformation of stress and strain. Fig. 3.041.1 shows these axes and in it α, β are the axes taken along the "natural" axes of the laminate, parallel and perpendicular to the warp of the fabric, for which the mechanical properties of the laminate are known. Any other mutally perpendicular axes for which the mechanical properties are required are designated as x, y. Axes x, y make an angle ϕ with axes α, β respectively.

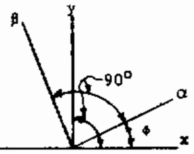


FIG. 3.041.1 AXES OF LAMINATE, α AND β, AND OF APPLIED STRESS, x AND y

3.041.2 The first step in the development of the necessary equations is to relate the physical constants, μ and E, for the natural axes. Use is made of Maxwell's Law of reciprocal deformations which states that the deformation in the β-direction caused by a unit load in the α-direction is equal to the deformation in the α-direction caused by a unit load in the β-direction. In Fig. 3.041.2a:

$\delta_{\beta\alpha}$ = Deformation in β-direction caused by unit load in α-direction, and

$\mu_{\alpha\beta}$ = Poisson's Ratio for strain in β-direction caused by stress in the α-direction.

From Fig. 3.041.2a,

$$\epsilon_\beta = \frac{\delta_{\beta\alpha}}{L_{de}} = -\mu_{\alpha\beta}\frac{\sigma_\alpha}{E_\alpha}$$

and similarly from Fig. 3.041.2b,

$$\epsilon_\alpha = \frac{\delta_{\alpha\beta}}{L_{cd}} = -\mu_{\beta\alpha}\frac{\sigma_\beta}{E_\beta}$$

From Maxwell's Law, $\delta_{\alpha\beta} = \delta_{\beta\alpha}$

$$-\mu_{\beta\alpha}\frac{\sigma_\beta}{E_\beta}L_{cd} = -\mu_{\alpha\beta}\frac{\sigma_\alpha}{E_\alpha}L_{de}$$

which results in Eq 3.041.2.

$$\mu_{\beta\alpha}E_\alpha = \mu_{\alpha\beta}E_\beta \quad \ldots\ldots\ldots\ldots \text{Eq } 3.041.2$$

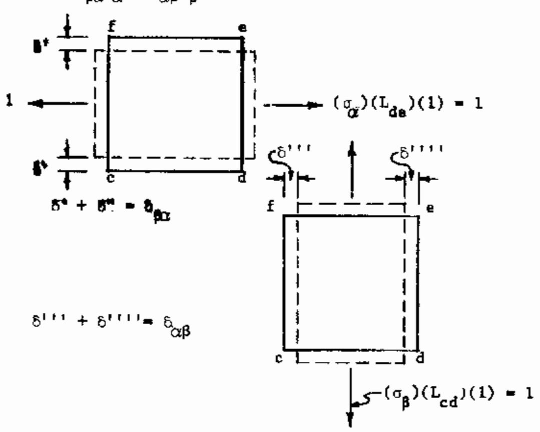


FIG. 3.041.2 DEFORMATIONS ALONG NATURAL AXES

3.041.3 To find the relationships between the physical constants in the α, β directions and those in the x, y directions, apply a stress, σ_x, in the x-direction only. The expression for the Modulus of Elasticity for the x-axis, E_x, may be found by using the transformation equations and other relationships previously developed in section 3.03. Using the stress transformation equations first, and realizing that the a-axis ≡ x-axis, 1-axis ≡ α-axis, and $\theta \equiv \phi$, the result is:

$$\sigma_\alpha = \sigma_x \cos^2\phi,\ \sigma_\beta = \sigma_x \sin^2\phi,\ \tau_{\alpha\beta} = \sigma_x \sin\phi\cos\phi$$

The strain in the x-direction, ϵ_x, may be obtained from the strain transformation equations, but it must be noted that in this case the a-axis ≡ α-axis, 1-axis ≡ x-axis and $\theta \equiv -\phi$:

$$\epsilon_x = \epsilon_\alpha \cos^2\phi + \epsilon_\beta \sin^2\phi - \gamma_{\alpha\beta}\sin\phi\cos\phi$$

In terms of stress,

$$\epsilon_\alpha = \frac{\sigma_\alpha}{E_\alpha} - \mu_{\beta\alpha}\frac{\sigma_\beta}{E_\beta} = \frac{\sigma_\alpha}{E_\alpha} - \mu_{\alpha\beta}\frac{\sigma_\beta}{E_\alpha}$$

$$\epsilon_\beta = \frac{\sigma_\beta}{E_\beta} - \mu_{\alpha\beta}\frac{\sigma_\alpha}{E_\alpha}$$

$$\gamma_{\alpha\beta} = \frac{\tau_{\alpha\beta}}{G_{\alpha\beta}}$$

Substitution of these values of the strains in the equation for ϵ_x gives:

$$\epsilon_x = \sigma_x\ \frac{\cos^4\phi}{E_\alpha} + \frac{\sin^4\phi}{E_\beta} + \left(\frac{1}{G_{\alpha\beta}} - \frac{2\mu_{\alpha\beta}}{E_\alpha}\right)\sin^2\phi\cos^2\phi$$

which may be written as Eq 3.041.3a.

$$\frac{\epsilon_x}{\sigma_x} = \frac{1}{E_x} = \left[\frac{\cos^4\phi}{E_\alpha} + \frac{\sin^4\phi}{E_\beta} + \left(\frac{1}{G_{\alpha\beta}} - \frac{2\mu_{\alpha\beta}}{E_\alpha}\right)\sin^2\phi\cos^2\phi\right] \quad \ldots\ldots \text{Eq } 3.041.3a$$

Performing similar substitutions and simplifications on the equation for ϵ_y results in Eq 3.041.3b.

$$\frac{1}{E_y} = \frac{\cos^4\phi}{E_\beta} + \frac{\sin^4\phi}{E_\alpha} + \left(\frac{1}{G_{\alpha\beta}} - \frac{2\mu_{\alpha\beta}}{E_\alpha}\right)\sin^2\phi\cos^2\phi \quad \ldots\ldots \text{Eq } 3.041.3b$$

3.041.4 The value of Poisson's Ratio (μ_{xy}) for strain in the y-direction when σ_x is applied in the x-direction is:

$$\mu_{xy} = -\frac{\epsilon_y}{\epsilon_x} = -\frac{\epsilon_y}{\sigma_x}(E_x)$$

The strain in the y-direction, ϵ_y, is obtained from the strain transformation equations as before.

$$\epsilon_y = \epsilon_a \sin^2\phi + \epsilon_\beta \cos^2\phi + \gamma_{\alpha\beta}\sin\phi\cos\phi$$

Substitution for the strains in terms of stress, and replacing ϵ_y in the expression for μ_{xy}, results in Eq 3.041.4:

$$\mu_{xy} = \frac{E_x}{E_\alpha}\left[\mu_{\alpha\beta} - \frac{1}{4}\left(1 + 2\mu_{\alpha\beta} + \frac{E_\alpha}{E_\beta} - \frac{E_\alpha}{G_{\alpha\beta}}\right)\sin^2 2\phi\right] \quad \ldots\ldots \text{Eq } 3.041.4$$

3.041.5 The shear strain on the x, y planes, γ_{xy}, caused by σ_x may also be expressed in terms of the physical constants of the laminate for the α, β planes. Again noting that $\theta = -\phi$, the shear strain on the x, y plane may be expressed from Eq 3.031.3c as:

$$\gamma_{xy} = -2(\epsilon_\beta - \epsilon_\alpha)\sin\phi\cos\phi + \gamma_{\alpha\beta}(\cos^2\phi - \sin^2\phi)$$

Into this expression values of ϵ_α, ϵ_β, and $\gamma_{\alpha\beta}$ used in previous developments are substituted and after simplification the result is Eq 3.041.5a:

$$\gamma_{xy} = \frac{-\sigma_x}{E_\alpha}\sin 2\phi\left[\left(\mu_{\alpha\beta} + \frac{E_\alpha}{E_\beta} - \frac{E_\alpha}{2G_{\alpha\beta}} - \cos^2\phi\left(1 - \frac{E_\alpha}{E_\beta} + 2\mu_{\alpha\beta}\right)\right]\right. \quad \ldots\ldots \text{Eq } 3.041.5a$$

The expression for γ_{xy} may be expressed in simpler form as:

$$\gamma_{xy} = -m_x\frac{\sigma_x}{E_\alpha} \quad \ldots\ldots\ldots\ldots \text{Eq } 3.041.5b$$

Where the known constants of the material appear in m_x:

$$m_x = \sin 2\phi \left[(\mu_{\alpha\beta} + \frac{E_\alpha}{E_\beta} - \frac{E_\alpha}{2G_{\alpha\beta}} - \cos^2\phi \ (1 + 2\mu_{\alpha\beta} + \frac{E_\alpha}{E_\beta} - \frac{E_\alpha}{G_{\alpha\beta}}) \right] . \ . \text{Eq } 3.041.5c$$

3.041.6 Eq 3.041.5b may be used to compute the shearing strain on the x, y axes when a direct stress is applied along the x-axis, and the physical constants for the natural axes are known. Note that a shearing strain exists for orthotropic materials in this case, but that it would have been zero if the material had been isotropic.

3.041.7 With Eq 3.041.3 and 3.041.4 and the physical constants for the natural axes of the orthotropic material, the physical constants for any other set of axes in the plane of the laminate may be determined. Agreement between mathematical analysis and experimentally determined values for these constants is within reasonable limits for the initial, unloading, and reloading phases of the loading cycle with the best agreement occuring in the initial phase of loading. Agreement is relatively poor for the secondary phase (2).

3.041.8 In order to derive an expression that may be used to relate the Modulus of Rigidity about any axes, x, y, to that about the natural axes, α, β, a shearing stress, τ_{xy}, is applied to an element of the orthotropic material in the x, -y plane. Then:

$$\tau_{xy} = \frac{\gamma_{xy}}{G_{xy}}$$

and from the strain transformation Eq 3.031.3, again with $\theta = -\phi$:

$$\gamma_{xy} = -(\epsilon_\beta - \epsilon_\alpha) \sin 2\phi + \gamma_{\alpha\beta} \cos 2\phi$$

Transformation of this equation to the form in which γ_{xy} is expressed in terms of E_α, E_β and $G_{\alpha\beta}$ is accomplished by use of the stress transformation Eq 3.031.2. The substitution for ϵ_β is as follows:

$$\epsilon_\beta = \frac{\sigma_\beta}{E_\beta} - \mu_{\alpha\beta} \frac{\sigma_\alpha}{E_\alpha} = \tau_{xy} \frac{\sin 2\phi}{E_\beta} - \mu_{\alpha\beta} \frac{\tau_{xy} \sin 2\phi}{E_\alpha}$$

ϵ_α and $\gamma_{\alpha\beta}$ are treated in a similar fashion with the result that

$$\frac{\gamma_{xy}}{\tau_{xy}} = \frac{1}{G_{xy}} = (\frac{1}{E_\beta} + \frac{\mu_{\alpha\beta}}{E_\alpha} + \frac{1}{E_\alpha} + \frac{\mu_{\alpha\beta}}{E_\alpha}) (1 - \cos^2 2\phi) + \frac{\cos^2 2\phi}{G_{\alpha\beta}} \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ \text{Eq } 3.041.8a$$

$$\frac{G_{\alpha\beta}}{G_{xy}} = \frac{G_{\alpha\beta}}{E_\alpha} \left[\frac{E_\alpha}{E_\beta} + 2\mu_{\alpha\beta} + 1 - (1 + 2\mu_{\alpha\beta} + \frac{E_\alpha}{E_\beta} - \frac{E_\alpha}{G_{\alpha\beta}}) \cos^2 2\phi \right] . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ \text{Eq } 3.041.8b$$

An alternate form of this equation may be used:

$$\frac{G_{\alpha\beta}}{G_{xy}} = (\frac{G_{\alpha\beta}}{E_\beta} + \frac{2\mu_{\alpha\beta} G_{\alpha\beta}}{E_\alpha} + \frac{G_{\alpha\beta}}{E_\alpha}) \sin^2 2\phi + \cos^2 2\phi \ . \ . \ . \ . \ . \ . \ . \ \text{Eq } 3.041.8c$$

3.041.9 Because of the difficulty of determining $G_{\alpha\beta}$ experimentally, it has been found to be more satisfactory to determine $G_{\alpha\beta}$ by computation. Experimental values for E_α, E_β, $\mu_{\alpha\beta}$, and E_{45} are determined. Then using Eq 3.041.3a with $E_{xy} = E_{45}$ and $\phi = 45$:

$$\frac{1}{E_{45}} = \frac{1}{4E_\alpha} + \frac{1}{4E_\beta} + (\frac{1}{G_{\alpha\beta}} - \frac{2\mu_{\alpha\beta}}{E_\alpha}) \frac{1}{4}$$

or simplified:

$$\frac{E_\alpha}{G_{\alpha\beta}} = \frac{4E_\alpha}{E_{45}} - \frac{E_\alpha}{E_\beta} + 2\mu_{\alpha\beta} - 1 \ . \ . \ . \ . \ . \ . \ \text{Eq } 3.041.9a$$

If both $\mu_{\alpha\beta}$ and $\mu_{\beta\alpha}$ are determined experimentally, the relationship given in Eq 3.041.2 may be used resulting in:

$$\frac{E_\alpha}{G_{\alpha\beta}} = \frac{4E_\alpha}{E_{45}} - \frac{E_\alpha}{E_\beta} (1 - \mu_{\beta\alpha}) - (1 - \mu_{\alpha\beta}) . . \text{Eq } 3.041.9b$$

Furthermore, when the element is subjected to the condition of pure shear ($\sigma_\alpha = +1$ and $\sigma_\beta = -1$, at $\phi = 45$, $\tau_{45} = 1$), Eq 3.041.8a results in:

$$\gamma_{45} = (\frac{1}{E_\beta} + \frac{\mu_{\alpha\beta}}{E_\alpha} + \frac{1}{E_\alpha} + \frac{\mu_{\alpha\beta}}{E_\alpha}) = \frac{1}{E_\alpha} + \frac{1}{E_\beta} + \frac{2\mu_{\alpha\beta}}{E_\alpha}$$

$$G_{45} = \frac{\tau_{45}}{\gamma_{45}} = \frac{E_\alpha E_\beta}{E_\alpha + E_\beta + 2E_\beta \mu_{\alpha\beta}} \ . \ . \ . \ . \ . \ \text{Eq } 3.041.9c$$

3.041.10 When an isotropic material is considered, $E_\alpha = E_\beta = E$, $\mu_{\alpha\beta} = \mu$ and Eq 3.041.9c simplifies to:

$$G = \frac{E}{2(1 + \mu)}$$

which is the familiar relationship between Modulus of Elasticity and Modulus of Rigidity for isotropic materials.

3.041.11 Additional relationships between strain and the shearing stress, τ_{xy}, may be deduced. Maxwell's Law is again applied and the shearing strain, γ_{xy}, caused by the direct stress, σ_x, must be equal to the direct strain, ϵ_x, caused by the shearing stress, τ_{xy}. The result of the application of Maxwell's Law is:

$$\epsilon_y = -m_y \frac{\tau_{xy}}{E_\alpha} \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ \text{Eq } 3.041.11a$$

where m_x is identical in value to that of Eq 3.041.5b. Similarly,

$$\epsilon_y = -m_y \frac{\tau_{xy}}{E_\alpha} \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ \text{Eq } 3.041.11b$$

m_y may be derived from

$$\epsilon_y = \epsilon_\alpha \sin^2\phi + \epsilon_\beta \cos^2\phi + \gamma_{\alpha\beta} \sin\phi\cos\phi$$

by substituting, again, the values for ϵ_α, ϵ_β, $\gamma_{\alpha\beta}$ in terms of stress and τ_{xy}. After simplification:

$$\epsilon_y = - \frac{\tau_{xy}}{E_\alpha} (\sin 2\phi) \left[(\mu_{\alpha\beta} + \frac{E_\alpha}{E_\beta} - \frac{E_\alpha}{2G_{\alpha\beta}}) - \sin^2\phi \ (1 + 2\mu_{\alpha\beta} + \frac{E_\alpha}{E_\beta} - \frac{E_\alpha}{G_{\alpha\beta}}) \right]$$

and

$$m_y = \sin 2\phi \left[\mu_{\alpha\beta} + \frac{E_\alpha}{E_\beta} - \frac{E_\alpha}{2G_{\alpha\beta}} - \sin^2\phi \ (1 + 2\mu_{\alpha\beta} + \frac{E_\alpha}{E_\beta} - \frac{E_\alpha}{G_{\alpha\beta}}) \right] . \ . \ . \ . \ . \ . \ . \ . \ . \ . \text{Eq } 3.041.11c$$

(2) Based on tests of tensile properties reported in Forest Products Laboratory Report No. 1853.

3.042 When layers of two different reinforcements or reinforcement orientation are laminated to form a composite, a better product is produced if the final laminate is fabricated of several interleaved plies of each, in the fashion of plywood, instead of bonding together only the two layers. That is to say, it is better to make a composite laminate of materials A and B by sandwiching two layers of B between three layers of A, for example, than to take one layer of A and bond it to one layer of B. The interleaving of the plies produces a better laminate because the effects of warping caused by temperature, moisture, stress, etc. are minimized in this type of construction. With this plied configuration of the laminate, however, a stress applied to it along one axis will result in shear stresses and direct stresses along the axis at right angles because the physical constants for the different plies are different and because the bonding of the layers restrains each layer to the same deformation as every other layer.

3.042.1 To analyze a composite laminate for the stresses caused by the application of a direct stress, σ_x, applied parallel to the x-axis with σ_x taken as the average stress applied to the total thickness of the laminate, the procedure is as follows. In Fig. 3.042.1, the following notation is used:

- t_n = thickness of Laminate n
- σ_{xn} = direct stress in Laminate n parallel to x-axis
- σ_{yp} = direct stress in Laminate p parallel to y-axis
- ϵ_{xn} = direct strain in Laminate n parallel to x-axis
- $E_{\alpha n}$ = Modulus of Elasticity of Laminate n in the direction of the natural axis

The other notations used follow directly from this system.

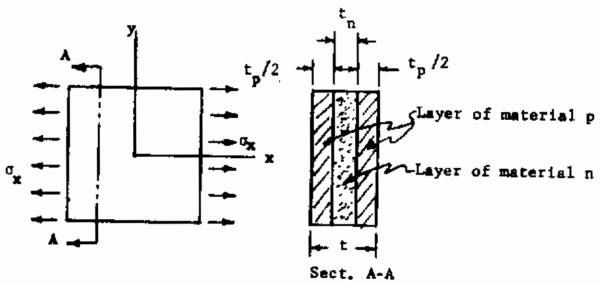


FIG. 3.042.1 NOTATIONS FOR A COMPOSITE LAMINATE

3.042.2 The direct strains, ϵ_{xn}, ϵ_{yn} and the shear strain, γ_{xyn}, occurring in layer n will result from the direct stresses, σ_{xn}, σ_{yn}, and from the shear stress, τ_{xyn}, through the relationships derived in the previous sections and for shear, in particular, from Eq 3.041.11a and c:

$$\epsilon_{xn} = \frac{\sigma_{xn}}{E_{xn}} - \mu_{xyn}\frac{\sigma_{yn}}{E_{yn}} - m_{xn}\frac{\tau_{xyn}}{E_{\alpha n}} \quad \text{. . . Eq 3.042.2a}$$

$$\epsilon_{yn} = -\mu_{xyn}\frac{\sigma_{xn}}{E_{xn}} + \frac{\sigma_{yn}}{E_{yn}} - m_{yn}\frac{\tau_{xyn}}{E_{\alpha n}} \quad \text{. . Eq 3.042.2b}$$

$$\gamma_{xyn} = -m_{xn}\frac{\sigma_{xn}}{E_{\alpha n}} - m_{yn}\frac{\sigma_{yn}}{E_{\alpha n}} + \frac{\tau_{xyn}}{G_{xyn}} \quad \text{. . Eq 3.042.2c}$$

Similarly, the strains in layer p are:

$$\epsilon_{xp} = \frac{\sigma_{xp}}{E_{xp}} - \mu_{xyp}\frac{\sigma_{yp}}{E_{yp}} - m_{xp}\frac{\tau_{xyp}}{E_{\alpha p}} \quad \text{. . . Eq 3.042.2d}$$

$$\epsilon_{yp} = -\mu_{xyp}\frac{\sigma_{xp}}{E_{xp}} + \frac{\sigma_{yp}}{E_{yp}} - m_{yp}\frac{\tau_{xyp}}{E_{\alpha p}} \quad \text{. . . Eq 3.042.2e}$$

$$\gamma_{xyp} = -m_{xp}\frac{\sigma_{xp}}{E_{\alpha p}} - m_{yp}\frac{\sigma_{yp}}{E_{\alpha p}} + \frac{\tau_{xyp}}{G_{xyp}} \quad \text{. . . Eq 3.042.2f}$$

3.042.3 The strain in each direction for each laminate must be equal to the strain in each direction for the composite because of the construction, or

$$\epsilon_{xn} = \epsilon_{xp} = \epsilon_x \quad \text{. . . . . Eq 3.042.3a}$$

$$\epsilon_{yn} = \epsilon_{yp} = \epsilon_y \quad \text{. . . . . Eq 3.042.3b}$$

$$\gamma_{xyn} = \gamma_{xyp} = \gamma_{xy} \quad \text{. . . . . Eq 3.042.3c}$$

Also, the summation of stress in each laminate in each direction must equal the summation of the supplied stress in that direction for the composite. This condition results in the following equations:

$$\sigma_{xn}t_n + \sigma_{xp}t_p = \sigma_x t \quad \text{. . . . . Eq 3.042.3d}$$

$$\sigma_{yn}t_n + \sigma_{yp}t_p = 0 \quad \text{. . . . . Eq 3.042.3e}$$

$$\tau_{xyn}t_n + \tau_{xyp}t_p = 0 \quad \text{. . . . . Eq 3.042.3f}$$

3.042.4 Utilizing the relations between Modulus of Elasticity and Poisson's Ratio (Eq 3.041.2), Eqs 3.042.2a and d become:

$$\epsilon_{xn} = \epsilon_x = \frac{\sigma_{xn}}{E_{xn}} - \mu_{xyn}\frac{\sigma_{yn}}{E_{xn}} - m_{xn}\frac{\tau_{xyn}}{E_{\alpha n}}$$

$$\epsilon_{xp} = \epsilon_x = \frac{\sigma_{xp}}{E_{xp}} - \mu_{xyn}\frac{\sigma_{yp}}{E_{xp}} - m_{xp}\frac{\tau_{xyp}}{E_{\alpha p}}$$

Eliminating ϵ_x from these two equations, then substituting for all stresses involving layer p by using Eq 3.042.3d through f and collecting terms, yields the equation:

$$+\left(\frac{\sigma_x}{E_{xp}}\right)\left(\frac{t}{t_n t_p}\right) = \sigma_{xn}\left(\frac{1}{E_{xn}t_n} + \frac{1}{E_{xp}t_p}\right) + \sigma_{yn}\left(-\frac{\mu_{xyn}}{E_{xn}t_n} - \frac{\mu_{xyp}}{E_{xp}t_p}\right) + \tau_{xyn}\left(-\frac{m_{xn}}{E_{\alpha n}t_n} - \frac{m_{xp}}{E_{\alpha p}t_p}\right)$$

$$= \sigma_{xn}\cdot A_{11} + \sigma_{yn}\cdot A_{12} + \tau_{xyn}\cdot A_{13} \quad \text{. . . . . Eq 3.042.4a}$$

where A_{11}, A_{12}, and A_{13} are equal respectively to the coefficients of σ_{xn}, σ_{yn}, and τ_{xyn}.
By performing the same manipulations on the expressions for ϵ_{yn} and ϵ_{yp} the resulting equation is:

$$-(\sigma_x)\left(\frac{\mu_{xyp}}{E_{xp}}\right)\left(\frac{t}{t_n t_p}\right) = \sigma_{xn}\left(-\frac{\mu_{xyn}}{E_{xn}t_n} - \frac{\mu_{xyp}}{E_{xp}t_p}\right) + \sigma_{yn}\left(\frac{1}{E_{yn}t_n} + \frac{1}{E_{yp}t_p}\right) + \tau_{xyn}\left(-\frac{m_{yn}}{E_{\alpha n}t_n} - \frac{m_{yp}}{E_{\alpha p}t_p}\right)$$

$$= \sigma_{xn}\cdot A_{21} + \sigma_{yn}\cdot A_{22} + \tau_{xyn}\cdot A_{23} \quad \text{. . . . . Eq 3.042.4b}$$

Note that the coefficient $A_{21} = A_{12}$.
Finally, for the shearing strains, γ_{xyn} and γ_{xyp}:

$$-(\sigma_x)\left(\frac{m_{xp}}{E_{\alpha p}}\right)\left(\frac{t}{t_n t_p}\right) = \sigma_{xn}\left(-\frac{m_{xn}}{E_{\alpha n}t_n} - \frac{m_{xp}}{E_{\alpha p}t_p}\right) + \sigma_{yn}\left(-\frac{m_{yn}}{E_{\alpha n}t_n} - \frac{m_{yp}}{E_{\alpha p}t_p}\right) + \tau_{xyn}\left(\frac{1}{G_{xyn}t_n} + \frac{1}{G_{xyp}t_p}\right)$$

or, as before,

$$= \sigma_{xn}\cdot A_{31} + \sigma_{yn}\cdot A_{32} + \tau_{xyn}\cdot A_{33} \quad \text{. . . . . Eq 3.042.4c}$$

And again note that $A_{31} = A_{13}$; $A_{32} = A_{23}$.

3.042.5 If the laminate of Fig. 3.042.1 is subjected to an external shear stress, τ_{xy}, uniformly distributed along its edges, Eqs 3.042.2 and 3.042.3 remain the same and the equations of stress equilibrium in each lamina become:

$$\sigma_{xn}t_n + \sigma_{xp}t_p = 0 \quad \text{Eq 3.042.5a}$$

$$\sigma_{tn}t_n + \sigma_{yp}t_p = 0 \quad \text{Eq 3.042.5b}$$

$$\tau_{xyn}t_n + \tau_{xyp}t_p = \tau_{xy}t \quad \text{Eq 3.042.5c}$$

3.042.6 The coefficients A_{11}, A_{12}, A_{13} etc. in Eq 3.042.4 remain the same, but the other side of each of the three equations is changed. The substitutions and manipulations that must be performed to arrive at the final set of equations are exactly similar to those performed to obtain Eq 3.042.4 in their final form. The results are:

$$A_{11}\sigma_{xn} + A_{12}\sigma_{yn} + A_{13}\tau_{xyn} = \tau_{xy}\left(\frac{m_{xp}}{E_{\alpha p}}\right)\left(\frac{t}{t_n t_p}\right) \quad \text{Eq 3.042.6a}$$

$$A_{21}\sigma_{xn} + A_{22}\sigma_{yn} + A_{23}\tau_{xyn} = -\tau_{xy}\left(\frac{m_{yp}}{E_{\alpha p}}\right)\left(\frac{t}{t_n t_p}\right) \quad \text{Eq 3.042.6b}$$

$$A_{31}\sigma_{xn} + A_{32}\sigma_{yn} + A_{33}\tau_{xyn} = +\tau_{xy}\left(\frac{1}{G_{xyp}}\right)\left(\frac{t}{t_n t_p}\right) \quad \text{Eq 3.042.6c}$$

As before, $A_{12} = A_{21}$, $A_{13} = A_{31}$, and $A_{23} = A_{32}$.

3.042.7 The results obtained for σ_x acting alone and τ_{xy} acting alone may be used to obtain the equations for the general state of stress, i.e. when σ_x, σ_y, and τ_{xy} are applied simultaneously. The results of this superposition are:

$$A_{11}\sigma_{xn} + A_{12}\sigma_{yn} + A_{13}\tau_{xyn} = \frac{t}{t_n t_p}\left(\frac{\sigma_x}{E_{xp}} - \frac{\mu_{xyp}}{E_{xp}}\sigma_y - \frac{m_{yp}}{E_{\alpha p}}\tau_{xy}\right) \quad \text{Eq 3.042.7a}$$

$$A_{21}\sigma_{xn} + A_{22}\sigma_{yn} + A_{23}\tau_{xyn} = \frac{t}{t_n t_p}\left(-\frac{\mu_{xyp}}{E_{xp}}\sigma_x + \frac{\sigma_y}{E_{yp}} - \frac{m_{yp}}{E_{\alpha p}}\tau_{xy}\right) \quad \text{Eq 3.042.7b}$$

$$A_{31}\sigma_{xn} + A_{32}\sigma_{yn} + A_{33}\tau_{xyn} = \frac{t}{t_n t_p}\left(-\frac{m_{xp}}{E_{xp}}\sigma_x - \frac{m_{yp}}{E_{\alpha p}}\sigma_y + \frac{\tau_{xy}}{G_{xyp}}\right) \quad \text{Eq 3.042.7c}$$

3.042.8 These equations when solved simultaneously will give the stress condition for layer n. To find the stress situation for layer p, these values may be substituted in the equilibrium equations for the general state of stress, Eq 3.042.8.

$$\sigma_{xn}t_n + \sigma_{xp}t_p = \sigma_x t \quad \text{Eq 3.042.8a}$$

$$\sigma_{yn}t_n + \sigma_{yp}t_p = \sigma_y t \quad \text{Eq 3.042.8b}$$

$$\tau_{xyn}t_n + \tau_{xyp}t_p = \tau_{xy}t \quad \text{Eq 3.042.8c}$$

The above series of equations may have to be applied to elements taken from the laminate at several differing orientations. The state of stress, σ_x, σ_y and τ_{xy}, for the element at each orientation must be computed using Mohr's Circle or the stress equations, Eq 3.031.2 before application of Eq 3.042.7.

3.042.9 In certain stress situations, Eq 3.042.7 may be simplified considerably if the properties of the laminate exhibit some symmetry. For instance, if a balanced orthotropic material, with the physical constants the same about the α - β axes, is laminated with the α - β axes in each layer parallel to the same axes in the other layer, many of the constants equal zero and others equal each other. For instance:

$$E_{xn} = E_{xp} = E_{yn} = E_{yp}$$

$$\mu_{xyn} = \mu_{yxn} = \mu_{xyp} = \mu_{yxp}$$

$$m_{xn} = m_{xp} = m_{yn} = m_{yp} = 0$$

$$A_{13} = A_{31} = A_{32} = A_{23} = 0$$

$$A_{11} = A_{22}$$

In such a case Eq 3.042.7 reduces to

$$A_{11}\sigma_{xn} + A_{12}\sigma_{yn} = \frac{t}{t_n t_p}\left(\frac{\sigma_x}{E_{xp}} - \frac{\mu_{xyp}}{E_{xp}}\sigma_y\right) \quad \text{Eq 3.042.9a}$$

$$A_{12}\sigma_{xn} + A_{11}\sigma_{yn} = \frac{t}{t_n t_p}\left(-\frac{\mu_{xyp}}{E_{xp}}\sigma_x + \frac{\sigma_y}{E_{yp}}\right) \quad \text{Eq 3.042.9b}$$

$$A_{33}\tau_{xyn} = \frac{t}{t_n t_p}\left(\frac{\tau_{xy}}{G_{xyp}}\right) \quad \text{Eq 3.042.9c}$$

Similar simplifications in the equations occur for other arrangements of the lamina, or for other conditions of symmetry.

3.043 Failure of orthotropic laminated materials under combined stress and the theories developed to predict failure have received extensive study at the Forest Products Laboratory. Although these are based on the energy of distortion theory developed for isotropic materials, agreement between failure strengths determined by test and by analysis is good.

3.043.1 For symmetrically laminated materials, the theory may be applied directly when the stress conditions referred to the natural axes of the laminate are known. Care should be taken to determine interlaminar shear for this case, however, by use of Eq 3.042.7 or their modifications, since failure may occur from this type of stress which would not be considered otherwise in the failure theory. For unsymmetrically laminated cases, since the state of stress of the individual lamina may be markedly different from the state of stress of the laminate as a whole, the preferred procedure is to use Eq 3.042.7 and check each lamina for failure under its own stress condition as determined by these equations.

3.043.2 The energy of distortion theory states that failure in an isotropic material will occur when the energy of distortion involved in the state of stress under consideration reaches a maximum value that is independent of the state of stress. Expressed in symbolic form, an isotropic material subjected to a three dimensional state of stress will have for its energy of distortion:

$$W_s = \frac{1}{12G}\left[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + \frac{1}{2G}(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2)\right]$$

In the above, σ and τ represent direct and shearing stresses referred to the various axes. For failure to occur this value of W_s must not exceed a maximum value; this maximum value is commonly taken as that resulting from a simple tensile test to failure since the maximum is assumed to be independent of the stress condition. Therefore, if the failure stress in the tension test is S_x, $W_s = S_x^2/6G$ for this case, and the energy of distortion theory of failure becomes:

$$S_x^{\ 2} = \frac{1}{2}\Big[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 3(\tau_{xy}^{\ 2} + \tau_{yz}^{\ 2} + \tau_{xz}^{\ 2})\Big]$$

3.043.3 For orthotropic materials, the equations have to be modified because of the different directional proportions these materials exhibit. The assumed modification of structure proposed by Forest Products Laboratory considers the orthotropic material to be approximated by an isotropic material containing equal prismatic voids. Or, rephrased, the approximation assumes equal prismatic voids enclosed by walls of isotropic material. Through this fiction, the theory of failure may be applied to the isotropic part while the material as a whole is orthotropic. The state of stress in the walls of isotropic material is annalyzed in each of three directions to determine the energy of distortion since each of these walls is subjected to a two-dimensional stress system. (The wall surfaces are free of stress.) Neglecting the effect of bending in the walls, the internal distortion energy for each set of walls around a void would be:

$$W_s = \frac{1}{6G}(s_\alpha^{\ 2} - s_\alpha s_\beta + s_\beta^{\ 2}) + \frac{1}{2G} v_{\alpha\beta}^{\ 2}$$

$$W_s = \frac{1}{6G}(s_\beta^{\ 2} - s_\beta s_\gamma + s_\gamma^{\ 2}) + \frac{1}{2G} v_{\alpha\gamma}^{\ 2}$$

$$W_s = \frac{1}{6G}(s_\gamma^{\ 2} - s_\alpha s_\gamma + s_\alpha^{\ 2}) + \frac{1}{2G} v_{\alpha\gamma}^{\ 2}$$

The voids are assumed oriented to the natural axes of the material and these axes are taken as α, β, and γ. Assuming that the stresses s and v, in the walls are directly proportional to the stresses, σ and τ, applied to the orthotropic material, the proportionality may be established by applying the maximum value of each of these stresses for the material and in each case computing the energy of distortion involved. If these failure stresses are called S and T, then the resulting equations defining failure of an orthotropic material are:

$$\frac{\sigma_\alpha^{\ 2}}{S_\alpha^{\ 2}} - \frac{\sigma_\alpha \sigma_\beta}{S_\alpha S_\beta} + \frac{\sigma_\beta^{\ 2}}{S_\beta^{\ 2}} + \frac{\tau_{A\beta}^{\ 2}}{T_{\alpha\beta}^{\ 2}} = 1 \ldots\ldots \text{Eq } 3.043.3a$$

$$\frac{\sigma_\beta^{\ 2}}{S_\beta^{\ 2}} - \frac{\sigma_\beta \sigma_\gamma}{S_\beta S_\gamma} + \frac{\sigma_\gamma^{\ 2}}{S_\gamma^{\ 2}} + \frac{\tau_{\beta\gamma}^{\ 2}}{T_{\beta\gamma}^{\ 2}} = 1 \ldots\ldots \text{Eq } 3.043.3b$$

$$\frac{\sigma_\gamma^{\ 2}}{S_\gamma^{\ 2}} - \frac{\sigma_\alpha \sigma_\gamma}{S_\alpha S_\gamma} + \frac{\sigma_\alpha^{\ 2}}{S_\alpha^{\ 2}} + \frac{\tau_{\alpha\gamma}^{\ 2}}{T_{\alpha\gamma}^{\ 2}} = 1 \ldots\ldots \text{Eq } 3.043.3c$$

3.043.4 When a plane state of stress exists, and the α-β plane is chosen, $\sigma_\gamma = \tau_{\beta\gamma} = \tau_{\alpha\gamma} = 0$ and the equations reduce to:

$$\frac{\sigma_\alpha^{\ 2}}{S_\alpha^{\ 2}} - \frac{\sigma_\alpha \sigma_\beta}{S_\alpha S_\beta} + \frac{\sigma_\beta^{\ 2}}{S_\beta^{\ 2}} + \frac{\tau_{\alpha\beta}^{\ 2}}{T_{\alpha\beta}^{\ 2}} = 1 \ldots\ldots \text{Eq } 3.043.4a$$

$$\frac{\sigma_\beta^{\ 2}}{S_\beta^{\ 2}} = 1 \ldots\ldots\ldots\ldots\ldots \text{Eq } 3.043.4b$$

$$\frac{\sigma_\alpha^{\ 2}}{S_\alpha^{\ 2}} = 1 \ldots\ldots\ldots\ldots\ldots \text{Eq } 3.043.4c$$

Equations 3.043.4 give excellent agreement with the results of tests performed on glass reinforced plastics at Forest Products Laboratory.

3.043.5 In previous work done at Forest Products Laboratory, an interaction formula for determining failure similar to Eq 3.043.4 had been proposed. This equation was of the form:

$$\frac{\sigma_\alpha^{\ 2}}{S_\alpha^{\ 2}} + \frac{\sigma_\beta^{\ 2}}{S_\beta^{\ 2}} + \frac{\tau_{12}^{\ 2}}{T_{12}^{\ 2}} = 1 \ldots\ldots\ldots\ldots \text{Eq } 3.043.5$$

In this equation the second term of Eq 3.043.4 does not appear.

3.043.6 Eqs 3.043.4 define an ellipsoid of failure while Eq 3.043.5 defines a sphere. The limited tests available show better agreement with the values obtained from Eqs 3.043.4 than with those obtained from Eq 3.043.5. However, a much more extensive program of testing is necessary before conclusive evidence is available for the adoption of either of these equations or perhaps even some other. In both sets of equations, the character of the stress, σ, whether tensile or compressive, determines the character of the failure stress, S. If σ is tensile then S should be taken as the tensile ultimate, etc.

3.044 Both sets of equations that define the failure conditions for a laminate given in the preceding article may be transformed into equations that may be used to predict the failure strength of the laminate when stress is applied to the laminate along axes differing from the natural axes.

3.044.1 If an ultimate tensile stress, S_x, is applied to the laminate element along the x-axis making an angle ϕ with the α-axis, then Eq 3.031.2 may be applied for this condition of plane stress, resulting in:

$$\sigma_\alpha = S_x \cos^2\phi; \quad \sigma_\beta = S_x \sin^2\phi; \quad \tau_{\alpha\beta} = -S_x \sin\phi\cos\phi$$

Substitution of these values into Eq 3.043.4a yields:

$$\frac{S_x^{\ 2}\cos^4\phi}{S_\alpha^{\ 2}} - \frac{S_x^{\ 2}\sin^2\phi\cos^2\phi}{S_\alpha S_\beta} + \frac{S_x^{\ 2}\sin^4\phi}{S_\beta^{\ 2}} + \frac{S_x^{\ 2}\sin^2\phi\cos^2\phi}{T_{\alpha\beta}} = 1, \text{ and}$$

$$\frac{1}{S_x^{\ 2}} = \frac{\cos^4\phi}{S_\alpha^{\ 2}} + \frac{\sin^4\phi}{S_\beta^{\ 2}} + \left(\frac{1}{T_{\alpha\beta}} - \frac{1}{S_{\alpha\beta}}\right)\sin^2\phi\cos^2\phi \ldots\ldots\ldots \text{Eq } 3.044.1$$

3.044.2 Similar substitution in Eq 3.043.5 results in:

$$\frac{1}{S_x^{\ 2}} = \frac{\cos^4\phi}{S_\alpha^{\ 2}} + \frac{\sin^4\phi}{S_\beta^{\ 2}} + \frac{\sin^2\phi\cos^2\phi}{T_{\alpha\beta}^{\ 2}} \ldots \text{Eq } 3.044.2$$

3.044.3 When the failure stress along axes x-y is shearing stress, T_{xy}, then substitution into Eq 3.043.4 results in:

$$\frac{1}{T_{xy}^{\ 2}} = \left(\frac{1}{S_\alpha^{\ 2}} + \frac{1}{S_\beta^{\ 2}} + \frac{1}{S_\alpha S_\beta}\right)\sin^2 2\phi + \frac{\cos^2 2\phi}{T_{\alpha\beta}} \ldots\ldots\ldots \text{Eq } 3.044.3$$

3.044.4 Similar substitution in Eq 3.043.5 gives:

$$\frac{1}{T_{xy}^{\ 2}} = \left(\frac{1}{S_\alpha^{\ 2}} + \frac{1}{S_\beta^{\ 2}}\right)\sin^2 2\phi + \frac{\cos^2 2\phi}{T_{\alpha\beta}^{\ 2}} \ldots \text{Eq } 3.044.4$$

3.044.5 These equations provide a means of estimating a particular strength (tensile, compressive or shear) for a laminate referred to a set of axes different from the natural axes as long as the corresponding values of strength are known for the natural axes.

3.045 For many applications the stress analysis given in section 3.042 is unnecessarily elaborate and time consuming. This situation arises if interlaminar shear is not a factor in design, if the physical constants for the laminate have not been determined precisely, or if the character and magnitude of the imposed loads are not exactly defined. Furthermore, certain classes of problems (columns, beams) do not, in every case, fit into an analysis of this type.

3.045.1 Another procedure is available under these circumstances. It is based also on the condition of equal deformation in the direction of stress in all the lamina. In Fig. 3.045.1 a laminate made of layers of materials a and b is subjected to an axial tensile load, P. The change in length of material "a" must equal the change in length of material "b", or:

$$\Delta L_a = \Delta L_b$$

Applying Hooke's Law:

$$\frac{P_a L}{A_a E_a} = \frac{P_b L}{A_b E_b} \quad \text{or} \quad \frac{\sigma_a}{E_a} = \frac{\sigma_b}{E_b} \; . \; . \; . \; . \; . \; . \; . \text{Eq } 3.045.1$$

Coupled with the condition of equilibrium, i.e. $P = P_a + P_b = \sigma_a A_a + \sigma_b A_b$, the stresses in the two materials and the distribution of the load, P, between a and b may be computed.

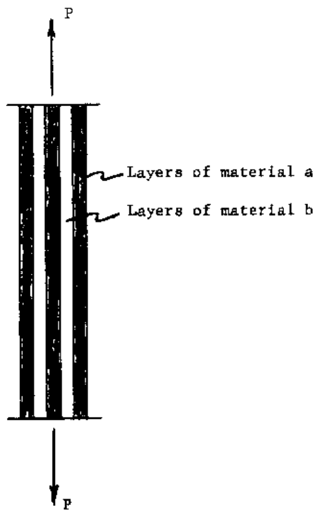


FIG. 3.045.1 MULTIPLE LAYER LAMINATE SUBJECTED TO AXIAL TENSILE LOAD, P

3.045.2 Another way of approaching the problem would be to determine the relationship between areas of the two materials in order that they be capable of sustaining the same load. In Eq 3.045.1 when $P_a = P_b$, then:

$$A_a E_a = A_b E_b \quad \text{or} \quad A_a = A_b \frac{E_b}{E_a} \; . \; . \; . \; . \; . \; . \quad \text{Eq } 3.045.2$$

3.045.3 A further extension of this principle may be obtained from a consideration of beam cross-sections. For laminates of differing Moduli to carry equal bending moments, it is necessary that the moments of inertia of the two cross-sections bear a relationship to each other similar to the area relationship for the axially loaded member, i.e.

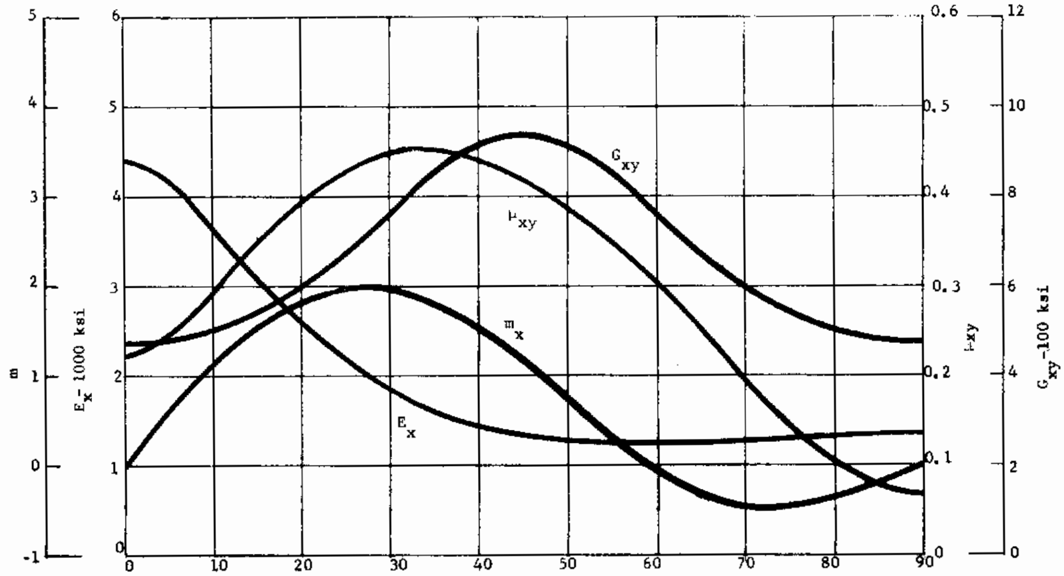
$$E_a I_a = E_b I_b \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \text{Eq } 3.045.3$$

3.045.4 The two Eqs 3.045.2 and 3.045.3 may be used to transform sections made up of lamina of different moduli into an equivalent section which may be considered to have a single modulus. With Eq 3.045.2 the area of material "a" that is equivalent to the area of material "b", A_b, is $A_b \left(\frac{E_b}{E_a}\right)$. Using Eq 3.045.3, the equivalent moment of inertia in terms of material "a" for a section of material "b" with I_b is $I_b(E_b/E_a)$.

3.045.5 When an orthotropic material made up of lamina with different moduli is transformed by the use of Eq 3.045.2 and Eq 3.045.3, the resultant section may be considered isotropic, and for many design purposes the equations for isotropic materials may be used to give adequate design and analysis results. These transformations are particularly useful in determining cross-sectional properties for column and beam design.

3.05 Helpful Stress Analysis Charts

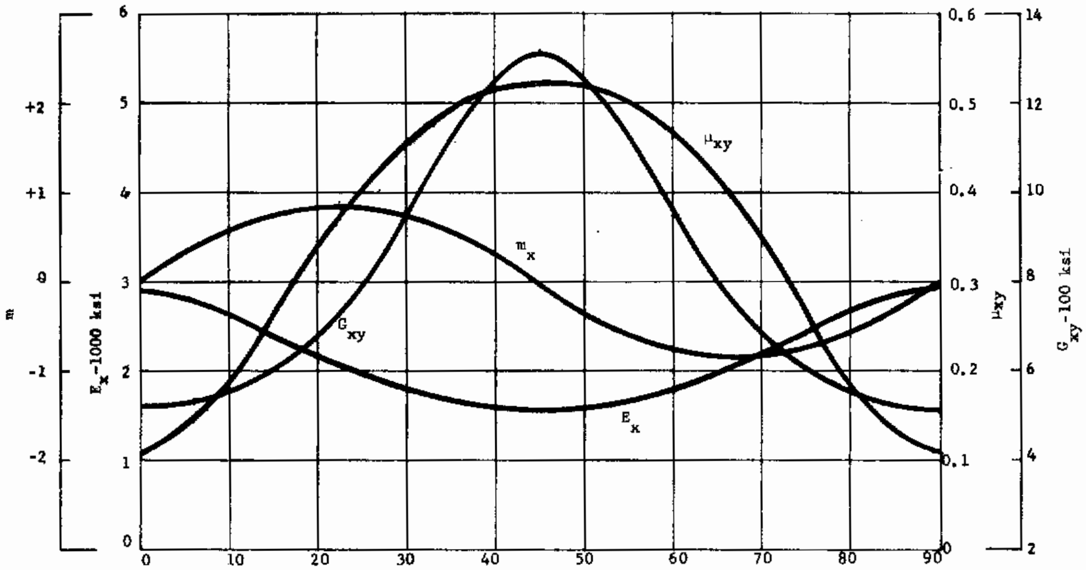
3.051 The theoretical equations defining the variation of mechanical properties of two typical orthotropic materials with orientation are shown graphically in Figs. 3.051a and 3.051b. When the designer deals with particular materials over a period of time, it is extremely helpful to prepare similar charts for these materials. In most design problems, the use of values based on these charts of the theoretical equations will give results well within the accuracy of the other data used in the design problem. Future editions of this manual may contain additional design charts as appropriate.



ANGLE WITH NATURAL AXIS
(for m_y, enter with $90^o-\phi$)

FIG. 3.051a PHYSICAL CONSTANTS FOR POLYESTER/GLASS CLOTH LAMINATE
(Selectron 5003/143-114)

Note: Test data from FPL 1853; Curves derived by SURI.



ANGLE WITH NATURAL AXIS
(for m_y, enter with $90^o-\phi$)

FIG. 3.051b PHYSICAL CONSTANTS FOR POLYESTER/GLASS CLOTH LAMINATE
(Selectron 5003/181-114)

Note: Test data from FPL 1853; Curves derived by SURI.

4.0 LAMINATES, CLASS L III

Buckling of Laminates

4.01 Physical Description

4.011 The physical description of these laminates is the same as that for Laminates, Class L II (Section 3.01), and is repeated here for convenience.

Laminates, Class L III, include those laminates composed of resin reinforced with woven cloth of fiberglass or similar material, which are principally applicable to structural parts.

4.012 Laminates are composed of layers of reinforcing, usually some form of fiber glass, that are impregnated and bonded together with resin. The reinforcement for these Class L III structural laminates takes the form of a woven cloth in which the fibers occur as warp and fill and provide reinforcement in two directions at right angles to each other, or as roving or continuous filaments which provide reinforcement in only one principal direction. The bonding of the fibers is accomplished by impregnation with any one of several possible resins, the most common of which are the polyesters, the epoxies, the phenolics, and the polystyrenes. Polystyrene resins are thermoplastic; the others are thermosetting. An almost infinite variety of laminates is possible through the combination of the various reinforcements with various resins. Even further variation can be obtained through the use of combinations of reinforcement in a single laminate.

4.02 Stress Analysis Discussion

4.021 The introductory stress analysis discussion is identical to that for Laminates, Class L II (Section 3.021), and is repeated here for convenience.

Structural plastic laminates may be divided into three general types:

4.021.1 Those laminates whose strength and other mechanical properties are the same in all directions and, consequently, are said to be isotropic.

4.021.2 Those laminates whose properties vary depending on the orientation of the laminate but are based on the properties in two directions ninety degrees apart, commonly said to be orthotropic (1).

4.021.3 Those laminates built up of combinations of either or both of the first two.

4.022 The stress analysis of reinforced laminates is carried out by applying one of two basic approaches to design. The particular approach depends on the mechanical characteristics of the laminate as determined by the type of reinforcement used in its fabrication.

4.023 Since Class L III laminates are fabricated using cloth or roving as the reinforcement, the mechanical properties of the resulting combination depend on the direction in which they are measured. These laminates, therefore, are not isotropic; they are orthotropic. Variation of strength and other properties of the material, dependent on the orientation of load to direction of fiber in the reinforcement, results in a significant modification of the conventional design equations, and calls for an approach to design different from the approach used with mat reinforced laminates. Whether the reinforcement consists of cloth woven of yarn fabrics oriented at right angles to each other, rovings with strands parallel to each other, or multi-layers of fabrics or rovings placed parallel or perpendicular to each other, the resultant laminate has two principal directions parallel and perpendicular to the direction of the main reinforcement, and all of these combinations result in an orthotropic material.

(1) During investigations for this work the term "aeolotropic" was sometimes used synonimously with "orthotropic". Due to definition connotation and accepted usage, orthotropic will be used in this Handbook for the laminate type described. See Glossary of Terms in Manual IA for more complete information on these two terms.

4.03 Fundamental Stress Formulas

4.031 The equations for the buckling of flat plates of isotropic materials are used as the basis for arriving at the basic equations for orthotropic plates.

4.031.1 From standard works (2) on the buckling of flat plates, the equation denoting the condition of equilibrium of a plate subjected to action of forces in its middle plane is:

$$\frac{\partial^2 M_x}{\partial x^2} + 2\frac{\partial^2 M_{xy}}{\partial x \partial y} + \frac{\partial^2 M_y}{\partial y^2} = -\left[N_x \frac{\partial^2 w}{\partial x^2} + 2N_{xy}\frac{\partial^2 w}{\partial x \partial y} + N_y \frac{\partial^2 w}{\partial y^2}\right] \quad \text{Eq 4.031.1}$$

where the axes and positive signs of the various terms are shown in Fig. 4.031.1.

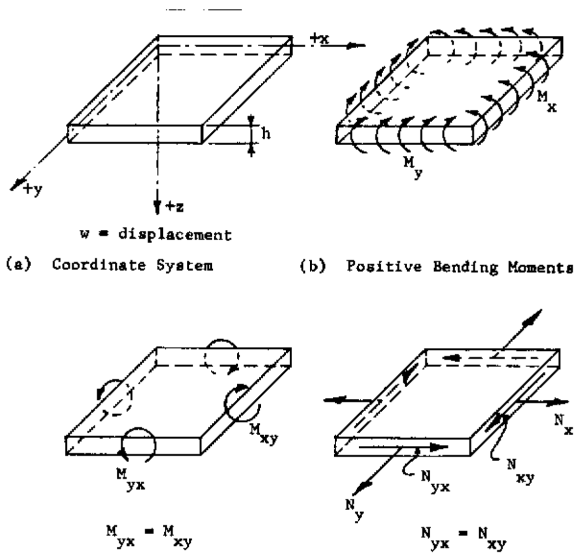


FIG. 4.031.1 ASSUMED LOADING CONDITIONS FOR ANALYSIS OF BUCKLING OF FLAT PLATE

4.031.2 Considering a differential element of the plate, and summing up the stress components on each face for a unit width of plate results in Eq 4.031.2.

$$M_x = \int_{-h/2}^{+h/2} \sigma_x z\,dz \quad \text{Eq 4.031.2a}$$

$$M_y = \int_{-h/2}^{+h/2} \sigma_y z\,dz \quad \text{Eq 4.031.2b}$$

$$M_{xy} = \int_{-h/2}^{+h/2} \tau_{xy} z\,dz \quad \text{Eq 4.031.2c}$$

4.031.3 The strain-displacement relationships based on geometry, small deflections, and a thin plate are:

$$\epsilon_x = -z\frac{\partial^2 w}{\partial x^2} \quad \text{Eq 4.031.3a}$$

$$\epsilon_y = -z\frac{\partial^2 w}{\partial y^2} \quad \text{Eq 4.031.3b}$$

$$\gamma_{xy} = -2z\frac{\partial^2 w}{\partial x \partial y} \quad \text{Eq 4.031.3c}$$

(2) For instance: Gerard, George, "Introduction of Structural Stability Theory, p 35, McGraw-Hill Book Co., Inc (1962)

4.031.4 For an orthotropic material, the equations relating strain to stress are taken from Section 3.041.3, Manual IE, as follows:

$$\epsilon_x = \frac{\sigma_x}{E_x} - \mu_{yx}\frac{\sigma_y}{E_y}$$

$$\epsilon_y = \frac{\sigma_y}{E_y} - \mu_{xy}\frac{\sigma_x}{E_x}$$

$$\gamma_{xy} = \frac{\tau_{xy}}{G_{xy}}$$

Solving the first two of these equations for σ_x and σ_y and rearranging the third results in:

$$\sigma_x = \frac{E_x}{1-\mu_{xy}\mu_{yx}}(\epsilon_x + \mu_{yx}\epsilon_y)$$

$$\sigma_y = -\frac{E_y}{1-\mu_{xy}\mu_{yx}}(\epsilon_y + \mu_{xy}\epsilon_x)$$

$$\tau_{xy} = \gamma_{xy}G_{xy}$$

Substituting the values for ϵ_x and ϵ_y from Eqs 4.031.3 into the above expressions for σ_x, σ_y and τ_{xy} results in:

$$\sigma_x = -\frac{E_x}{1-\mu_{xy}\mu_{yx}}\left[z\frac{\partial^2 w}{\partial x^2} + \mu_{yx} z\frac{\partial^2 w}{\partial y^2}\right] \;..\text{Eq 4.031.4a}$$

$$\sigma_y = -\frac{E_y}{1-\mu_{xy}\mu_{yx}}\left[z\frac{\partial^2 w}{\partial y^2} + \mu_{xy} z\frac{\partial^2 w}{\partial x^2}\right] \;..\text{Eq 4.031.4b}$$

$$\tau_{xy} = -2zG_{xy}\frac{\partial^2 w}{\partial x\partial y} \;\ldots\ldots\ldots\; \text{Eq 4.031.4c}$$

4.031.5 The values obtained for σ_x, σ_y, τ_{xy} in Eqs 4.031.4 may now be substituted in Eqs 4.031.2 with the following results:

$$M_x = \int_{-h/2}^{+h/2}\sigma_x z\,dz = -\frac{E_x}{1-\mu_{xy}\mu_{yx}}\left[\frac{\partial^2 w}{\partial x^2} + \mu_{yx}\frac{\partial^2 w}{\partial y^2}\right]\int_{-h/2}^{+h/2} z^2 dz = -\frac{E_x h^3}{12(1-\mu_{xy}\mu_{yx})}\left[\frac{\partial^2 w}{\partial x^2} + \mu_{yx}\frac{\partial^2 w}{\partial y^2}\right]$$

$$\ldots\ldots\ldots\; \text{Eq 4.031.5a}$$

$$M_y = \int_{-h/2}^{+h/2}\sigma_y z\,dz = -\frac{E_y h^3}{12(1-\mu_{xy}\mu_{yx})}\left[\frac{\partial^2 w}{\partial y^2} + \mu_{xy}\frac{\partial^2 w}{\partial x^2}\right]$$

$$\ldots\ldots\ldots\; \text{Eq 4.031.5b}$$

$$M_{xy} = \int_{-h/2}^{+h/2}\tau_{xy} z\,dz = -\frac{G_{xy}h^3}{6}\left[\frac{\partial^2 w}{\partial x\partial y}\right]$$

$$\ldots\ldots\ldots\; \text{Eq 4.031.5c}$$

4.031.6 To simplify the above, constants may be collected as follows:

$$D_x = \frac{E_x h^3}{12(1-\mu_{xy}\mu_{yx})} \;\ldots\ldots\ldots\; \text{Eq 4.031.6a}$$

and

$$D_y = \frac{E_y h^3}{12(1-\mu_{xy}\mu_{yx})} \;\ldots\ldots\ldots\; \text{Eq 4.031.6b}$$

4.031.7 The constants, D_x and D_y, are now inserted in Eqs 4.031.5 and the partial differentiations completed as follows:

$$M_x = -D_x\left[\frac{\partial^2 w}{\partial x^2} + \mu_{yx}\frac{\partial^2 w}{\partial y^2}\right]$$

$$\frac{\partial^2 M_x}{\partial x^2} = -D_x\left[\frac{\partial^4 w}{\partial x^4} + \mu_{yx}\frac{\partial^4 w}{\partial x^2\partial y^2}\right]$$

$$M_y = -D_y\left[\frac{\partial^2 w}{\partial y^2} + \mu_{xy}\frac{\partial^2 w}{\partial x^2}\right]$$

$$\frac{\partial^2 M_y}{\partial y^2} = -D_y\left[\frac{\partial^4 w}{\partial y^4} + \mu_{xy}\frac{\partial^4 w}{\partial x^2\partial y^2}\right]$$

$$M_{xy} = -\frac{G_{xy}h^3}{6}\left[\frac{\partial^2 w}{\partial x\partial y}\right]$$

$$\frac{\partial^2 M_{xy}}{\partial x\partial y} = -\frac{G_{xy}h^3}{6}\left[\frac{\partial^4 w}{\partial^2 x\partial^2 y}\right]$$

These expressions are substituted in equation 4.031.1, obvious simplifications performed, and the following equation obtained:

$$D_x\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial x^2\partial y^2}\left[\frac{1}{2}(D_x\mu_{yx} + D_y\mu_{xy}) + 2G_{xy}\frac{h^3}{12}\right] + D_y\frac{\partial^4 w}{\partial y^4} = N_x\frac{\partial^2 w}{\partial x^2} + 2N_{xy}\frac{\partial^2 w}{\partial x\partial y} + N_y\frac{\partial^2 w}{\partial y^2}$$

$$\ldots\ldots\ldots\; \text{Eq 4.031.7}$$

4.031.8 Eq 4.031.7 may be further simplified by letting $D_{xy} = 1/2\,(D_x\mu_{yx} + D_y\mu_{xy}) + 2G_{xy}h^3/12$. Then the general differential equation for the deflection of an orthotropic plate subjected to the action of forces in its mid-plane is obtained (3).

$$D_x\frac{\partial^4 w}{\partial x^4} + 2D_{xy}\frac{\partial^4 w}{\partial x^2\partial y^2} + D_y\frac{\partial^4 w}{\partial y^4} = N_x\frac{\partial^2 w}{\partial x^2} + 2N_{xy}\frac{\partial^2 w}{\partial x\partial y} + N_y\frac{\partial^2 w}{\partial y^2} \;\ldots\ldots\; \text{Eq 4.031.8}$$

4.04 <u>Derivation of Design Formulas</u>

4.041 In the case of an orthotropic plate with coordinate axes parallel to the natural axes of the laminate, the x-y axes correspond to the α-β axes.

4.041.1 Therefore, subjecting an orthotropic plate to an axial compression, $-N_\alpha$, in the mid-plane of the plate and parallel to the α-axis, as shown in Fig. 4.041.1, Eq 4.031.8 becomes:

$$D_\alpha\frac{\partial^4 w}{\partial\alpha^4} + 2D_{\alpha\beta}\frac{\partial^4 w}{\partial\alpha^2\partial\beta^2} + D_\beta\frac{\partial^4 w}{\partial\beta^4} + N_\alpha\frac{\partial^2 w}{\partial\alpha^2} = 0$$

$$\ldots\ldots\ldots\; \text{Eq 4.041.1}$$

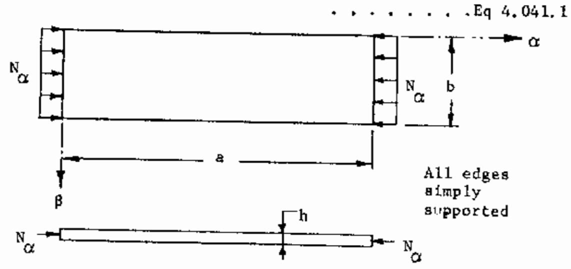


FIG. 4.041.1 LOADING CONDITIONS FOR DERIVATION OF EQUATIONS FOR σ_{cr}

(3) Timoshenko, S., "Theory of Elastic Stability", McGraw-Hill Book Co., Inc., New York (1936).

4.041.2 If all edges of the plate are simply supported, and it is assumed that it buckles into "n" half-waves along the length "a" and one half-wave along the length "b", the expression for displacement will be:

$$w = A \sin \frac{n\pi\alpha}{a} \sin \frac{\pi\beta}{b} \quad \text{. . . . . Eq 4.041.2}$$

4.041.3 The value of the critical buckling stress, σ_{cr}, may be obtained by performing the differentiations on Eq 4.041.2 indicated in Eq 4.041.1 and substituting the results in Eq 4.041.1. Realizing that $\sigma_{cr} = X_\alpha/h$, the resulting expression is (3):

$$\sigma_{cr} = \frac{\pi^2}{b^2 h}\left[D_\alpha \frac{n^2 b^2}{a^2} + 2D_{\alpha\beta} + D_\beta \frac{a^2}{n^2 b^2}\right] \quad \text{. . . . . . . Eq 4.041.3}$$

4.041.4 To find the minimum value at the buckling stress for the above condition of loading, the derivative of Eq 4.041.3 is set equal to zero and it is found that:

$$\frac{a}{b} = n\sqrt[4]{\frac{D_\alpha}{D_\beta}} = n\sqrt[4]{\frac{E_\alpha}{E_\beta}} \quad \text{. . . . . . . Eq 4.041.4}$$

4.041.5 Solving Eq 4.041.4 for a and substituting of this value Eq 4.041.3, with n = 1, results in the following expression for minimum value of the critical buckling stress in a simply supported orthotropic plate subjected to an axial compressive force:

$$\sigma_{cr(min)} = \frac{2\pi^2}{b^2 h}\left[\sqrt{D_\alpha D_\beta} + D_{\alpha\beta}\right] \quad \text{. . . . Eq 4.041.5a}$$

When D_α, D_β, and $D_{\alpha\beta}$ are replaced by their equivalents involving E_α, E_β, $G_{\alpha\beta}$, $\mu_{\alpha\beta}$, etc. and realizing that $E_\alpha\mu_{\beta\alpha} = E_\beta\mu_{\alpha\beta}$, Eq 4.042.1a becomes:

$$\sigma_{cr(min)} = \frac{\pi^2 h^2}{6(1-\mu_{\alpha\beta}\mu_{\beta\alpha})b^2}\left[\sqrt{E_\alpha E_\beta} + E_\alpha\mu_{\beta\alpha} + G_{\alpha\beta}\,(1 - \mu_{\alpha\beta}\mu_{\beta\alpha})\right] \quad \text{. . . . . . . Eq 4.041.5b}$$

For other size plates, for which the dimentional ratio a/b is an interger multiple of the critical ratio found in Eq 4.041.4, Eqs 4.041.5a and b will give the critical buckling stress. This is due to the plates buckling into a series of half-waves having ratios of dimensions corresponding to those necessary to give the minimum critical stresses.

4.041.6 For other plates which do not fit into the above case, the buckling stress will be higher. The stress can be found by using Eq 4.041.3 directly as follows. Substitution of the values for the constants, D, in Eq 4.041.3 and rearrangement of the terms, results in:

$$\sigma_{cr} = \frac{\pi^2 h^2}{12b^2(1-\mu_{\alpha\beta}\mu_{\beta\alpha})}\left\{E_\alpha \frac{n^2 b^2}{a^2} + E_\beta \frac{a^2}{n^2 b^2} + 2\left[E_\alpha\mu_{\beta\alpha} + 2G_{\alpha\beta}\,(1-\mu_{\alpha\beta}\mu_{\beta\alpha})\right]\right\} \quad \text{. . . . . . . Eq 4.041.6}$$

4.041.7 Eq 4.041.6, above, may be put into a more workable form by the following collection of terms:

$$c = \frac{E_\alpha\mu_{\beta\alpha} + 2G_{\alpha\beta}\,(1-\mu_{\alpha\beta}\mu_{\beta\alpha})}{\sqrt{E_\alpha E_\beta}} \quad \text{. . . . . Eq 4.041.7a}$$

$$q = \frac{a}{b}\left[\frac{E_\beta}{E_\alpha}\right]^{0.25} \quad \text{. . . . . Eq 4.041.7b}$$

$$\text{and } k = \frac{\pi^2}{12}\left[\frac{n^2}{q^2} + \frac{q^2}{n^2} + 2c\right] \quad \text{. . . . . Eq 4.041.7c}$$

4.041.8 Using the above equations, Eq 4.041.6 will reduce to the following expression for the critical stress on a plate with simply supported edges, loaded parallel to the "a" direction only.

$$\sigma_{cr} = k\,\frac{\sqrt{E_\alpha E_\beta}}{1-\mu_{\alpha\beta}\mu_{\beta\alpha}}\left(\frac{h}{b}\right)^2 \quad \text{. . . . . Eq 4.041.8}$$

Values of k in the above equation may be compiled by plotting k vs. q for various values of c and using these plots for design purposes. Section 4.05 discusses these plots further. It should be noted that for values of n, other than 1 and 2, the minimum buckling stress occurs when q = n, and has the same value as that given by Eqs 4.041.5a and b.

4.05 Helpful Stress Analysis Charts

4.051 Application of buckling theory to analysis can be considerably simplified by the use of appropriate charts to determine the various terms in the equations for the critical buckling stress.

4.052 Stress analysis charts for buckling of rectangular plates loaded in one direction which is parallel to a natural axis.

4.052.1 All edges simply supported, Fig. 4.052.1.

Values of k from Eq 4.041.7c are plotted against corresponding values of q from Eq 4.041.7b for various values of c from Eq 4.041.7a. The data for only one and two half-waves are plotted, and it will be noted that the minimum value of k is the same regardless of the value for n. The use of this minimum value of k for n = 3, can result in a maximum underestimate of critical buckling stress of approximately 8.5% when c = 0, but only half that when c = 1.0. For larger values of n, the error decreases as n increases. The equation for k, Eq 4.041.7c, is repeated below for convenience.

$$k = \frac{\pi^2}{12}\left[\frac{n^2}{q^2} + \frac{q^2}{n^2} + 2c\right] \quad \text{. . . . . Eq 4.052.1}$$

4.052.2 Loaded edges simply supported, other edges fixed, Fig. 4.052.2.

Again only data for n = 1 and 2 are provided. When n = 3, use of the minimum value of k will result in errors, on the safe side, of from 5 to 7.5% maximum in estimating the critical buckling stress. For larger values of n, the per cent error successively decreases. The values of k cannot be obtained by direct integration for these conditions of support. However, by using other methods (4), k may be approximated by the following expression:

$$k = \frac{4\pi^2}{9}\left[\frac{3n^2}{16q^2} + \frac{q^2}{n^2} + \frac{c}{2}\right] \quad \text{. . . . . . . Eq 4.052.2}$$

4.052.3 Loaded edges fixed, other edges simply supported, Fig. 4.052.3. Data for 4 half-waves are provided. It should be noted that successive half-waves have different minimum values. Again, values of k cannot be obtained by direct integration, but may be approximated by the following expressions (4):

For n = 1, $0.8 \leq q \leq 1.662$, k_{min} at q = 1.520

$$k = \frac{\pi^2}{48}\left[\frac{16}{q^2} + 3q^2 + 8c\right] \quad \text{. . . . . Eq 4.052.3a}$$

For n = 2, $1.662 \leq q \leq 2.711$, k_{min} at q = 2.530

$$k = \frac{\pi^2}{60}\left[\frac{41}{q^2} + q^2 + 10c\right] \quad \text{. . . . . . . Eq 4.052.3b}$$

(4) ANC-17, Part I

For n = 3, $2.711 \leq q \leq 3.632$, k_{min} at q = 3.415

$$k = \frac{\pi^2}{120}\left[\frac{136}{q^2} + q^2 + 20c\right] \quad \text{. . . . . . . Eq 4.052.3c}$$

For n = 4, $3.632 \leq q$ with q taken to the minimum value for k, which occurs at q = 4.335

$$k = \frac{\pi^2}{204}\left[\frac{353}{q^2} + q^2 + 34c\right] \quad \text{. . . . . . . Eq 4.052.3d}$$

4.052.4 All edges fixed, Fig. 4.052.4. As in 4.052.3 above, data for 4 half-waves are provided and successive half-waves have different minimum values. Again, values of k cannot be obtained by direct integration, but may be approximated by the following expressions (4):

For n = 1, $0.8 \leq q \leq 1.094$, k_{min} at q = 1.000

$$k = \frac{\pi^2}{9}\left[\frac{3}{q^2} + 3q^2 + 2c\right] \quad \text{. . . . . .Eq 4.052.4a}$$

For n = 2, $1.094 \leq q \leq 1.784$, k_{min} at q = 1.665

$$k = \frac{\pi^2}{180}\left[\frac{123}{q^2} + 16q^2 + 40c\right] \quad \text{. . . . . . .Eq 4.052.4b}$$

For n = 3, $1.784 \leq q \leq 2.390$, k_{min} at q = 2.247

$$k = \frac{\pi^2}{45}\left[\frac{51}{q^2} + 2q^2 + 10c\right] \quad \text{. . . . . . . Eq 4.052.4c}$$

For n = 4, $2.390 \leq q$ with q taken to minimum value for k, which occurs at q = 2.852

$$k = \frac{\pi^2}{612}\left[\frac{1059}{q^2} + 16q^2 + 136c\right] \quad \text{. . . . Eq 4.052.4d}$$

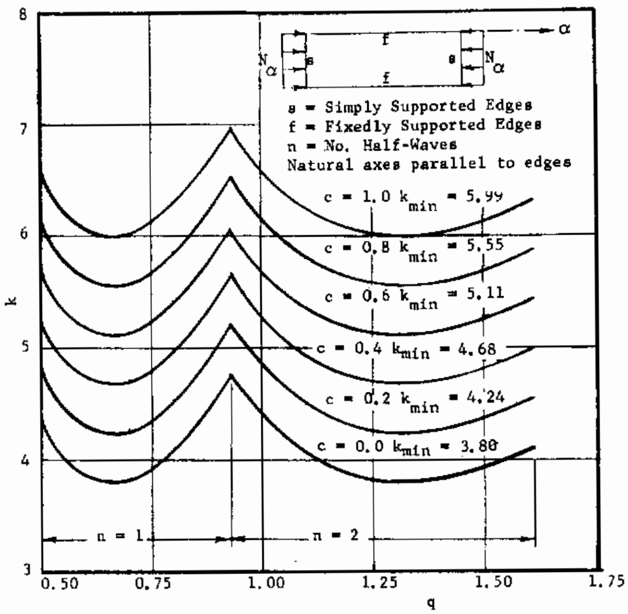


FIG. 4.052.2 k vs. q FOR CALCULATING σ_{cr} FOR BUCKLING OF FLAT PLATE WITH LOADED EDGES SIMPLY SUPPORTED AND OTHER EDGES FIXED

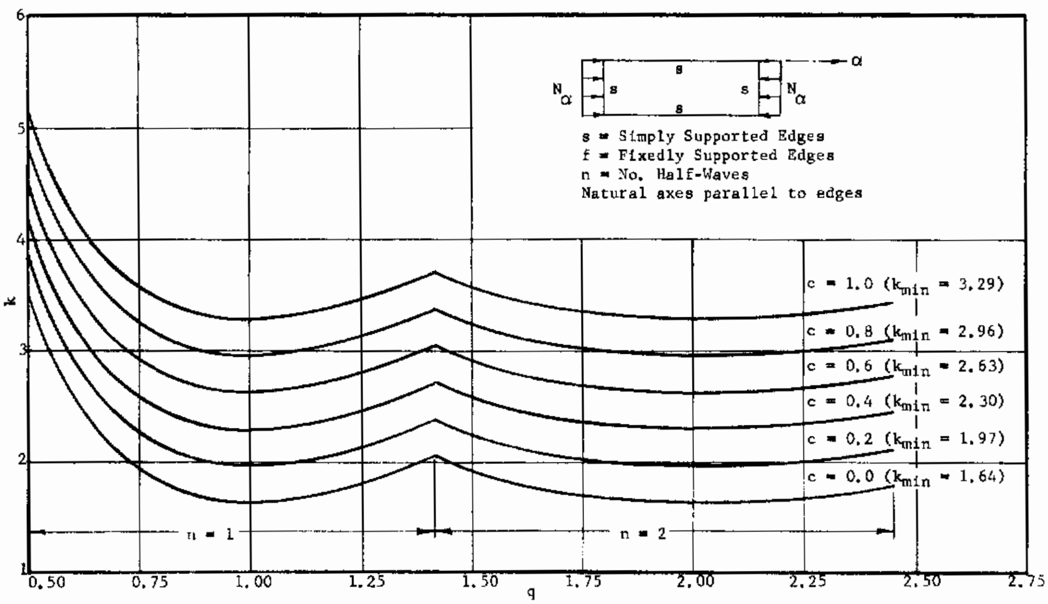


FIG. 4.052.1 k vs. q FOR CALCULATING σ_{cr} FOR BUCKLING OF FLAT PLATE WITH ALL EDGES SIMPLY SUPPORTED

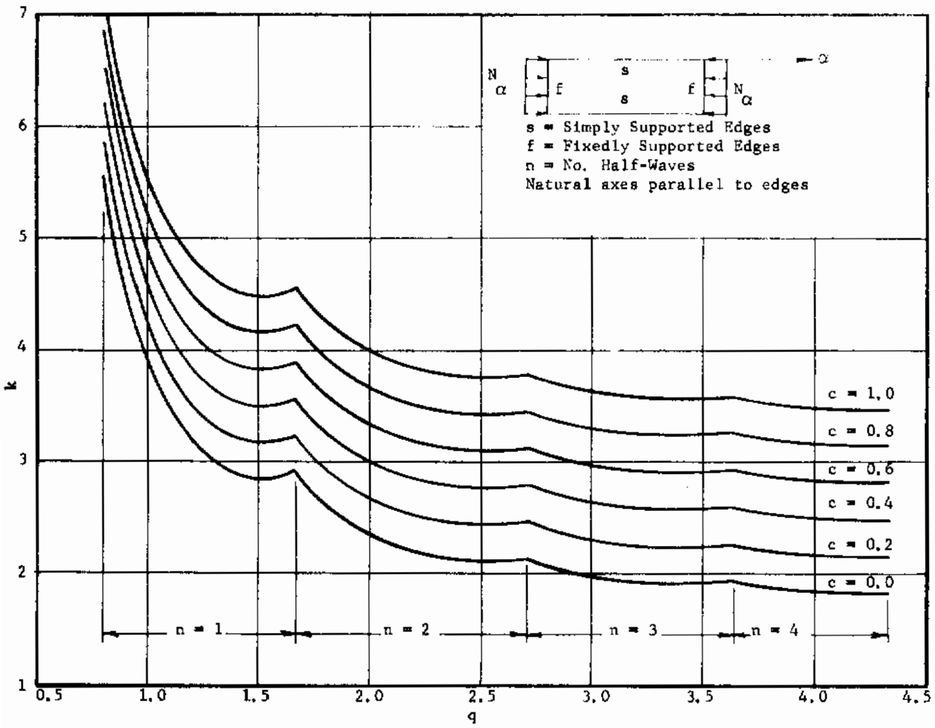


FIG. 4.052.3 k vs. q FOR CALCULATING σ_{cr} FOR BUCKLING OF FLAT PLATE WITH LOADED EDGES FIXED AND OTHER EDGES SIMPLY SUPPORTED

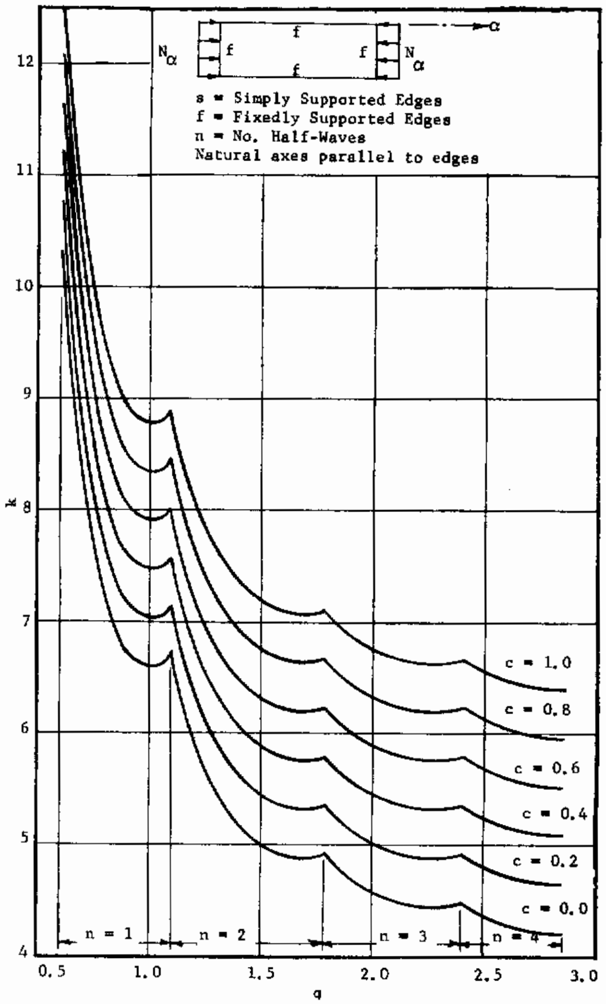


FIG. 4.052.4 k vs. q FOR CALCULATING σ_{cr} FOR BUCKLING OF FLAT PLATES WITH ALL EDGES FIXED

20.0 FILAMENT WINDING, CLASS F I

Simple pressure bottles without integral end closures.

20.01 Physical Description

20.011 Filament Winding Class F I includes those wound cylindrical tubes used for pressure vessels which are fabricated from resin bonded fiber glass using either chopped random fiber, woven fabric, or continuous filaments as the reinforcement. Neither the chopped random fiber nor the woven fabric, when used for this application, offers the potential and actual strength that a continuous filament offers in a netting system composed of a combination of helical and circumferential windings. Other disadvantages of these first two types of reinforcement stem from the manufacturing processes needed in fabrication that result in serious problems of quality control.

20.02 Stress Analysis Discussion

20.021 Filament winding developed as an art rather than a science. Large pressure vessels in particular were fabricated on a trial and error basis, but, as the importance of this type of structure increased, an improved understanding of the structural action developed. Based on this understanding, design techniques have evolved. In certain areas where complex loadings are involved, or where discontinuities exist in the structural form, empirical methods of design are still in use.

20.022 The discussion in this section of the Manual IE will be limited to the analysis and design of cylindrical pressure vessels in which the filament is wound as a system of low helix angle windings used to carry the longitudinal forces in the cylinder shell. Assistance in resisting the circumferential or hoop stresses may be provided the helical windings by using circular (or circumferential) windings as well. The circular windings cannot be used in winding an end closure, however, since they tend to slip off as winding progresses. The combination winding permits the resulting vessel to approximate balanced strength and allows the fibers to be stressed in tension only. A possible combination of windings is shown in Fig. 20.022.

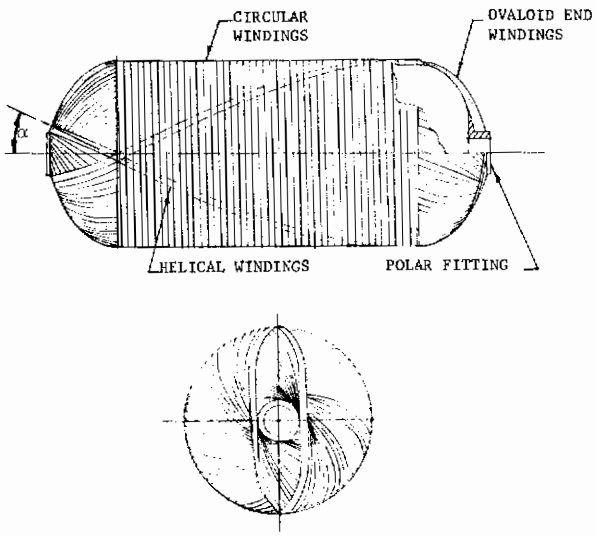


FIG: 20.022 TYPICAL PRESSURE BOTTLE WINDING CONFIGURATION

20.023 In the analysis of continuous filament wound structures, the following assumptions are made:

20.023.1 The continuous filament or fiber carries all the load.

20.023.2 The resin bonding material serves to hold the reinforcing fibers to the desired structural shape.

20.023.3 There is no interaction between fiber layers.

20.023.4 Individual fiber layers may be wound at different helix angles.

20.024 The stress analysis for continuous filament structures used as pressure vessels can be handled in either of two ways depending on the system of winding used. Single netting analysis is used when the cylinder is fabricated from a single system of helical windings at a constant helix angle, α, as shown in Fig. 20.031. Complex netting analysis is used when a combination of helical and circumferential windings are used for fabrication of the cylinder, as indicated in Fig. 20.022.

20.03 Fundamental Stress Formulas

20.031 The equations for use with the single netting helical winding illustrated in Fig. 20.031 are developed first. In this figure and the equations developed therefrom, the following notation is used:

T = Filament force over width Δw
F_H = Hoop force provided by filaments
F_L = Longitudinal force provided by filaments
σ = Filament stress
σ_H = Hoop stress provided by filaments
σ_L = Longitudinal stress provided by filaments

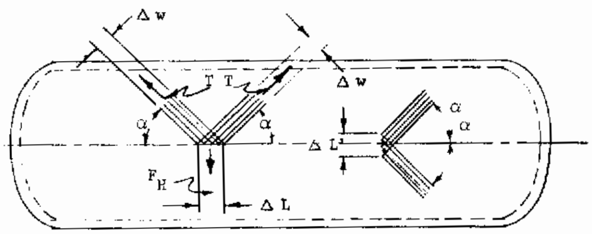


FIG: 20.031 DETAILS FOR ANALYSIS OF A SINGLE SYSTEM OF HELICAL WINDINGS.

20.031.1 Assuming only one half the thickness, t, of the cylinder acts with each of the helical tensile forces, T, then the following expression may be derived for the strength in the hoop direction:

$$F_H = 2T \sin \alpha$$

Since:

$$\Delta L = \Delta w/\sin \alpha, \text{ then:}$$

$$\sigma_H = \frac{F_H}{t\Delta L} = \frac{2T \sin^2\alpha}{t\Delta w}$$

$$T = \sigma(\Delta w)t/2, \text{ therefore:}$$

$$\sigma_H = \frac{2\sigma(\Delta w)t \sin^2\alpha}{t(\Delta w)2} = \sigma \sin^2\alpha \quad . . . \text{ Eq 20.031.1}$$

20.031.2 The analysis in the longitudinal direction is carried out in a similar fashion:

$$F_L = 2T \cos \alpha$$

Since:

$$\Delta L' = \Delta w/\cos \alpha, \text{ then:}$$

$$\sigma_L = \frac{F_L}{t\Delta L'} = \frac{2T \cos^2\alpha}{t\Delta w}$$

$$T = \sigma(\Delta w)t/2, \text{ therefore:}$$

$$\sigma_L = \frac{2\sigma(\Delta w)\ t \cos^2\alpha}{t\ (\Delta w)\ 2} = \sigma \cos^2\alpha \quad . . . \text{ Eq 20.031.2}$$

20.031.3 When a single helical system is used, balanced strength is provided when the helix angle, α, is determined on the basis of the ratio of hoop to longitudinal stress as follows.

$$\frac{\sigma_H}{\sigma_L} = \frac{\sigma \sin^2\alpha}{\sigma \cos^2\alpha}$$

$$\tan^2\alpha = \sigma_H/\sigma_L$$

$$\alpha = \tan^{-1}\sqrt{\sigma_H/\sigma_L} \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \text{ Eq 20.031.3}$$

20.031.4 Fig. 20.031.4 shows the relative proportions of σ taken in the hoop and longitudinal directions as the helix angle, α, varies.

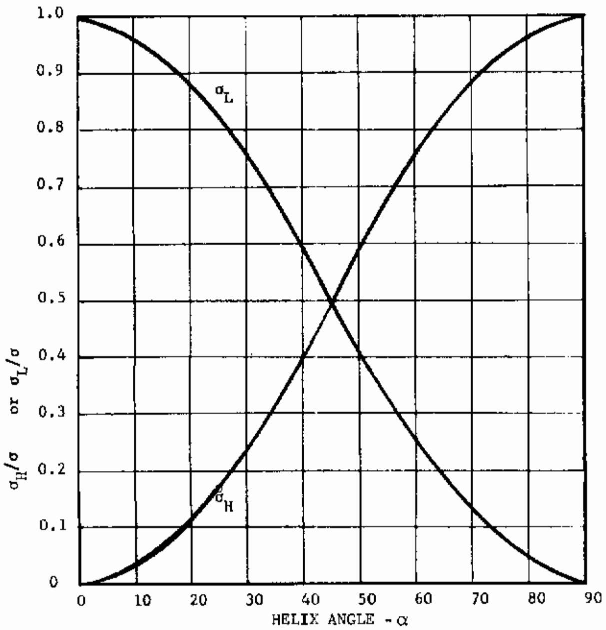


FIG 20.031.4 VARIATION OF σ_H AND σ_L WITH HELIX ANGLE, α

20.031.5 When the cylinder is subjected to internal pressure alone, $\sigma_H = 2\sigma_L$, and in order to achieve balance, Eq 20.031.3 reduces to:

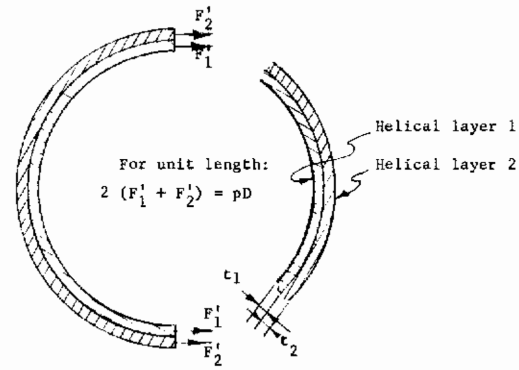
$$\alpha = \tan^{-1}\sqrt{2} = 54^\circ 45' \; . \; . \; . \; . \; . \; . \; . \text{ Eq 20.031.5}$$

20.031.6 An optimal angle can be derived in a similar fashion for any other ratio of hoop to longitudinal stresses.

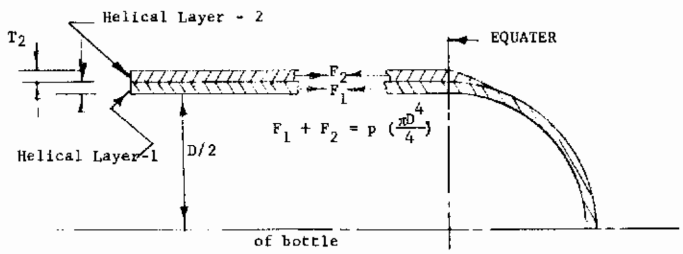
20.032 The equations for a complex netting system are now developed.

20.032.1 When pressure cylinders are constructed with integral end closures, it becomes impractical to use the optimum winding angle of 54°45'. Imperfect packing of the helical fibers around the end closure and the changes in the radius of curvature going from tangent point to end closure cause the helical winding to perform at levels below the optimum strength of the fibers. Therefore, it is necessary to use a helical winding system with a low helix angle to form the ends as well as to carry the longitudinal loads. The low helix angle will not provide sufficient strength in the hoop direction when the helical layers are of sufficient thickness to carry the longitudinal load. To overcome this deficiency, circumferential windings are provided to carry the remainder of the hoop stress. These windings are actually at a helix angle very close to 90°. Additional windings are not required for the end dome and a balanced design may be achieved by selecting an end dome configuration that fits the helix angle chosen.

20.032.2 The analysis of such a pressure cylinder is based on the following procedure for the general case of two layers with different helix angles. When one layer consists of circumferential windings these general equations will apply by making the helix angle 90° for that layer. In Fig. 20.032.2 a typical two layer system is shown in longitudinal section and cross-section. Two helical layers form the cylindrical portion of the vessel, but only one is extended to form the end dome. The basic assumption is that the two systems act independently of each other. Layer 1 has a helix angle of α_1 and layer 2 of $-\alpha_2$.



(a) Partial Cross Section Through Vessel Showing Circumferential Hoop Forces.



(b) Partial Longitudinal Section Through Vessel Showing Longitudinal Forces.

FIG 20.032.2 DETAILS FOR ANALYSIS OF A TWO LAYER SYSTEM OF HELICAL WINDINGS.

20.032.3 For a unit length ($\Delta L = 1$) of cylinder, the total hoop force resisting the internal pressure, see Fig. 20.032.2a, is:

$$F_H = 2(F'_1 + F'_2) = pD(1),$$

where:

F_1 and F_2 = the hoop forces provided by filaments in layer 1 and 2 respectively

p = internal pressure

Using the previously derived expression, Eq 20.031.1, to compute the component of the hoop stress contributed by each helical winding, results in the following:

$$\sigma_H = \sigma \sin^2\alpha$$

$$F'_1 = (\sigma_{H1})\, t_1\, (1) = \sigma_1 t_1 \sin^2\alpha_1$$

$$F'_2 = (\sigma_{H2})\, t_2\, (1) = \sigma_2 t_2 \sin^2\alpha_2$$

$$\frac{p\,D}{2} = \sigma_H\,(t_1 + t_2) = \sigma_1 t_1 \sin^2\alpha_1 + \sigma_2 t_2 \sin^2\alpha_2 \; . \; . \; . \; . \; . \; . \text{ Eq 20.032.3}$$

where:

σ_1 and σ_2 are the filament stresses in layer 1 and 2 respectively.

20.032.4 The total longitudinal force resisting the internal pressure, see Fig. 20.032.2b, is:

$$F_L = F_1 + F_2 = p\left(\frac{\pi D^2}{4}\right),$$

where:

F_1 and F_2 = the longitudinal forces provided by filaments in layer 1 and 2 respectively.

Again using the previously derived expression, Eq 20.031.2, to compute the component of the longitudinal stress contributed by each helical winding, in a manner similar to 20.032.3 above, results in the following:

$$\sigma_L = \sigma \cos^2\alpha$$

$$F_1 = (\sigma_{L1})(\pi D t_1) = \sigma_1 \pi D t_1 \cos^2\alpha_1$$

$$F_2 = (\sigma_{L2})(\pi D t_2) = \sigma_2 \pi D t_2 \cos^2\alpha_2$$

$$p\left(\frac{\pi D^2}{4}\right) = \pi D \sigma_L (t_1 + t_2) = \pi D(\sigma_1 t_1 \cos^2\alpha_1 + \sigma_2 t_2 \cos^2\alpha_2)$$

$$\frac{pD}{4} = \sigma_L(t_1 + t_2) = \sigma_1 t_1 \cos^2\alpha_1 + \sigma_2 t_2 \cos^2\alpha_2 \quad \ldots\ldots \text{Eq } 20.032.4$$

20.032.5 When the outer layer is wound in a circumferential direction, the helix angle, α_2, approaches 90° and equations 20.032.3 and 20.032.4 reduce to:

$$\frac{pD}{2} = \sigma_1 t_1 \sin^2\alpha_1 + \sigma_2 t_2$$

$$\frac{pD}{4} = \sigma_1 t_1 \cos^2\alpha_1$$

Eliminating pD in these equations results in:

$$2\sigma_1 t_1 \cos^2\alpha_1 = \sigma_1 t_1 \sin^2\alpha_1 + \sigma_2 t_2 \quad \ldots\ldots\ldots \text{Eq } 20.032.5a$$

$$\frac{t_2}{t_1} = \frac{\sigma_1(2\cos^2\alpha_1 - \sin^2\alpha_1)}{\sigma_2} \quad \ldots\ldots \text{Eq } 20.032.5b$$

20.032.6 Since σ_1 and σ_2 are the maximum stresses that can be developed in the helical and hoop fibers respectively, their summation must equal the strength of the fibers, σ, or:

$$\sigma_1 = \sigma_2 = \sigma$$

Eq 20.032.5 may now be rewritten as:

$$\frac{t_2}{t_1} = \frac{t_{Hoop}}{t_{Helix}} = 2\cos^2\alpha_1 - \sin^2\alpha_1 = 3\cos^2\alpha_1 - 1 \quad \ldots\ldots \text{Eq } 20.032.6$$

20.032.7 The thickness ratio of hoop to helical windings may now be determined by using Eqs 20.032.5b and 20.032.6.

20.033 Another approach to determining the ratio of helical to hoop windings may be applied.

20.033.1 This approach is based on the number of layers, L, required in each direction, and upon the fiber strengths as determined by test. Such an attack to the problem removes the difficulties inherent in attempting to measure the thicknesses of a number of different helical layers as required in the previous results.

20.033.2 The strength of a layer of helically wound fibers is given by:

$$F_s = \frac{\pi}{4}(d)^2 \sigma f A \quad \ldots\ldots\ldots\ldots \text{Eq } 20.033.2a$$

where:

F_s = Force per inch of width

d = Diameter of reinforcing filament

σ = Strength of reinforcing filament

L = No. of layers of reinforcing filament

f = No. of filaments per strand

A = No. of strands per inch per layer

Note: subscript indicates which helical system considered.

Assuming that the number of strands per inch per layer is the same, the force in the direction of the fiber for all layers with the same helix angle is:

$$\sigma_1 t_1 = F_s L_1$$

$$\sigma_2 t_2 = F_s L_2 \quad \ldots\ldots\ldots\ldots \text{Eq } 20.033.2b$$

20.033.3 Substitution of Eq 20.033.2b into Eq 20.032.5a and noting that L_1 designates the helical system and L_2 the hoop system results in:

$$2F_s L_1 \cos^2\alpha_1 = F_s L_1 \sin^2\alpha_1 + F_s L_2. \quad \text{Eq } 20.033.3a$$

$$\frac{L_2}{L_1} = \frac{L_{Hoop}}{L_{Helix}} = 2\cos^2\alpha_1 - \sin^2\alpha_1 = 3\cos^2\alpha_1 - 1. \quad \ldots \text{Eq } 20.033.3b$$

20.033.4 Eq 20.033.3b may be used in a fashion similar to Eq 20.032.6. However, the results are in terms of the ratio of the number of layers required in each direction rather than the thicknesses of those layers.

20.033.5 To determine the required number of layers to resist a given applied force, the strength of the layers in the direction of the applied force is equated to that force. For a pressure vessel, in the longitudinal direction, for instance, the number of helical layers may be determined from

$$\frac{pD}{4} = \frac{\pi}{4}(d)^2 \sigma f A L \cos^2\alpha_1 \qquad \text{or}$$

$$L_{Helix} = \frac{pD}{\pi d^2 \sigma f A \cos^2\alpha_1} \quad \ldots\ldots \text{Eq } 20.033.5$$

20.033.6 When Eq 20.033.5 is used in conjunction with Eq 20.033.3b, the required number of layers in each direction, both helical and hoop, may be computed. Only the physical dimensions and properties of the fibers need be known and an appropriate helix angle selected.

20.034 When several helical systems are used, the solution may be approached by extrapolating beyond Eqs. 20.031.1 and 20.031.2.

20.034.1 It has been assumed in the previous analyses that each layer of fibers acts independently. Therefore, their contributions to strength will be additive. For several layers in a pressure vessel, then, the total hoop force, F_H, may be expressed by the general expression indicated as Eq 20.034.1a below:

$$F_H = \Sigma(\sigma_1 t_1 \sin^2\alpha_1 + \sigma_2 t_2 \sin^2\alpha_2 \ldots\ldots\ldots + \sigma_n t_n \sin^2\alpha_n). \quad \text{Eq } 20.034.1a$$

In like manner, the total logitudinal force, F_L, may be expressed by the general expression indicated as Eq 20.034.1b below:

$$F_L = \Sigma(\sigma_1 t_1 \cos^2\alpha_1 + \sigma_2 t_2 \cos^2\alpha_2 . . . . + \sigma_n t_n \cos^2\alpha_n) . . \text{Eq } 20.034.1b$$

20.04 Derivation of Design Formulas

The foregoing analyses result in a number of formulas applicable to the design of filament wound pressure bottles. Additional approaches and different loading conditions are currently being studied and will be added to this section in the future.

20.05 Helpful Stress Analysis Charts

20.06 Special Considerations

20.036.1 When loading conditions become more complicated, or other circumstances of use more complex, it is still necessary to predict the potentialities of the structure. In these situations, strength tests of a model or prototype of the proposed structure are invaluable. The netting concept of analysis becomes less valuable in such cases, and an evaluation of the test results in most advantageously carried out on the assumption that the actual netting structure is homogeneous. Such an approach will enable the overall properties of the model to be determined.

20.036.2 One of the complexities of loading commonly encountered is that produced by concentrated loads. In general, this type of loading should be avoided in filament-wound structures since it causes areas in which the stress is increased over the stress caused by internal pressure alone. Where concentrated loadings cannot be avoided, every effort should be made to apply them in an axial direction at the polar fitting or fittings, or introduce them to the filament-wound structure as a uniformly distributed circumferential load.

20.036.3 Another complexity occurs when local layers of additional material are inserted in a filament wound structure. When a balanced netting system has been used as a pressure vessel under these circumstances the additional localized material increases the stiffness of the structure in that area and as a result the maximum strain is reduced. If the elastic properties of the local reinforcement are similar to those of the complete pressure vessel, it is apparent from a consideration of the strains, that the reinforcement cannot be over stressed. However, the locally stiff region will generate secondary bending stresses in the adjacent shell as it adjusts its strain to accommodate the discontinuity in strain pattern produced by the stiffer area of local reinforcement.

21.0 FILAMENT WINDING, CLASS F II

Bottles with end ports.

21.01 Physical Description

21.011 Filament Winding, Class F II includes wound pressure vessels with openings in either or both ends.

21.012 See Class F I, Section 20.01.

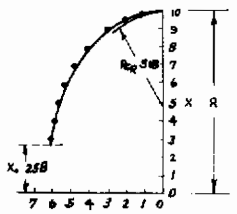
21.02 Stress Analysis Discussion

21.021 In the early designs of filament wound pressure vessels that included end closures as an integral part of the winding, the end domes were made hemispherical. Unfortunately, the hemispherical configuration produced changes in the stress along the length of a helically wound filament as the path of the filament progresses from the end of the cylinder to the pole of the hemisphere. These changes in stress must be carried by the matrix and cause a weakened structure. The result of such an end closure is to destroy the balanced design since a greater number of windings are required in the dome than are required in the cylinder to carry the same internal pressure. The helical windings are necessarily continuous over both cylinder and end dome, and use of a hemispherical end closure increases the weight of the cylindrical portion beyond the weight necessary to carry its share of the load.

21.022 To minimize the unbalanced design inherent in the spherical end dome, the elliptical or ovaloid shape has been developed. Two approaches have been made to this type of shape.

21.022.1 In the first, a geodesic path has been chosen for the filament with the result that the fiber is capable of carrying both the longitudinal and hoop stresses at each point along its path. Such a path orients the fiber to the axis of the cylinder by a continuously varying angle. This solution produces what has been called the "geodesic ovaloid" profile, and a typical one is dimensioned in Table 21.022.1. It has been derived using an analytical approach.

TABLE 21.022.1 GEODESIC OVALOID PROFILE, $\alpha = 15^{\circ}$



X	Y
1.00	0.0
0.99	0.10144
0.96	0.20044
0.90	0.30917
0.80	0.4188
0.70	0.4904
0.60	0.5004
0.50	0.5756
0.40	0.6004
0.30	0.618

21.022.2 In the second solution to the problem, the winding is done at low helix angles, as low as 4°, and these angles remain constant throughout. The fibers, in this case, are oriented in a plane and the solution is a special case of the plane-ovaloid end dome. The fiber orientation is such that it results in zero hoop stress in the fiber but leaves a residual longitudinal stress. This type of end configuration is derived using an analog technique in which a netting of fine threads is constructed by hand around an end closure fitting and fastened with uniform spacing to a circular ring representing the meridian at which the end dome is fastened to the cylindrical portion of the vessel. The threads are wound over an inflated rubber diaphragm in a semi-loose condition. When all the threads are in place the diaphragm pressure is increased and the thread positions recorded, usually by photography. Stereo photography would seem to offer an excellent method for determining the position of the filaments.

21.03 Fundamental Stress Formulas

21.031 To develop the basic equation for the geodesic ovaloid end dome, two procedures are available: one is analytical and the other is semi-graphical. In both approaches, the helix angle, α, is controlled by the diameter of polar-opening required. This diameter-helix angle relationship is given in Table 21.031.

TABLE 21.031

Helix Angle, α	Ratio of Polar-Opening Diameter to Cylinder Diameter
5	0.087
10	0.173
15	0.258
20	0.342
25	0.422
30	0.500

21.032 Analytically, the hoop and logitudinal stresses from the netting analysis presented in Section 20.031 of this manual (Eqs. 20.031.1 and 20.031.2) are equated to the hoop and longitudinal stresses for surfaces of revolution.

21.032.1 From the netting analysis:

$$\sigma_H = \sigma \sin^2\alpha \text{ and } \sigma_L = \sigma \cos^2\alpha$$

21.032.2 For surfaces of revolution:

$$\sigma_H = \frac{p\, r_3}{t}\left(1 - \frac{r_3}{2r_m}\right) \text{ and } \sigma_L = \frac{p\, r_3}{2t}$$

where:

- p = internal pressure
- r_3 = radius of curvature of the dome perpendicular to the meridian line.
- r_m = radius of curvature of the dome in the direction of the meridian
- t = thickness of dome material

Note: r_3 = R where dome joins cylinder.

21.032.3 Combining the foregoing expressions will result in the following:

$$\sigma_H = \sigma \sin^2\alpha = \frac{p\, r_3}{t}\left(1 - \frac{r_3}{2r_m}\right)$$

$$\sigma_L = \sigma \cos^2\alpha = \frac{p\, r_3}{2t}$$

$$\frac{\sigma_H}{\sigma_L} = \tan^2\alpha = 2 - \frac{r_3}{r_m} \quad \text{. . . . . . . Eq 21.032.3}$$

21.04 Derivation of Design Formulas

21.041 To develop the general equations of the end dome profile the nomenclature shown in Fig. 21.041 is needed. This figure illustrates the contour of the end dome and details a small element along the meridian at point a (x, r). In this figure and the equations developed therefrom, the following notation is used.

- R = radius of cylinder
- θ = angle r_m and r_3 make with vertical coordinate axis
- x,r = coordinates of point a
- r_3 = radius of curvature of end closure perpendicular to meridian at point a
- r_m = radius of curvature of meridian at point a

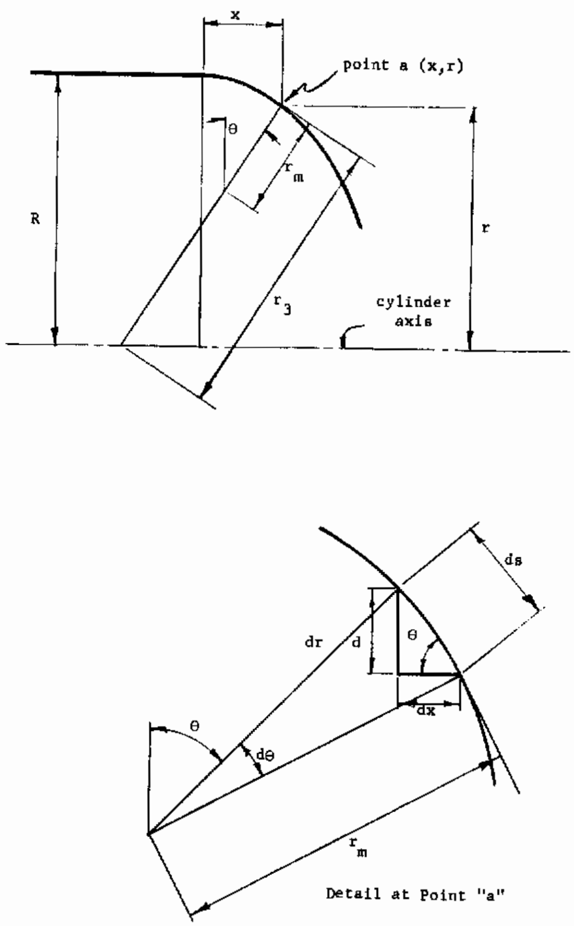


FIG 21.041 END DOME PROFILE

21.041.1 Utilizing Fig. 21.041, the following relationships evolve:

$$r = r_3 \cos\theta \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \text{ Eq 21.041.1a}$$

$$\frac{dr}{dx} = -\tan\theta \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \text{ Eq 21.041.1b}$$

$$ds = r_m\, d\theta \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \text{ Eq 21.041.1c}$$

$$\frac{dx}{ds} = \cos\theta \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \text{ Eq 21.041.1d}$$

21.041.2 To find the coordinate, r, of the point a (x, r), Eq 21.041.1c and d are used:

$$\left(\frac{ds}{d\theta}\right)\left(\frac{dx}{ds}\right) = \frac{dx}{d\theta} = r_m \cos\theta$$

or: $$\frac{d\theta}{dx} = \frac{1}{r_m \cos\theta}$$

Multiplying by r:

$$r\,\frac{d\theta}{dx} = \frac{r}{r_m \cos\theta} = \frac{r_3}{r_m}$$

From Eq 21.041.1b:

$$dx = -\frac{dr}{\tan\theta}$$

or: $$r\,\frac{d\theta}{dx} = -r\tan\theta\,\frac{d\theta}{dr}$$

and from Eq 21.032.3:

$$\frac{r_3}{r_m} = 2 - \tan^2\alpha$$

or: $$-r\tan\theta\,\frac{d\theta}{dr} = 2 - \tan^2\alpha$$

$$\frac{dr}{r} = -\frac{\tan\theta}{2-\tan^2\alpha}\,d\theta$$

If the expression $-\dfrac{\tan\theta}{2-\tan^2\theta}$ is taken as a function of θ [F(θ)], using the following procedure will result in Eq 21.041.2 below.

$$\frac{dr}{r} = F(\theta)d\theta$$

$$\ln(r) = \int_0^\theta F(\theta)d\theta + \ln c$$

$$\ln\left(\frac{r}{c}\right) = \int_0^\theta F(\theta)d\theta$$

Realizing that at θ = 0, r = R and therefore c = R in the above:

$$\ln\left(\frac{r}{R}\right) = \int_0^\theta F(\theta)d\theta \; . \; . \; . \; . \; . \; . \; . \; . \; . \text{ Eq 21.041.2}$$

21.041.3 The results represented by Eq 21.041.2 may be expressed in another form by letting a equal the integral portion:

$$a = \int_0^\theta F(\theta)d\theta \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \text{ Eq 21.041.3a}$$

then:

$$r = Re^a \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \text{ Eq 21.041.3b}$$

21.041.4 The other coordinate of the point (x, r) is found by using Eq 21.041.1b and the results just obtained:

$$dx = -\frac{dr}{\tan\theta}$$

and since $r = Re^a$

$$dr = Re^a\,[F(\theta)]\,d\theta$$

$$dx = \frac{(-Re^a)\,F(\theta)d\theta}{\tan\theta}$$

Integrating and noting that x = 0 when θ = 0:

$$x = -R\int_0^\theta \frac{e^a F(\theta)d\theta}{\tan\theta} \; . \; . \; . \; . \; . \; . \; . \text{ Eq 21.041.4}$$

21.041.5 Eqs 21.041.3b and 21.041.4 may be integrated (within certain limits of initial helix angle and θ) using Simpson's Rule and a computer if at all times Eq 21.032.3 is satisfied. For the simplest case, when α = 0, the expressions for r and x may be reduced to a more manageable form. To find an expression for r under these conditions, it is noted that F(θ) becomes = $-(\tan\theta)12$ since $\tan^2\alpha = 0$. Therefore:

$$\ln\left(\frac{r}{R}\right) = -\int_0^\theta \frac{\tan\theta d\theta}{2} = +\frac{1}{2}\ln\cos\theta$$

or: $$r = R\sqrt{\cos\theta} \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \text{ Eq 21.041.5a}$$

Taking Eq 21.041.4 for x and substituting for F(θ) as before:

$$x = -R\int_0^\theta e^a\left(-\frac{\tan\theta}{2}\right)\frac{d\theta}{\tan\theta} = \frac{1}{2}\int_0^\theta Re^a d\theta$$

or: $$x = \frac{1}{2}\int_0^\theta r\,d\theta = \frac{R}{2}\int_0^\theta (\sqrt{\cos\theta})\,d\theta \; . \; . \; . \; . \; . \text{ Eq 21.041.5b}$$

21.041.6 Eqs 21.041.5a and b define a surface of revolution that has the property of zero stress in the hoop direction. This surface was developed forty years ago by Mr. G. I. Taylor for the design of a parachute. He felt that a parachute on the verge of wrinkling between cords (zero hoop stress) would provide the minimum weight of material. These equations are more readily soluable than the general ones previously derived.

21.042 Further discussion of Eqs 21.041.3b and 21.041.4 is necessary to clarify their application to the design of a dome profile when angle $\alpha > 0$. For any of those cases, $F(\theta)$ becomes difficult to express precisely since it is a function of α, and α varies over the dome surface. This difficulty may be resolved approximately by writing empirical expressions for $F(\theta)$ or otherwise determining its value at selected points on the surface. When the helix angle, α, of the cylindrical portion is small, the analog technique based on a zero hoop stress configuration for determining values of α and θ around the dome is satisfactory. $F(\theta)$ may then be computed for each set of values and numerical methods of integration may be used on Eqs 21.041.3b and 21.041.4.

21.05 <u>Helpful Stress Analysis Charts</u>

0.0 INTRODUCTION

0.01 Purpose of Manual

0.011 The general purpose of this Manual is to present various processes and fabrication methods as they are used in the reinforced plastics industry. Included will be discussions of procedures, methods, equipment, effects and, where possible, details of the foregoing.

0.012 The primary objective is to provide general background information on the processes used in fabricating structural plastics parts. The first edition of this Manual presents only general discussions of various basic processes and their variations. Future editions will add specific information on particular methods used by various concerns.

0.013 The information included herein has been developed from reviewing literature, formal and informal, industry published data, and personal visits to a majority of the reinforced plastics fabricators.

0.02 Identification Code

0.021 For the purposes of organization and cross referencing the information presented in this Manual is divided into sections as indicated in the Table of Contents which follows.

0.022 Each section is coded to identify the process category involved. The titles indicated in the Table of Contents will clarify this procedure.

0.023 In future editions, specific detailed methods will carry the process category code plus an identifying number or letter.

0.03 Contents of Manual IF

0.031 This Manual is divided into sections as follows:

Section No.	Subject
0.0	INTRODUCTION
1.0	PROCESS CODE CM Contact Molding
10.0	PROCESS CODE B Bag Molding
11.0	PROCESS CODE VB Vacuum Bag Molding
12.0	PROCESS CODE PB Pressure Bag Molding
17.0	PROCESS CODE AB Autoclave Bag Molding
20.0	PROCESS CODE PM Press Molding
21.0	PROCESS CODE PM-C Press Molding-Contact Pressure
22.0	PROCESS CODE PM-S Press Molding-Against Stops
23.0	PROCESS CODE PM-H Press Molding-High Pressure
27.0	PROCESS CODE CPM Continuous Press Molding
40.0	PROCESS CODE W Winding Process
41.0	PROCESS CODE FW Filament Winding
45.0	PROCESS CODE RW Roving Winding
48.0	PROCESS CODE TW Tape Winding
60.0	PROCESS CODE C Sandwich Cores
90.0	PROCESS CODE S Sandwich Parts
100.0	MACHINING
150.0	FINISHING

0.032 Only the general discussions on contact molding, bag molding and pressure molding are included in this first edition. However, the Table of Contents will indicate future expanded coverage.

0.033 Each Section of this Manual which covers a Process is sub-divided into major subjects as follows using Section 2.0 as an example:

Paragraph	Subject
2.0	SECTION TITLE
2.01	General
2.011	General Description
2.012	Applications
2.013	Advantages and Disadvantages
2.02	Materials Used
2.021	Release Agent
2.022	Gel Coat
2.023	Resin
2.024	Reinforcement
2.025	Premix
2.026	Prepreg
2.027	Precured
2.03	Equipment Used
2.031	Lay-Up
2.032	Molds
2.033	Pressure
2.034	Temperature
2.035	Other
2.04	Process Description
2.041	Lay-Up
2.042	Pressure and Temperature
2.043	Curing
2.044	Other
2.05	Finishing
2.051	Trimming
2.052	Machining
2.053	Surfacing
2.054	Coloring
2.055	Attachments

0.034 It will be noted that for each process category one paragraph number will always indicate the same subject. This will facilitate use of the Manual.

0.035 For complete Table of Contents for the entire Handbook see Manual 1A.

0.04 Abbreviations and Glossary

0.041 In cross referencing the process identification code to other Manuals, particularly IC and ID, it will be noted that additional information is given along with the process category. Several examples follow which will clarify this procedure.

0.041.1 Example 1 from Manual ID, PolGc, Fig. 3.034.4:

Process: PM, 15 psi, 30 min, 220F + 3 hrs, 500F

PM	=	Process Category (press molded)
15 psi	=	Applied pressure
30 min	=	Time at pressure
220F	=	Temperature during pressure
+	=	Additional cure at pressure
3 hrs	=	Time for additional cure
500F	=	Temperature for additional cure

0.041.2 Example 2 from Manual ID, Po2Gc, Fig. 3.043.1:

Process: PM, psi indicated, 30 min, 176-248F + PC, 24 hr, 350F

PM	=	Process Category (press molded)
psi indicated	=	Applied pressure is indicated elsewhere in data
30 min	=	Time at pressure
176-248F	=	Temperature during pressure, in this case given as an allowable range.
+ PC	=	Additional post cure without pressure
24 hr	=	Time of post cure
350F	=	Temperature of post cure

0.041.3 In some cases additional information is given such as percent of additives or curing agents or lay-up procedure, for example: XL = cross laminated in contrast to normal parallel laminated.

0.042 Certain terminology is used in subsequent discussions which is considered as standard, known, or understood from context. Where appropriate, these are defined in the text.

0.043 For complete listing of all abbreviations and definitions used throughout this Handbook, see Manual IA.

0.05 Information Sources

0.051 Where particularly important, the information source is footnoted directly within the text or figure involved.

0.052 A general bibliography of pertinent reference works used in compiling this Manual includes the following more important items.

1. Anonymous, "Technical Data on Plastics", Manufacturing Chemists' Association, Inc., Washington, D. C. (1957).
2. Anonymous, "Polyester Handbook", Scott Bader and Co., Ltd., London W.C. 2 (1959).
3. Duffin, D. J., "Laminated Plastics", Reinhold Publishing Corporation, New York (1958).
4. Golding, B., "Polymers and Resins", D. Van Nostrand Company, Inc., New Jersey (1959).
5. Lawrence, R. J., "Polyester Resins", Reinhold Publishing Corporation, New York (1960).
6. "Modern Plastics Encyclopedia Issue for 1963", Modern Plastics, New York (September 1962).
7. "Plastics Engineering Handbook", Reinhold Publishing Corporation, New York (1960).
8. Numerous personal contact visits and conferences.

0.53 A complete source index is given in Manual IA.

1.0 PROCESS CODE CM

Contact Molding

1.01 General

1.011 General Description. Contact molding was developed in the late 1940's and has been referred to as Wet Lay-Up Process, Single Mold Process, Open Mold Fabrication and Hand Lay-Up Molding. The term "contact molding" suggests fabrication of reinforced plastic articles without the use of pressure, the use of heat being optional. The reinforcement is laid in the mold by hand or spray techniques and is generally composed of cloth, chopped fibers, or glass mat, either pre-impreganted with resin or untreated. If untreated, it is wetted with a liquid resin applied with a brush, spatula, or spray gun. The filler is rolled or otherwise worked by hand to remove entrapped air and to ensure intimate wetted contact between fibers, filler and mold surface. The molding is then allowed to cure at room temperature or by the application of mild heat. Figure 1.011 illustrates a contact molding before and after cure. Contact molding may be sub-categorized into two processes based on the method of lay-up namely: Hand Lay-Up and Spray Lay-Up. Subsequent articles in this section will clarify this.

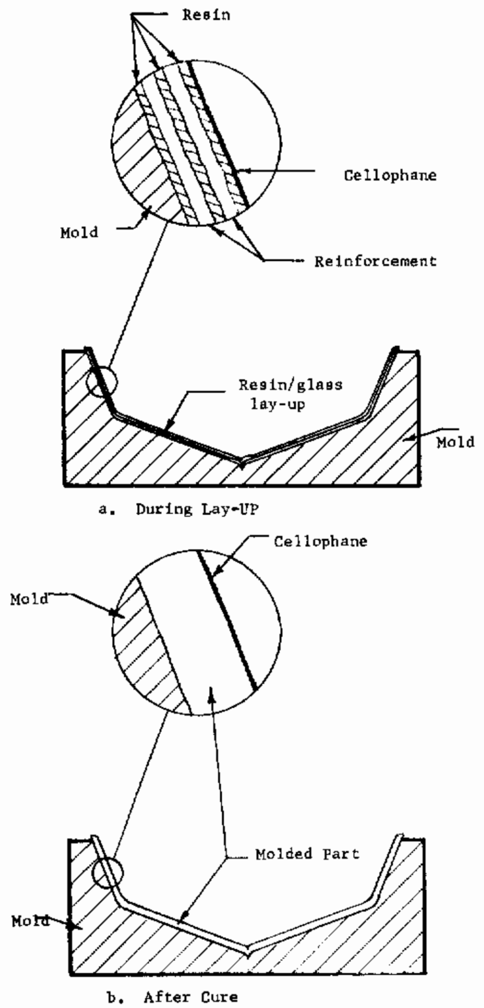


FIG. 1.011 TYPICAL CONTACT MOLDING BEFORE AND AFTER CURE (Owens-Corning Fiberglass Corp.)

1.012 Applications. The contact molding of reinforced plastics is widely used in the manufacture of boats, ranging from 6-ft. dinghies to 40-ft. auxiliary sailboats. An increasingly large percentage of the total outboard motor boat market now involves plastic boats fabricated from polyester resin reinforced with glass fiber materials. Additional applications include radomes, furniture, swimming pools, storage tanks, and aircraft components. Contact molding is, perhaps, the most widely used process in the reinforced plastics industry today.

1.013 Advantages and Disadvantages

1.013.1 Advantages. Contact molding is one of the simplest processes for manufacturing reinforced plastic parts. Minimum equipment is required since critical pressures, temperatures and time cycles are excluded. Hence, tooling costs may be kept at a minimum, particularly for production runs on a limited number of parts. To minimize the disadvantage of excessive "handling" involved, increasing use is being made of preformed reinforcement, pre-impregnated reinforcement, spray-up techniques and the like.

1.013.2 Disadvantages. As indicated above, disadvantages become apparent when a production run of a large number of parts is involved. An economic point is usually reached where it is more advantageous to use some form of press molding or bag molding when "mass production" becomes necessary. From the standpoint of structural parts several major disadvantages become apparent. These include: poor dimensional accuracy, low strength due to the relatively high ratio of resin to reinforcement necessary, and difficulty in maintaining uniformity throughout the part.

1.02 Materials Used

1.021 Release Agent

1.021.1 To prevent the finished part from sticking to the mold, a suitable release agent is required.

1.021.2 Criteria for selection of the release agent include:

a. Ease of application,
b. Uniformity of coverage,
c. Compatability with mold, and
d. Compatability with plastic part.

1.021.3 Colored release agents are often used to assist in distinguishing potential weaknesses in the coating.

1.022 Gel Coat

1.022.1 To impart certain desirable characteristics to the surface of the finished part, a gel coat is often applied to the working surface of the mold prior to placing the reinforcement and resin. During processing this gel coat, usually a resin and filler compatable with that being used for the molding, becomes an integral part of the surface of the finished product.

1.022.2 A gel coat is used to provide one or a combination of several features:

a. A tough abrasion-resistant surface to prevent fibers from blooming on the surface,
b. A continuous colored surface that suppresses fiber pattern and needs no further finishing, and
c. A surface with special chemical, weathering, impact or other properties.

1.022.3 Criteria for selection of the gel coat include:

a. Ease of application,
b. Uniformity of coverage,
c. Compatability with materials used in finished product, and
d. Intended surface design requirements.

1.022.4 Gel coats are usually kept as thin as possible (10 to 20 mils) to avoid unbalanced construction and excessive brittleness on the outside of the molding.

1.022.5 On more simply curved surfaces, a fine textural material, such as glass fiber surfacing tissue, synthetic fabric or even paper, can be used to form the first ply of the molded part in place of a gel coat. However, it is difficult to uniformly apply such materials to complex shapes.

1.023 Resin

1.023.1 The requirements of the resin system for use in contact molding will vary somewhat to conform to the particular handling problems involved and the desired physical properties of the finished product. The following basic characteristics generally apply to all contact molding operations:

a. Liquid Characteristics. Low to medium viscosity with some thixotropy if hang-up on vertical surfaces is required.
b. Curing Characteristics. Room temperature gel in 15 minutes to 2 hours with subsequent fast development of hardness at room temperature or slightly elevated temperature. If carried out solely at room temperature, final cure may develop over a period of several days.
c. Cured Properties. Semirigid to rigid with no variation in properties or appearance over the entire surface of the molding. In some cases tack-free cure of air-exposed surfaces is desired.

1.023.2 Resin may be used as commercially available in various liquid or dry forms, or may be applied as part of a prepreg material, etc.

1.023.3 For structural applications, polyester resins are most commonly used in contact molding parts. However, other thermoset resins are certainly applicable.

1.024 Reinforcement

1.024.1 The requirements of the reinforcement system for use in contact molding will vary considerably to conform to the particular handling problems involved and the desired shape and physical properties of the finished product. The following basic characteristics generally apply to all contact molding operations:

a. Drapability, the ability of the reinforcement to uniformly conform to the shape of the mold,
b. Wetability, the ability of the reinforcement to thoroughly "wet out" or absorb the resin assuring complete surface coverage of each fiber, and
c. Uniformity of distribution of reinforcement throughout the finished part.

1.024.2 Commercially available reinforcements may be applied in dry condition or pre-impregnated with resin or in various preform or premix conditions. Since the use of "preformed" reinforcement is more common in the various processes involving pressure, it is discussed in detail under these.

1.024.3 For structural applications, glass reinforcing in such forms as cloth, chopped fiber, mat, etc. are most commonly used in contact molding. However, asbestos reinforcing has been used and fibrous graphite is under experimentation.

1.025 Premix. Mixtures of resin and reinforcement combined immediately prior to placement in the mold may be used under certain circumstances. However, these are far more common in the various processes involving pressure and are discussed in detail under these.

1.026 Prepreg. Although not usually encountered in contact molding processes, "prepreg" materials may, under certain circumstances, be used. Since they are more applicable to processes involving pressure, they are discussed in detail later in this Manual.

1.027 Precured. Not applicable.

1.028 Others. Certain additives may be used in the contact molding process to impact desired characteristics such as color, durability, temperature resistance, and the like, to the finished product, or to influence cure or other phases of the production. These will depend entirely on the basic materials used and the desired results. The important thing to realize is that such additives do increase the flexibility inherent in "tailor making" reinforced plastic parts.

1.03 Equipment Used

1.031 Lay-Up. Lay-Up, or placement of materials in the mold, can be accomplished in two ways for contact molding, by hand or by spray techniques. The equipment involved will be dependent on the method used.

1.031.1 Equipment necessary for Hand Lay-Up of contact molded parts is quite minimal and normally includes such small items as: resin containers; resin applicators such as brushes, spatulas, rollers, etc.; reinforcement trimmers; and protective equipment such as gloves, aprons, and, possibly, glasses. If preformed reinforcement is used, appropriate racks will be required to adequately support the preforms prior to placement in the molds.

1.031.2 Equipment necessary for Spray Lay-Up of contact molded parts is relatively more complicated. The single important item here is the "spray gun". A number of these are commercially available and range in complexity from simple "guns" to spray resin on previously placed reinforcement to dual headed "guns" which simultaneously spray resin and chopped fiber reinforcement in predetermined ratios into the mold. Auxiliary equipment includes material storage tanks or bins and the like. Protective equipment is the same as for Hand Lay-Up except emphasis should now be placed on the use of glasses and gloves.

1.032 Molds. Contact molding involves the use of only one mold which can be either male or female according to which face of the finished part is required to be smooth. The mold is made from a wooden, metal or plaster prototype, and can be fabricated from any material of sufficient rigidity to maintain the shape of the molding during impregnation and curing. Wood, plaster, concrete, metal and reinforced plastics are all being used successfully. Porous materials, however, must be properly sealed. The working surface of the mold should be finished as smoothly as possible, since any imperfection will be evident on the surface of the final molding.

1.033 Pressure. Not applicable.

1.034 Temperature. Contact molding sometimes incorporates the use of heat to accelerate the curing process. The equipment commonly used is a standard oven usually of the circulating warm air variety. In certain application of this process, it may be desirable to use heated molds. These usually involve electrical heating elements or circulating hot water or steam piping built into the body of the mold itself or affixed thereto.

1.035 Others. Other equipment which may be necessary includes jigs or forms to hold the laminated part in shape after removal from the mold and during curing, transport and storage equipment, etc.

1.04 Process Description

1.041 Lay-Up

1.041.1 Hand lay-up. Before the hand lay-up laminating process begins a coat of release agent is spread evenly over the entire mold surface by spray, brush or sponge. Care should be taken since the molding may stick to any part of the mold surface not coated by release agents. The use of a colored release agent will help in distinguishing weaknesses in the film.

Next the gel coat is applied by either brush or paint roller. Besides being able to stand up under the service intended, the gel coat must also handle properly during application. This is necessary to obtain an easily applied uniform coating which can be built-up to a thickness of 10 to 20 mil. The gel coat resin mixture should be allowed to stand for a few minutes prior to use to permit the escape of entrapped air bubbles. To ensure proper adhesion the laminating process should be started as early as practical after the gel coat has hardened sufficiently.

Previously cut glass mat or tailored glass cloth is placed in position on the mold prior to application of the resin solution. It is important to maintain a resin-to-glass ratio which has been found to give satisfactory performance. This is generally accomplished by using measured quantities of glass and resin rather than arbitrary addition of resin until the glass becomes completely saturated. The latter procedure leads to an excess of resin and, consequently, lower strength. On female molds, it is best to apply a liberal coat of resin first thus helping to keep the mat in position and also forcing air away from the mold surface.

The best method of applying the resin is by a stippling action with a saturated brush. Various spraying techniques can also be used, but since they are not always entirely satisfactory it is inadvisable to use these before the hand lay-up technique has been mastered. The impregnation of the glass reinforcement should be thorough and must always be followed by rolling with a suitable roller, preferably transversely ribbed. This consolidates the glass fiber and forces air bubbles, which will weaken the final molding, out of the resin. As many layers of glass mat as necessary can be laminated in this way, each layer being rolled individually. It will usually be found that the final layer can be placed in position and rolled without the addition of extra resin, since the rolling action will force sufficient resin out of the laminate to impregnate this layer. Excess resin on the surface should always be avoided. Where the reverse surface of a component will be visible and some improvement in the appearance is required, the final ply can be a glass surfacing tissue. Alternatively, it can be flock sprayed.

1.041.2 Spray lay-up. The most recent innovation in contact molding is the use of dual spray guns for the application of the resin. Separate mixes of catalyzed and accelerated resin are combined in the gun, or just after they leave it, to yield very fast gel times on the work with no concern for short pot life. Some of these resin guns are used with glass choppers for simultaneous or separate application of glass fibers directly to the mold surface in a random pattern. This method of applying glass offers considerable possibilities for saving money by using glass roving (considerably cheaper than glass mat); by eliminating the wastage of time and material required to tailor preformed mat to fit contoured sections; and by reducing the loss of room temperature curing resin mixes which gel before they can all be used. As with hand lay-up, however, application of the release agent and often a gel coat is necessary. See Section 1.041.1 for discussion of these.

1.042 Pressure and Temperature. Contact molding does not involve the simultaneous application of pressure and temperature.

1.043 Curing. Curing can often be accelerated by the use of external heat or by means of heating elements built into the mold. Once the resin has set the molding can be removed from the mold and left to cure. This step can be carried out either at room temperature, which will take up to four weeks, or at 80 C for about two hours in an oven. In the latter case, it is generally necessary to age the molding for at least 24 hours at room temperature before placement in the oven. To prevent warping it may be necessary to hold large moldings in some simple jig while they cure. To minimize warping, laminates should be of a balanced construction.

1.044 Other

1.05 <u>Finishing</u>

It is not one of the objectives of this first edition to cover this topic fully.

1.051 Trimming

1.052 Machining

1.053 Surfacing. The use of gel coats and plies of surface tissue, etc., have been previously described. It is important to realize that virtually any surface texture or configuration may be obtained with contact molding.

1.054 Coloring. The final molding can be painted with any of the usual surface coating finishes after all traces of release agent have been removed. It is often worthwhile to incorporate a pigment in the resin, however too much pigmentation may result in and inferior molding.

1.055 Attachments.

10.0 PROCESS CODE B

Bag Molding - General

10.01 General

10.011 General Description. Bag molding follows the procedure used in contact molding (See Section 1.0) except that pressure is exerted upon the wet lay-up by means of a flexible bag. The pressure can be generated by either application of vacuum or positive pressure to the bag. Bag molding was developed to help over come some of the inherent difficiencies of the contact molding process, namely to improve strength and accuracy and to reduce curing time. Although a more complex method requiring particular equipment, this method has wide spread economical use. Bag molding may be sub-categorized into three processes based on the method of applying the pressure, namely: Vacuum Bag, Pressure Bag and Autoclave Bag. Because of the relative importance and use of each of these methods, the specifics of each will be discussed under separate section codes VB, PB and AB respectively. The following writeup in this section will describe the general method of bag molding as involved in all three methods.

10.012 Application. Bag molding of reinforced plastics is widely used in the manufacture of automobile bodies and parts, aircraft and aerospace craft components, boats, ductwork, tanks and prototype molds. In specific regard to the aerospace industry, bag molding is perhaps a more commonly used process than contact molding because of its basic advantages over the latter.

10.013 Advantages and Disadvantages

10.013.1 Advantages. Next to contact molding, bag molding is perhaps the simplest process for manufacturing reinforced plastic parts. Due to the use of pressure (negative or positive), structural parts of much higher strength and lower weight are possible. Furthermore, larger parts become practical by this method. The reduction in weight often reduces or even eliminates the need for expensive material handling equipment. Again, the use of pressure permits the manufacture of parts virtually unlimited in shape and contour. A further advantage over contact molding is a greater uniformity of finished part coupled with higher production rates. The use of preformed or preimpregnated reinforcement is almost universal in bag molding. Greater dimensional accuracy and uniformity throughout the finished part are also advantages when compared to contact molding.

10.013.2 Disadvantages. Bag molding does involve more equipment investment than contact molding although this is still considerably less than for the various press molding methods. Also, bag molding is, perhaps, more difficult to master and requires more accurate control. Therefore, bag molding usually requires the production of a sufficient number of parts to make it feasible and economical. Although strength, dimensional accuracy and uniformity are greatly improved, these are still not as good as those obtained with the various pressure molded techniques.

10.02 Materials Used

10.021 Release Agent. Comparable to that for contact molding. See Section 1.021. Common release agents used in bag molding include wax, silicone compounds or film forming types.

10.022 Gel Coat. Comparable to that for contact molding. See Section 1.022. Gel coats are required in bag molding particularly when the final finish of the end product is of prime importance.

10.023 Resin. Comparable to that for contact molding. See Section 1.023. Since heat is often applied during curing, the need for an accelerated catalyst system maybe eliminated. Although commercially available resins in liquid or dry forms are often used, the use of prepreg materials is more common in bag molding of aerospace vehicle parts. All classes of thermoset resins may be used in bag molding.

10.024 Reinforcement. Comparable to that for contact molding. See Section 1.024.

10.025 Premix. Comparable to that for contact molding. See Section 1.025.

10.026 Prepreg. The use of prepreg materials is becomming by far the most common in both bag and pressure molding processes. Further discussion of prepreg materials will be found in the writeups on press molding.

10.027 Precured. Not applicable.

10.028 Others. Comparable to that for contact molding. See Section 1.028.

10.03 Equipment Used

10.031 Lay-Up. Lay-up, or placement of materials in the mold, is usually accomplished by hand which requires such nominal equipment as that used for contact molding. Since bag molding will commonly involve use of prepreg materials, the lay-up stage will necessitate cutting, trimming and draping (referred to as "taloring") of the material, thereby requiring appropriate tools for same.

10.032 Molds. Bag molding involves the use of only one mold which can be either male or female according to which face of the finished part is required to be smooth. The mold is made from a wooden, metal or plaster prototype, and can be fabricated from any material of sufficient rigidity to maintain the shape of the molding during impregnation and curing. Wood, plaster, metal and reinforced plastics are all being used successfully. However, since hot setting methods are usually employed, metal is the most common mold material. The working surface of the mold should be finished as smoothly as possible, since any imperfection will be evident on the surface of the final molding. Provision for heating the mold electrically or by steam is often made. A very important feature of the mold set-up is adequate provision for clamping the bag (see next section) in place in such a way as to assure a complete seal permitting appropriate application of vacuum or pressure as the case may be.

10.033 Pressure. The most important piece of equipment in bag molding is the bag itself. The bag is usually made of rubber, heavy plastic such as poly vinyl alcohol or similar flexible material which is capable of holding pressure or vacuum. In most cases the bag is actually a single layer of material firmly clamped to the outside edges of the mold. In certain cases the bag may be two layers of material, surrounding the mold, which are sealed together around the perimeter. For applications of pressure, the bag can be one flexible layer permanently attached to a "rigid" layer. Associated with the bag is appropriate equipment to provide and control the vacuum or pressure involved. For production runs, re-use of the bag may be a factor in the selection of material for same.

10.034 Heating. Bag molding often involves heat during curing. This will involve ovens which can be adequately controlled and which will provide uniform heat distribution throughout the part. Circulating hot air ovens are often used. In certain cases provision is made for heating the mold itself with either steam, hot water, or electricity.

10.035 Other. Other equipment which may be necessary includes jigs or forms to hold the laminated part in shape after removal from the mold and during post curing, transport and storage equipment, etc. Storage equipment becomes particularly important if prepreg materials are stocked prior to use in the bag molding process.

10.04 Process Description

10.041 Bag molding is sub-categorized into three processes based on the method of applying the pressure as follows:

VB - Vacuum Bag
PB - Pressure Bag
AB - Autoclave Bag

10.042 Each one of the above processes are described separately in the following sections:

VB - Section 11.0
PB - Section 12.0
AB - Section 17.0

10.05 Finishing. It is not one of the objectives of this first edition to cover this topic fully.

10.051 Trimming

10.052 Machining

10.053 Surfacing. The use of gel coats and plies of surface tissue, etc., have been previously described. It is important to realize that many surface textures or configurations may be obtained with bag molding.

10.054 Coloring. The final molding can be painted with any of the usual surface coating finishes after all traces of release agent have been removed. It is often worthwhile to incorporate a pigment in the resin, however too much pigmentation may result in an inferior molding.

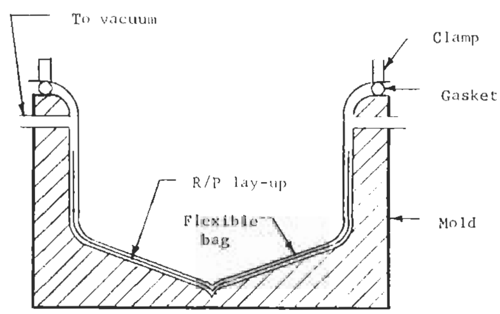
10.055 Attachments

11.0 PROCESS CODE VB

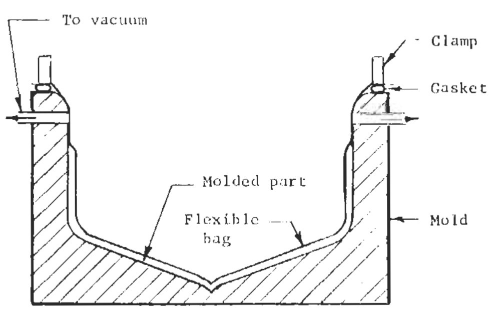
Vacuum Bag Molding

11.01 General

11.011 General Description. Vacuum bag molding is a particular form of bag molding which warrants certain discussion beyond that found in Section 10.01. This form of molding is quite similar to contact molding except that pressure is exerted during cure creating a more intimate contact between the part and the mold and to force out entrapped air. The use of heat is optional. The reinforcement is laid in the mold by hand and is generally composed of cloth, chopped fibers, or glass mat, either pre-impregnated with resin (most common, perhaps) or untreated. If untreated, it is wetted with a liquid resin applied with a brush, spatula, or spray gun. A flexible layer of impervious material is then placed over the molding and sealed around its perimeter. The space between this layer and the part being molded is then evacuated creating a pressure of up to approximately one atmosphere thus removing entrapped air and forcing intimate contact between fibers, filler and mold surface. The molding is then allowed to cure at room temperature or, more often, by the application of heat. Figure 11.011 illustrates a vacuum bag molding before and after application of the vacuum.



a. BEFORE VACUUM APPLICATION



b. AFTER VACUUM APPLICATION

FIG. 11.011 TYPICAL VACUUM BAG MOLDING BEFORE AND AFTER VACUUM APPLICATION (OWENS-CORNING FIBERGLASS CORP.)

11.012 Applications. See Section 10.012. Of the various bag molding techniques, the vacuum bag process is perhaps the most widely used for normal aerospace vehicle parts.

11.013 Advantages and Disadvantages. See Section 10.013.

11.02 Materials Used. See Section 10.02.

11.03 Equipment Used. See Section 10.03.

11.04 Process Description

11.041 Lay-Up. The first step in producing a part by the vacuum-bag method is to make certain that all foreign matter is removed from the mold surface. A release agent is then applied to the mold after which a gel coat may be added when the final finish of the end product is of prime importance. Either a dry or preimpregnated glass reinforcement is now laid in the mold, and sufficient layers placed in plied form to produce the desired thickness. When the reinforcement is dry, each layer can be wetted out individually or the entire complement of resin can be applied after all the layers have been positioned. A "bleeding" material is then placed over the lay-up so that when a vacuum is "pulled" the entrapped air can escape. Fig. 11.041a illustrates placement of prepreg material on a male mold.

FIG. 11.041a A thoroughly saturated ply of glass cloth is applied to the mold.

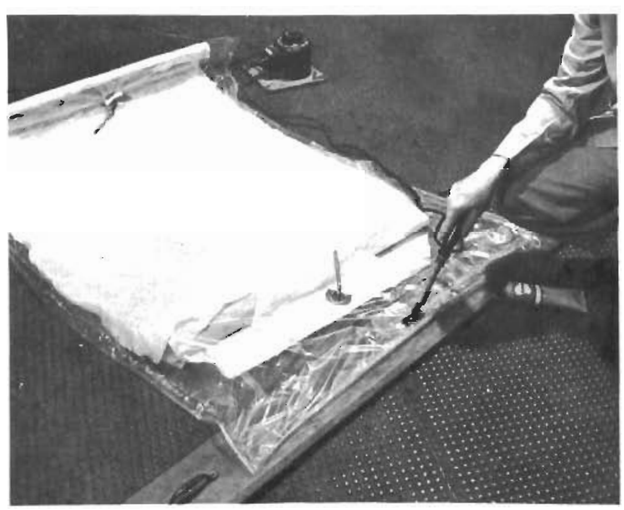


FIG. 11.041b The flexible bag is sealed fully enclosing the laminate and mold. Note the glass cloth "bleeding" layers on the top and bottom and the vacuum connections.

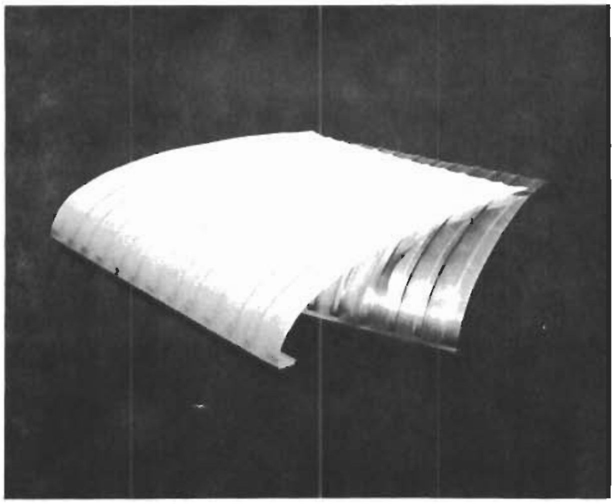


FIG. 11.041c Finished vacuum bag laminate is shown with its mold.

FIG. 11.041 THREE TYPICAL STEPS IN VACUUM BAG MOLDING PROCESS

11.042 Pressure and Temperature. Application of the vacuum is accomplished by placing the bag over the entire lay-up. The edges of the bag are ehld down by a hold-down ring or clamping device, made to the outside dimensions and contours of the mold, which seals off the perimeter of the vacuum bag. It is advisable to have the lay-up end at least 2 inches from the edge of the hold-down ring so that a "land" space exists between it and the ring, allowing the air that is trapped between the lay-up and the bag to escape to the vacuum ports. As an alternate to the above, the bag may entirely envelop the mold and the lay-up as shown in Fig. 11.041b.

A vacuum pump is used to remove air from the layers of reinforcing material, thereby utilizing atmospheric pressure to force the bag down uniformly against the entire surface of the lay-up. The entire lay-up and bag are then placed in an oven at temperatures ranging from 200 to 250°F or allowed to cure at room temperature.

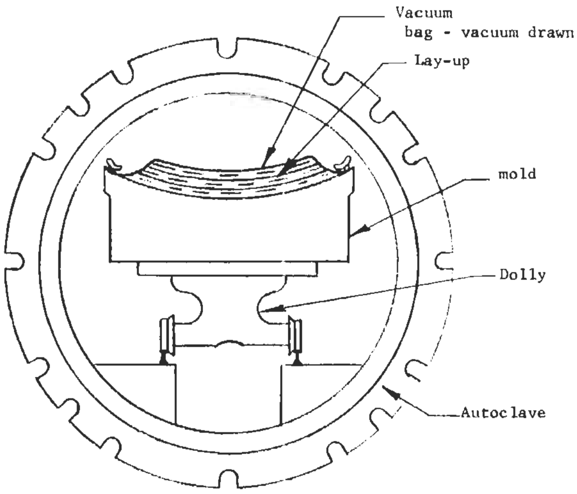


FIG. 11.042 TYPICAL END VIEW OF AUTOCLAVE WITH MOLD AND LAY-UP IN PLACE

11.043 Curing. If a heat-setting catalyst is employed, the oven heat must be used to effect the cure. When the part has been fully cured in accordance with pre-determined curing times and temperatures, the bag is removed and the part is taken from the mold. It has been found advisable to place the part in a second oven at a lower temperature (180°F for about 4 hr) to effect a postcure. Fig. 11.041c illustrates a typical finished part.

11.044 Other. Often the requirements of a part may call for a void-free lamination. To accomplish this the lay-up is hand spackled after the vacuum is applied but before the external heat is applied. The hand spackling helps remove the air and assists in the wetting out of the glass reinforcement. A void-free laminate has been found to possess the qualities of greater compressive and flexural strength. Reinforced plastic parts made to government specifications usually are required to be essentially void-free.

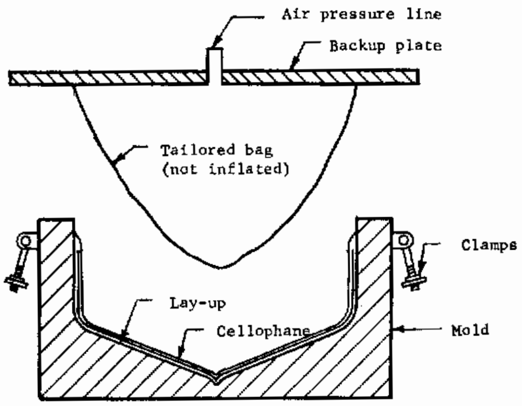
11.05 Finishing. See Section 10.05.

12.0 PROCESS CODE PB

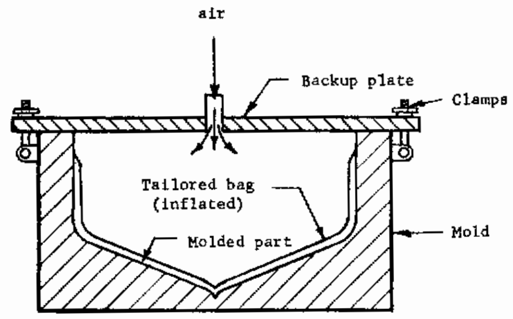
Pressure Bag Molding

12.01 General

12.011 General Description. Pressure bag molding is a particular form of bag molding which warrants a minimum discussion beyond that found in Sections 10.01 and 11.01. This form of molding is the same as vacuum bag molding except that positive pressure is applied via an inflated "bag" mechanism rather than by vacuum. The object of the pressure is, as in VB, to create a more intimate contact between the part and the mold and to force out entrapped air. Again the use of heat during cure is optional. The reinforcement is laid in the mold by hand and is generally composed of cloth, chopped fibers, or glass mat, either pre-impregnated with resin (most common, perhaps) or untreated. If untreated, it is wetted with liquid resin applied with a brush, spatula or spray gun. The "bag", formed by a flexible layer of impervious material, usually attached and sealed to a rigid backup plate, is brought into contact with the part being molded and then inflated. The pressure created, which may be greater than on atmosphere (the practical limit of vacuum bag molding), forces intimate contact between fibers, filler and mold surface. The molding is then allowed to cure at room temperature or, more often, by the application of heat. Figure 12.011 illustrates a pressure bag molding before and after application of pressure.



a. BEFORE PRESSURE APPLICATION



b. AFTER PRESSURE APPLICATION

FIG. 12.011 TYPICAL PRESSURE BAG MOLDING BEFORE AND AFTER PRESSURE APPLICATION (OWENS-CORNING FIBERGLASS CORP.)

12.012 Applications. See Section 10.012.

12.013 Advantages and Disadvantages.

12.013.1 Advantages. See Section 10.031.1. Pressure bag molding permits higher pressures to be used where greater densification than can be developed by vacuum bag methods is required. One definite advantage of pressure bag molding is that a flexible pressure bag may be inserted inside a "closed" part, such as a tank or bottle, and inflated.

12.02 Materials Used. See Section 10.02.

12.03 Equipment Used. See Section 10.03.

12.04 Process Description

12.041 Lay-Up. See Section 11.041. The lay-up procedure for pressure molding is the same as for vacuum bag molding.

12.042 Pressure and Temperature. Application of pressure is accomplished by use of the pressure "bag" in one of three ways which may be classified by the type of bag used as follows: Flexible bag, Semi-flexible bag, and Pillow bag.

The "flexible bag" is fabricated entirely of flexible impervious material tailored to form a "balloon" of shape compatible with the mold when inflated. This method is used with "enclosing" molds which surround hollow parts. The tacky lay-up is placed on the inside surfaces of the mold and the deflated bag inserted in the cavity. When inflated, the bag forces the lay-up outward against the inner surface of the enclosing mold thus forming the tank or bottle type structure. After cure, the bag may be deflated and removed. In some cases, however, the bag may be left in place forming a liner for the inner surface of the part.

The "semi-flexible bag" is fabricated of one layer of flexible material sealed to one layer of rigid material. This is perhaps the most common of pressure bag techniques and is illustrated in Fig. 12.011. The flexible portion is tailored to conform to the shape of the mold. While deflated, the rigid "backing plate" is clamped to the mold perimeter. When inflated, the bag forces the lay-up against the contact surface of the mold.

The "pillow bag" is actually an adaptation of the foregoing. In this case a pillow shaped bag is placed between a rigid backup plate and the mold. On inflation, the bag presses against both the lay-up and the backup place creating the desired pressure. This method is most effective for flat or slightly contoured moldings.

Air pressure is usually used to inflate the bag forcing the lay-up uniformly against the entire surface of the mold. However, oil or water can also be used to create the pressure. Unlike the vacuum bag method where the maximum pressure applied is limited to one atmosphere, the only limits to the amount of pressure applied in this method are the strength of the bag and mold and the capacity of the pressure system. Entrapped air is forced out and a dense molding produced.

The entire lay-up and bag are then placed in an oven or allowed to cure at room temperature as in the vacuum bag method.

12.043 Curing. See Section 11.043.

12.044 Other. See Section 11.044. The ability to apply greater pressures may often eliminate the necessity of hand spackling as required in the vacuum bag method to assist in removing air and wetting out of the glass reinforcement.

12.05 Finishing. See Section 10.05.

17.0 PROCESS CODE AB

Autoclave Bag Molding

17.01 General

17.011 General Description. Autoclave bag molding is a particular form of bag molding which warrants a minimum discussion beyond that found in Sections 10.01 and 11.01. This form of molding is the same as vacuum bag molding except that positive pressure is applied in addition to the vacuum imposed. The pressure is applied in an autoclave (actually a pressure tank), normally along with heat. Much greater pressures are possible with this system than with either VB or PB previously described. Therefore, the density of the finished part is considerably increased and the possibility of voids in the laminate correspondingly decreased. The general description of the process is identical with that for vacuum bag molding (Section 11.011) except that after drawing the vacuum the mold, lay-up and bag are placed in the autoclave. The autoclave is closed and pressure introduced by steam or air simultaneously with application of heat.

17.012 Applications. See Sections 10.012 and 11.012.

17.013 Advantages and Disadvantages

17.013.1 Advantages. See Section 10.131.1. Autoclave bag molding has the added advantage of greater applied pressure and increased cycling of the molds since cure time is reduced by simultaneous application of heat and pressure. Improved strength, higher density and decreased voids are also advantages over the vacuum bag or pressure bag techniques.

17.013.2 Disadvantages. See Section 10.131.2. A considerable disadvantage is introduced by the equipment needed. The autoclave must be of sufficient capacity to handle the molds planned. Also the expense of not only the autoclave itself but also its operation must be taken into account. Multiple molds may be desireable to use the process advantageously, but they necessitate additional capital investment.

17.02 Materials Used. See Section 10.02.

17.03 Equipment Used.

17.031 Lay-Up. See Section 10.031.

17.032 Molds. See Section 10.032.

17.033 Pressure. See Section 10.033. In addition to the bag and vacuum system discussed in the reference section, this process requires additional equipment, namely the autoclave and appropriate auxiliary pressure supply and control. The autoclave is, in effect, a pressure chamber openable at one end to permit introduction of the mold and lay-up. All sizes are in commercial use dependent entirely upon the size of the molds in production and the practical limitations of physical space. Applied pressures of from 30 to 60 psi are common although greater pressures can be and are used quite often. Larger autoclaves are equipped with tracks and dollies to permit greater ease in transporting the molds into and out of the chamber. Production line "set-ups" can be achieved by making the autoclave openable at both ends permitting introduction and discharge of molds simultaneously. Accurate pressure control is essential and it is suggested that pressure histories be recorded for each cycle.

17.034 Heating. See Section 10.034. Autoclave bag molding almost always incorporates application of heat simultaneously with pressure. If steam is used to create pressure, it may also be used to introduce the heat necessary. Otherwise, various heat sources must be incorporated in the autoclave design. Again, accurate temperature control is essential, and, as with pressure, it is suggested that temperature histories be recorded for each cycle.

17.035 Other. See Section 10.035.

17.04 Process Description

17.041 Lay-Up. See Section 11.041.

17.042 Pressure and Temperature. See Section 11.042. The autoclave molding method is a variation of the vacuum-bag process which utilizes steam or air as a source of pressure on the lay-up material after the vacuum has been drawn. The mold and lay-up are placed in an autoclave, which is a round or cylindrical container in which heat and pressure can be applied simultaneously, where pressure is built up with the vacuum still applied to the bag. This combination of vacuum and pressure results in a substantial increase in the force exerted on the lay-up. Therefore, parts made by this method usually have a low void content, resulting in a good strength-weight ratio. Appropriate temperatures are introduced simultaneously with the pressure to initiate and, often, complete the curing necessary. Fig. 11.042 illustrates a typical mold and lay-up in place within an autoclave.

17.043 Curing. See Section 11.043. Most often the lay-up is kept in the autoclave a predetermined amount of time and then removed before cure is complete. In this case, it is removed and placed in an oven either in its mold with vacuum applied or after removal of the bag and separated from the mold. The oven cycle will complete the cure in the first case or effect a post cure in the second case, as desired.

17.044 Other. See Section 11.044. The ability to apply greater pressures may often eliminate the necessity of hand spackling as required in the vacuum bag process to assist in removing air and wetting out of the glass reinforcement.

17.05 Finishing. See Section 10.05.

20.0 PROCESS CODE PM

Press Molding

20.01 General

20.011 General Description. Press molding, as the name indicates, involves the application of pressure to the lay-up by mecahnical means in contrast to bag molding previously discussed. This process involves the use of rigid molds which match, or conform to, the dimensions of all surfaces of the finished piece. This generally involves two dies: the male plug or force and the female or cavity. Some more complex moldings may involve dies containing cam-activated inserts or split sections to mold undercut sections which could not be formed on simple two-piece molds. Although matched molds can be formed from plaster, plastic or low melting alloys, the process is principally used for volume production with metal molds which can be internally heated. They are used to compress molding resins and fillers at pressures varying from 50 to 2000 psi and higher. Molding presses are required to develop these pressures and handle the dies on rapid cycles. The materials, which may be placed into the mold in a variety of ways, are forced to the mold shape and compressed as the press closes. Temperature is applied simultaneously with pressure to effect curing.

Press molding can be sub-categorized into several processes based on the pressure application procedure, namely: Press Molding, Press Molding - Contact Pressure, Press Molding - Against Stops, Press Molding - High Pressure, and Continuous Press Molding. The first of these, being the most general, will be discussed in this section and the other variations in subsequent sections.

20.012 Applications. Press molding is perhaps the most widely used process where mass production of reinforced plastic parts is required. This method is used quite often for manufacturing parts for aerospace vehicles, particularly when accuracy, uniformity and large numbers are required. Other applications include the boat industry, chairs, duct work, tool handles and the like.

20.013 Advantages and Disadvantages.

20.013.1 Advantages. In general, press molding permits the use of fast production cycles under uniform conditions which give optimum results in quality of the finished part and low production costs for runs involving a large number of units. The principal advantages of this process include: molding with high glass or other reinforcing contents; good finish on two surfaces; high density and resulting increased strength; reproducibility of dimensions, properties and appearance; minimum trimming of parts; high production rates with relatively low rejection percentage and scrap loss; less skilled labor required; and lower cost per unit for larger production runs. Certain advantages of the variations on this method will be discussed where more appropriate.

20.013.2 Disadvantages. The single greatest disadvantage to press molding is the tooling cost involved. Included in this cost is that for the molds themselves which must be very precise, the presses required, various auxiliary equipment required, and physical space necessary. The foregoing will generally prohibit the use of this process for short or limited runs of products.

20.02 Materials Used

20.021 Release Agent. See Section 1.021. As with other processes for molding reinforced plastic parts, a release agent may be used. This is often in the form of sheet material for press molding rather than hand coating. Often, however, with highly polished molds of appropriate material, the release agent may be omitted.

20.022 Gel Coat. See Section 1.022. In press molding, the desired effect of a gel coat is worked into the surface layers of the laminate or molding itself.

20.023 Resin. See Section 1.023. Resin characteristics are comparable to those required for other prdcesses previously discusssed with minor variations necessary to adapt them to the press molding technique. The press molding method permits the use of such thermoset resins as epoxies, phenolics and silicones which may not lend themselves to other processes because of their inherent curing characteristics. A large number of structural parts for the aerospace industry use resins in various pre-impregnated forms rather than in liquid form. Resins in dry powdered form are readily applicable to the press molding process.

20.024 Reinforcement

20.024.1 The requirements of the reinforcement system for use in various press molding processes will vary considerably to conform to the particular handling problems involved and the desired shape and physical properties of the finished product. (See Section 1.024.1) For structural applications, glass reinforcing in such forms as cloth, chopped fiber, mat, etc. are most commonly used in press molding. However, asbestos reinforcing has been used and fibrous graphite is under experimentation. Commerically available reinforcements may be applied in dry condition or pre-impregnated with resin or in various preform or premix conditions. Since the use of "preformed" reinforcement is very common in the various press molding processes it is discussed in detail in the following section.

20.024.2 Preforms consist of chopped glass fibers which are collected in a chamber on a preform screen shaped to match the mold to be used. There are three basic methods of making preforms: Plenum Chamber, Directed Fiber, and Water Slurry.

a) In the "plenum chamber method", chopped glass fibers (1 to 2 in. long) are introduced into a plenum chamber as shown in Fig. 20.024.2a. A vacuum draws the fibers onto a perforated steel-mesh "preform" screen mold, which is rotated on a turntable. The chopped glass is pulled down evenly around the screen by means of the vacuum at the lower part of the chamber. The quantity of glass deposited is controlled by a timing device connected to the roving feed mechanism. When the required amount of glass has been deposited on the preform screen, a binder, either a starch-water mixture or a modified resin,

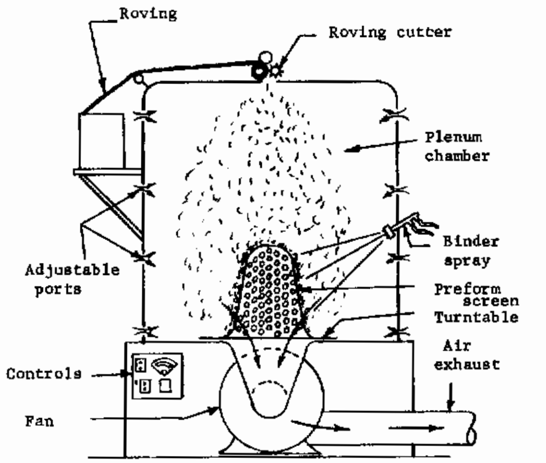


FIG. 20.024.2a SCHEMATIC OF THE PLENUM CHAMBER METHOD OF PRODUCING PREFORMS (OWENS-CORNING FIBERGLASS CORP.)

is sprayed onto the preform either by means of a nozzle fitted into the plenum chamber or by hand after removing the preform from the chamber. The preform is then placed in an oven to cure the binder after which it is removed and stored preparatory to the molding process. The entire preforming operation may require 8 to 10 minutes.

b) The "directed fiber method" is employed when preforms of larger size than can be conveniently handled in the plenum-chamber machine are required. For these larger preforms it is more practicable to mount the screen perpendicularly and blow the chopped glass rovings onto it through large hoses as shown in Fig. 20.024.2b. Since it is impractical to move the screen and preform into an oven, the oven itself may be so constructed that it can be lowered over the entire set-up.

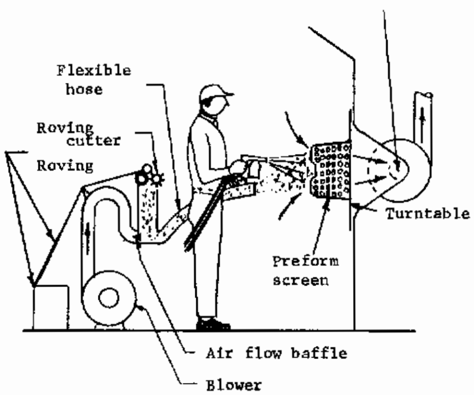


FIG. 20.024.2b SCHEMATIC OF THE DIRECTED FIBER METHOD OF PRODUCING PREFORMS (OWENS-CORNING FIBERGLASS CORP.)

c) More recently the "water slurry method" has been used to produce preforms as shown in Fig. 20.024.2c. This process is similar to that used in the pulp-molding industry or in the making of slurry plasters. Chopped glass fibers are suspended in an emulsion containing cellulosic fibers in a specially constructed tank having an agitator and a telescoping pipe and ram for raising and lowering the preform screen. The glass fibers are deposited on the screen as water is removed from the bottom of the tank after which the screen is raised and excess water is sucked out of the preform. The most satisfactory results are obtained with a ratio of 80 percent glass fibers to 20 percent of cellulosic fibers. The water slurry method requires a higher capital investment than the plenum chamber or directed fiber methods, but is faster and more automatic, as well as being better suited to the forming of intricate shapes or preforms having variable wall thicknesses.

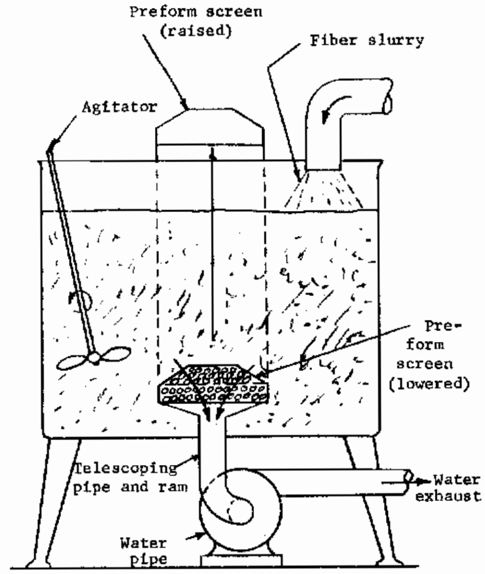


FIG. 20.024.2c SCHEMATIC OF THE WATER SLURRY METHOD OF PRODUCING PREFORMS (OWENS-CORNING FIBERGLASS CORP.)

20.025 Premix. Mixtures of resin and reinforcement combined prior to placement in the mold are called premixes and are often used in press molding.

20.025.1 Premixes, which are often called "gunk", "goop" or "slurry", involve the mixing of a combination of glass fibers and catalyzed resins with suitable fillers, in a dough-type mixer. The resulting material varies from a putty to a straw like mass depending on the type and proportion of ingredients used. A single "charge" of this mass is used in the press molding process.

20.025.2 There is no premix formulation which can be considered as a standard for all applications or resins. The specific requirements with respect to molding characteristics and cured properties must be considered for each application. Likewise a formulation which works well with one resin may have to be modified slightly if another is substituted. The formulation of premix molding compounds has become such a complex problem that many molders prefer to buy premixes manufactured by firms specializing in this field rather than mixing their own.

20.025.3 The equipment used in compounding premix molding compositions is extremely important since the procedure used controls the general type and quality of the compound which can be prepared. It is most important, for example, not to break down the strands of glass into individual fibers or otherwise weaken the fiber reinforcement. Most general-purpose compounds are made by the batch process in a sigma or spiral blade mixer. The sequence of mixing the various components and the over-all time of mixing are critical. The mixed compound is frequently fed through an extruder to prepare sausage-like lengths of material which can be easily handled and cut to individual mold charges. In some high volume operations continuous operating mixing-extruders are used to prepare premixes.

20.025.4 Premixes are widely used for the manufacture of lower-cost reinforced plastic products. For small parts or larger shaped sections which do not require maximum physical properties, the use of premixes gives high production rates with relatively low cost molding material. Because the premix compound flows as a homogeneous mass there is little tendency to form resin-rich area which are often the cause of crazing in mat and preform molding. This allows higher molding temperatures and shorter curing cycles. In addition, it is possible to mold more intricate shapes with varying wall thickness and molded-in inserts. By varying the formulation of the premix compound, it is possible to modify its properties with respect to such factors as cost, shelf life, flow, cure time, moisture absorption, color, heat resistance, electrical properties, strength, and surface finish.

20.025.5 The principle limitation in using premix for press molding is the decreased strength of the final part when compared to the results obtained by using mat, preform or prepreg material. This is caused by the necessity of using lower concentrations of shorter fibers to obtain proper flow. In the course of flowing within the closed mold, these shorter fibers develop planes of weakness which seldom occur in mat or preform molding where longer strands of glass are laid down in a random pattern.

20.026 Prepreg. "Prepregs", which are actually a special form of premixes, involve the combining of resin and reinforcement in such a way as to produce a semi-dry to dry material which may be readily stored prior to use or immediately used in the press molding process.

20.026.1 As the name implies, the glass or other reinforcement is impregnated with a catalyzed resin. The most common forms of the reinforcing are mat, roving, woven fiber, and woven roving, the latter two being most freqeuntly used, perhaps, in structural applications. The resin is partially cured into the so called "B-stage". The operation of impregnating the reinforcing with the compounded resin mixture at the press is somewhat messy and time-consuming particularly when only a limited number of small parts are to be produced. In such cases there is some advantage in preimpregnating the layers of reinforcement with the compounded resin beforehand and working with only the preimpregnated sheet at the press. Fig. 20.026.1 illustrates hand preimpregnation of glass mat just prior to use in a press molded process. Many manufacturers currently specialize in producing prepreg material using all combinations of resins and reinforcements.

FIG. 20.026.1 PREIMPREGNATION OF GLASS MAT BY HAND JUST PRIOR TO PRESS MOLDING (LUNN LAMINATES)

20.026.2 In prepreg molding, all resin calculations, mixing, and applying are eliminated, resulting in time and labor-savings. The resin systems used for pre-preg molding involve either special formulation of the base resin or special compounding of several resins to give the handling characteristics required. The following basic characteristics generally apply to resins for prepreg:

a. Liquid Characteristics. A high viscosity or solid resin, or one which can be compounded with fillers to give a dry to slightly tacky feel after impregnation into the reinforcing fibers. In some cases the resin system is applied from solvent or as a hot melt, and higher boiling monomers than styrene are sometimes used. Special inhibitor systems are often necessary to give prolonged storage life.

b. Curing Characteristics. Molding cycles of 3 to 8 minutes in press at 200 to 270F with cure completed by time part cools to room temperature. Freedom from crazing in resin rich areas.

c. Cured Properties. Semi-rigid to rigid with good hot strength to permit demolding without rupture or mold scumming. High uniform gloss with minimum development of surface fiber pattern as part cools. Strong adhesion to the reinforcing fibers is essential for high strength parts.

20.026.3 Prepreg materials are widely used in the production of structural reinforced plastics for aerospace vehicles in particular. Processing variables, with respect to the materials involved, are reduced to a minimum. Mass production techniques are readily applicable when prepregs are used.

20.026.4 Although prepreg cloth or roving is perhaps most common in processing structural parts, several innovations have been made by the prepreg industry. Preimpregnated cloth is often chopped into small squares with sizes ranging from 1/4 inch to over several inches. A specific amount of these squares, often called "wheat chex", are put into the mold as the material charge. A widely used application of this system is for producing such contoured parts as nose cones and exit nozzles. The same process can be achieved by using preimpregnated roving, usually flat tape, which is chopped into squares.

20.026.5 Perhaps the single biggest advantage of using preimpregnated materials is the ability to vary the reinforcing used in successive plies of the lay-up. Both the type or style of reinforcing and its orientation can be varied to meet virtually any design requirement.

20.027 Precured. Because of the high pressure and temperature available in the press molding process, it is possible to laminate a number of layers of precured material into one molding. Sometimes a thin layer of adhesive is placed between each ply of the precured material. More often fusion may be accomplished by pressure and heat. The term "precured" may be a misnomer in that the material used is most often almost but not completely cured. The final curing takes place along with the fusion while in the press. The largest application of this process is in producing thick flat or slightly curved sheet material having high strength and good dimensional stability.

20.029 Others. Certain additives may be used in the press molding process to impart desired characteristics such as color, durability, temperature resistance, and the like, to the finished product, or to influence cure or other phases of the production. These will depend entirely on the basic materials used and the desired results. The important thing to realize is that such additives do increase the flexibility inherent in "tailor making" reinforced plastic parts.

20.03 Equipment Used

20.031 Lay-Up. The equipment used for lay-up, or placement of materials in the mold, will depend upon the materials themselves. The most common procedures use preforms (previously discussed) or prepregs. The only equipment needed, other than for producing the materials, would be trimming or tailoring tools (for prepregs) and appropriate transportation and holding stacks.

20.032 Molds. The molds are usually made from steel, cast iron or aluminum in matched pairs. Chromeplated steel dies are preferred for best results from the standpoint of surface finish, ease of release and durability. Molds are normally designed with close-fitting, hardened shear edges to contain the resin in the mold and to trim excess fibers which may over-hang the area of the finished part. Stainless steel sheets are often used for molding flat parts. The male and female molds are usually made with provision for internal heating. The molds are often equipped with compressed air vents which assist in releasing the finished part from the mold.

20.033 Pressure. The presses required for the press molding process vary considerably. Their capacity require-ments are directly dependent upon the size molds and curing characteristics involved. Most presses are the vertical hydraulic type. Closure speed and pressure controls must be very accurate as both will influence the finished part. Operating pressures of from 50 psi to over 2000 psi are encountered in this process. A well equipped production plant will usually have a considerable number of presses having a variety of physical and pressure capacities. All accessory equipment for the press operation and control must be provided, of course. Due to the critical effect of pressure on the final product, automatic pressure recorders are often incorporated in the system.

20.034 Heating. Heat is applied simultaneously with pressure during the process via internal heating of the molds by steam, hot fluids or electrical strip heaters. It is common to also heat the press platens to reduce the heat flow away from the molds and to assist in providing better temperature control. It is also possible, though perhaps not done too often, to enclose the majority of the press in a surrounding oven, especially for small part production. The temperatures required in press molding will vary from 100F to 200F up to 500F or more. Since the temperature applied greatly effects the finished part, automatic temperature recorders are often incorporated in the system.
Post curing is accomplished in standard ovens as in previously described processes.

20.035 Other. Other equipment which may be necessary includes jigs or forms to hold the finished part of the preforms, etc. in shape, transport and storage equipment, etc.

20.04 Process Description. The basic press molding process will be discussed in this section and certain variations covered in subsequent sections as indicated in 20.011.

20.041 Lay-Up

20.041.1 Prior to lay-up of materials into the mold, certain preliminary steps must be followed. By far the most important of these is the thorough cleaning and polishing of the mold and contact surfaces as illustrated in Fig. 20.041.1. If any release agents or gel coats are required, they would be applied after cleaning.

The actual lay-up of the materials is most easily discussed in relation to the form these materials are in. The following categories will be discussed: Individual, Preform, Premix, Prepreg, and Precured.

FIG. 20.041.1 POLISHING THE MALE HALF OF A MOLD PRIOR TO PLACING LAY-UP IN A PRESS MOLDING OPERATION (LUNN LAMINATES)

20.041.2 "Individual" material lay-up involves the placement of dry reinforcing in the mold and then applying the resin in dry or liquid form. Any tailoring of the reinforcement is done at the mold. Since this method reduces production rates, it is very seldom used except, perhaps, where flat or slightly contoured parts are being produced. The use of preforms is much preferred.

20.041.3 "Preforms" (see Section 20.024) are very easy to handle. The preshaped reinforcement is placed on or in the mold and the resin added in dry or liquid form. Figs. 20.041.3a and b illustrate the placement of preformed mat reinforcement on the male mold and the addition of a previously measured amount of liquid resin. The preforms can be made from a wide variety of reinforcing materials including glass, asbestos and graphite. Since press molding applies high pressure, the resin will be forced throughout the preform and therefore preliminary distribution of it is usually unnecessary.

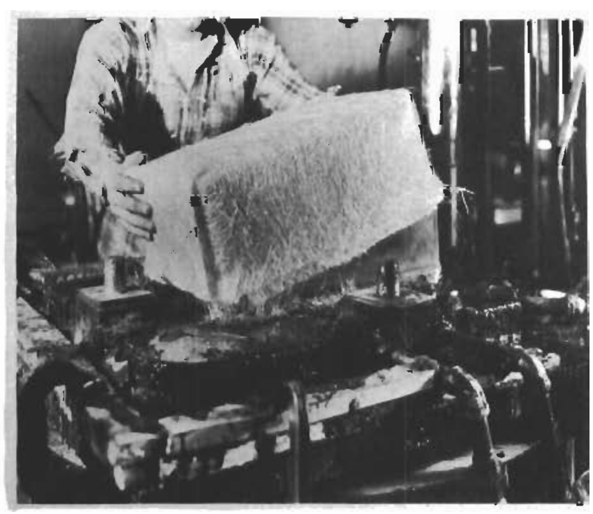


FIG. 20.041.3a PLACEMENT OF MAT PREFORM INTO POSITION ON THE MOLD IN A PRESS MOLDING OPERATION (LUNN LAMINATES)

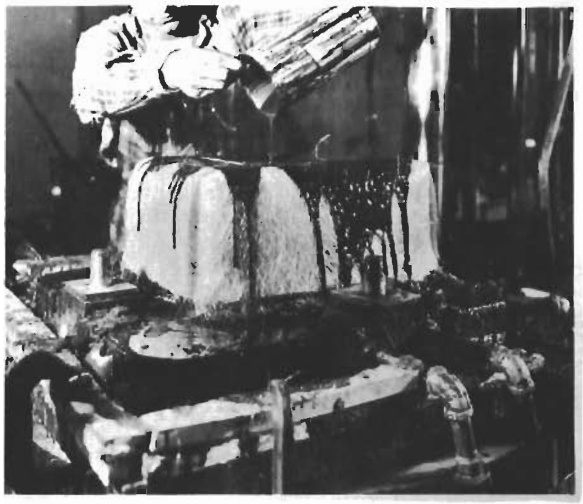


FIG. 20.041.3b A MEASURED AMOUNT OF RESIN IS ADDED TO THE PREVIOUSLY PLACED PREFORM IN A PRESS MOLDING OPERATION (LUNN LAMINATES)

20.041.4 "Premix" (see Section 20.025) materials are measured into a specific quantity known as a charge. The liquid or semi-liquid charge is usually placed into the female mold. On closing the press, the premix is forced into the contours of the mold itself. Premixes are easier to handle in some respects since no measurements of resin and reinforcement quantities are required. However, since only chopped fibers are usually available and higher resin contents are required, the desired strength of the finished part may be impared.

20.041.5 "Prepreg" (see Section 20.026) combines the advantages of premix with the fact that they are more easily handled. Again no measurements of resin and reinforcement are required as this is previously done. The prepreg material may be tailored to the shape of the mold at the press or, more frequently for the sake of faster production, cut to size and even preformed prior to placement in the mold. The actual lay-up, then, is similar to that for preforms except no addition of resin is necessary. Virtually any style or composition of reinforcement may be secured impregnated with almost any of the common thermoset resins. The use of prepregs is clean and precise. In laying up prepreg materials, careful attention must be paid to the direction of the reinforcing fibers in each layer.

Chopped prepreg cloth or roving is layed-up in much the same manner as premix. A specific amount of material is "charged" into the mold. The application of pressure with heat forces the chopped squares into the contours of the mold.

20.041.6 "Precures" are handled in lay-up in a manner similar to prepregs. Layers of appropriate precured material are precut to size and stacked in the mold. Each layer may actually consist of a number of plies of reinforcing. Since precures are usually relatively stiff they are normally only used for flat or slightly curved laminated parts. As with prepregs, the directional orientation of each layer of precure may be very critical.

20.042 Pressure and Temperature

20.042.1 Once lay-up is completed, the press is activated and the two halves of the mold brought together. Simultaneously, or shortly after closing, heat is applied.

20.042.2 The rate of closing is quite critical in press molding since the material must be allowed to "flow" into the contours of the mold as the pressure is applied. The rate and degree of closure of the matched dies are also of utmost importance in the quality of the finished product. The initial closing of the press can be that of the speed of the press until the last half-inch or so of closing. At this point, in the case of preforms particularly, the press should be slowed down considerably to allow sufficient time for the resin to flow and wet out the reinforcing completely before the heat from the molds begins to cure the resin.

20.042.3 For general press molding pressures up to several hundred pounds per square inch are used. The amount of pressure will be dependent on the type of reinforcing and resin being used and the requirements for the finished product. The amount of pressure will also determine the thickness and density of the finished part. A number of variations in the process may be introduced to further control these variables. Because of the importance and use of these variations, they are classified separately and discussed in later sections of this Manual. They include the use of stops, contact pressure and high pressure.

20.042.4 The temperature applied during press molding will depend greatly on the flow and cure properties of the material used. Temperatures of 200F to 250F are common but up to 400F or more may be used when required. The heat applied will cure the thermoset resin involved.

20.042.5 To illustrate the general process of Press Molding, Fig. 20.042.5 shows a schematic of the process using a premix for the mold charge. Note that the premix flows to the extremities of the mold as it is compressed during closing of the press.

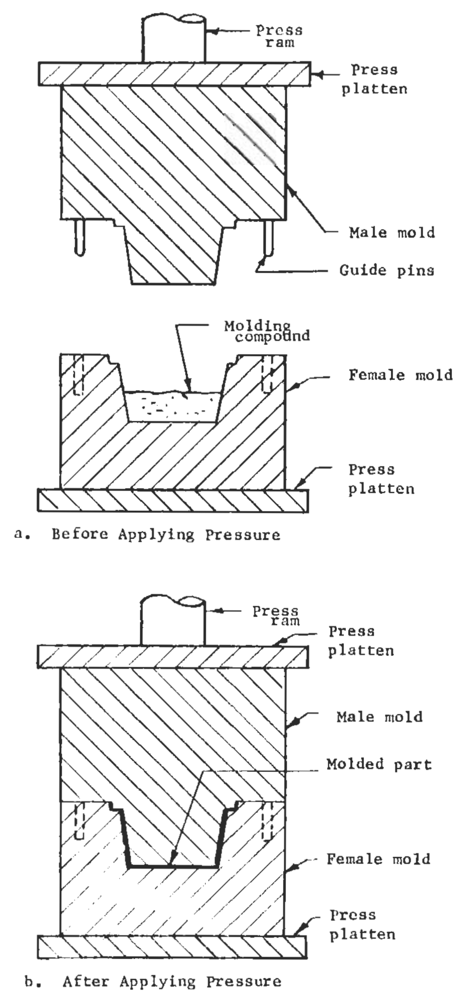


FIG. 20.042.5 SCHEMATIC OF TYPICAL PRESS MOLDING USING PREMIX MATERIAL (OWENS-CORNING FIBERGLASS CORP.)

20.042.6 After cure is as complete as required in the particular operation, finished parts may be removed by compressed air when the release is relatively easy to accomplish. When the release is more difficult, it is frequently necessary to maintain different temperatures on both male and female halves of the molds so that the coefficient of expansion differential will aid in accomplishing the release. In addition, mold-release agents composed of silicones or waxes are often required.

20.043 Curing. Cure takes place during the molding operation as a result of the pressure and temperature applied. However, it is often desirable to post cure press molded parts to assure their meeting design requirements. This is done in standard ovens. Although the part is cured before placing it in the oven, it may be desireable to hold it in some simple jig to limit possible warping during the post cure.

20.05 Finishing. It is not one of the objectives of this first edition to cover this topic fully.

20.051 Trimming

20.052 Machining

20.053 Surfacing. Press molding will produce very smooth surfaces which faithfully reproduce the contours of the molds. The use of gel coats and plies of surface tissue, etc., have been previously described under contact and bag molding. However, they will not usually be required in press molding. It is important to realize that virtually any surface texture or configuration may be obtained with press molding.

20.054 Coloring. The final molding can be painted with any of the usual surface coating finishes after all traces of release agent, if used, have been removed. It is often worthwhile to incorporate a pigment in the resin, however too much pigmentation may result in an inferior molding.

20.055 Attachments

21.0 PROCESS CODE PM-C

Press Molding - Contact Pressure

(See also Section 20.0)

21.01 General

21.011 General Description. This is a variation of the press molding process described in Section 20.011. In this process the molds are brought into contact with the lay-up and no additional pressure is applied. Items not specifically discussed herein will be found under Process Code PM.

21.012 Applications. The primary application of this variation on the press molding process is where excessive pressures may be detrimental or unnecessary with respect to the finished part.

21.013 Advantages and Disadvantages

21.013.1 Advantages. One possible advantage to this method is that premixes may flow more readily with out the high pressure involved in other methods.

21.013.2 Disadvantages. The principal disadvantages are decrease in accuracy of thickness, lower densities and lower strengths.

21.02 Materials Used. See Section 20.02.

21.03 Equipment Used. See Section 20.03.

21.04 Process Description. See Section 20.04. The only variation here is that the press is closed only until contact with the lay-up is made. Cycle times for curing may be increased as a result.

21.05 Finishing. See Section 20.05.

22.0 PROCESS CODE PM-S

Press Molding - Against Stops

(See also Section 20.0)

22.01 General

22.011 General Description. This is a variation of the press molding process described in Section 20.011. In this process shims or stops are placed between the molds to limit their closure and therby limit the thickness of the finished part. Item not specifically discussed herein will be found under Process Code PM.

22.012 Applications. Press molding - contact pressure is used where the thickness of a part is critical and must be carefully controlled.

22.013 Advantages and Disadvantages

22.013.1 Advantages. As indicated, the principal advantage of this process is the accurate control of the part thickness.

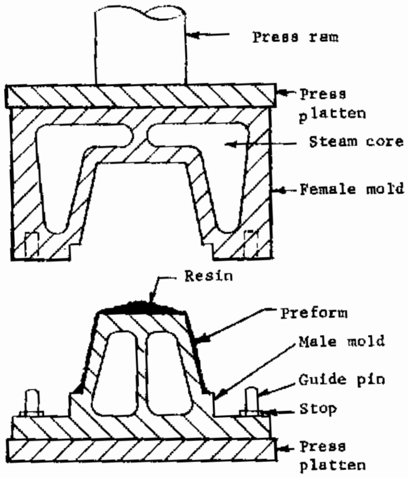
22.013.2 Disadvantages. Since thickness will be controlled by the mold, the amount of material charged will control the density of the finished part. As previously emphasized a decrease in density will usually be accompanied by a decrease in strength.

22.02 Materials Used. See Section 20.02.

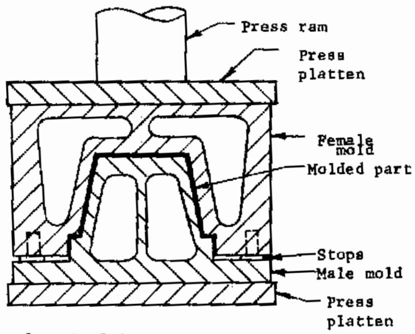
22.03 Equipment Used. See Section 20.03.

22.04 Process Description. See Section 20.04. The only variation here is that the press closes the molds against spacer stops. This, in effect, controls the thickness of the finished part. The quantity of material put into the lay-up may be very critical in this process because of density considerations. Fig. 22.04 schematically shows press molding against stops before and after closing the molds.

22.05 Finishing. See Section 20.05.



a. Before Applying Pressure



b. After Applying Pressure

FIG. 22.04. SCHEMATIC OF TYPICAL PRESS MOLDING - AGAINST STOPS USING PREFORM AND RESIN (OWENS-CORNING FIBERGLASS CORP.)

23.0 PROCESS CODE PM-H

Press Molding - High Pressure

(See also Section 20.0)

23.01 General

23.011 General Description. This is a variation of the press molding process described in Section 20.011. The entire process is the same as the general PM process except that very high pressures, from 500 to 2000 psi, or more, are used. Items not specifically discussed herein will be found under Process Code PM.

23.012 Application. Press molding - high pressure is used for several important reasons two of which are: to create very high density in the finished part and to assure highly accurate conformation to contour and tolerances. This method is also often used in producing parts, particularly sheet, from prepreg, especially "wheat chex", and precured materials since the higher pressures force more intimate contact between the layers of material and, therefore, a more uniform material composition. Common applications of high pressure press molding include radomes, nose cones, exit nozzles and the like.

23.013 Advantages and Disadvantages

23.013.1 Advantages. As indicated, the principal advantages of this process are the increase in density and the improvement of dimensional accuracy. The former induces increased strength of the part as well as reducing the probabilities of such things as delamination. High pressure molding may be the only way to produce multilayer laminates in many cases.

23.013.2 Disadvantages. The primary disadvantages to this process are the equipment requirements introduced by the high pressure application. Press capacity and mold strength and construction become very important. Care must also be exercised in selecting materials and process sequence to avoid the possibility of "crushing" the reinforcing fibers and causing similar detrimental effects.

23.02 Materials Used. See Section 20.02

For press molding - high pressure the prepreg and precured materials are most commonly used for aerospace vehicle applications.

23.03 Equipment Used. See Section 20.03.

In making sheet-form laminates the platten presses used are heated either by steam or by electric current. Electrically heated presses are usually confined to the manufacture of silicone laminates, where they provide precisely controlled curing temperatures, resulting in cleaner, flatter, and warp-free sheets. Temperatures and pressures average about 300 to 350F to 1000 to 1200 psi, depending on the nature of the filler material, the resin employed and the thickness of the final sheet.

23.04

23.04 Process Description. See Section 20.04.

23.041 In general, the only variation here is the amount of pressure, which may range up to 2000 psi or more, applied to the lay-up. No spacer stops or shims are used normally. Control of the pressure and the rate of increase to full pressure may be quite critical and should be carefully monitored.

23.042 The process used to produce laminated sheet material warrants some additional discussion here.

23.042.1 The individual sheets or plies of prepreg are "stacked" to a height which will result in the required thickness of the finished laminate. By varying the type of coated base sheets, a wide range of characteristics can be built into the laminate. The unfused or unbonded stack is placed between stainless steel end-sheets, approximately the same size as the individual layers, and the entire package placed as a unit between the heated platens of a vertical-acting multi-opening platen press. The press is closed and heat and pressure applied.

23.042.2 The resin in the base material, which begins the cycle in the thermoplastic state, gradually fuses the individual sheets together as the heat is applied and becomes thermosetting. The heat-pressure cycle may be as short as 1/2 hr or as long as 4, 8 or even 12 hr, depending, as before, on the resin, base material, and other factors such as press loading, thickness (number of sheets), and type of cure required for the particular application.

23.042.3 It should be noted that in the manufacture of high-pressure laminates no additional adhesive or bonding agent is required beyond that provided by the resin itself. The resin on the outside of each layer fuses with the resin coating on adjoining layers, as well as with the resin that has penetrated each ply in intimate contact with the molecules of the fibers in the base material. The result is a dense, solid, virtually homogeneous slab of predetermined thickness which will not separate or delaminate unless subjected to severe abuse or misapplication.

23.042.4 After fusion of the resin is accomplished, and the resin has become thermoset, there is an additional type of curing required which is analogous to the annealing of glass and other ceramics. The "raw" laminate cannot be immediately removed from the press and allowed to cool rapidly in air since embrittlement of the surface layers would occur, perhaps accompanied by warpage or buckling. As with newly cast or molded glass, laminated plastic materials must be slowly cooled by a gradual reduction of the heat and pressure to ambient conditions.

23.042.5 When curing is complete the laminated sheets are rough finished to remove flashings (laminate or resin squeezed out along the edges of the platens), trimmed to size, and otherwise prepared for final machining and finishing operations.

23.05 Finishing. See Section 20.05.

27.0 PROCESS CODE - CPM

Continuous Process Molding

27.01 General

27.011 General Description. Continuous press molding involves the following general operations: 1. impregnation, 2. combining, 3. curing, and 4. finishing. The first step involves the resin's dissolutionment in a suitable solvent to form a spirit varnish with which the filler is impregnated or coated by one of several processes. One technique, graphically described as the dip-and-scrape method, controls the final resin content of the filler by the resin concentration in the impregnating bath. Another method utilizes a pair of adjustable squeeze rolls or a doctor blade to control the amount of resin left on the coated web. A third method employs a series of roll coaters which meter the resin onto the web as it passes between the rolls. After impregnation, the wet web passes through a drying and curing oven which drives off the solvent and cures the resinous binder.

27.012 Application. The continuous press molding process is used to produce decorative and structural laminates. Although most of structural material is flat sheet other contours, either perpendicular or parallel to the length of the sheet, are possible. One such example is the production of the familiar corrugated sheeting. Other uses include electrical insulation, fuel cell backing board for supporting structures around self-sealing gas tanks in military aircraft, and in phototemplate work where dimensionally stable drawings for large size layout work are required.

27.013 Advantages and Disadvantages

27.013.1 Advantages. The greatest single advantage of continuous press molding is the economy of fully automated production runs for large volume output. With adequate programming and control, consistent uniformity may be achieved.

27.013.2 Disadvantages. One obvious potential disadvantage of this process is the cost of the equipment involved. Other possible disadvantages are the potential size limitations. The finished laminates are usually limited to 54 inches in width and 0.10 inch maximum in thickness. However, should production warrant, equipment with greater capacities could be developed. There are practical limitis to the pressure which can be applied by the combining rollers; and, therefore, full potential strength may not be developed in the laminate produced by this process.

27.02 Materials Used

27.021 Release Agent. Not applicable.

27.022 Gel Coat. Not applicable except as part of "carrier sheets" (See Section 27.028).

27.023 Resin.

27.023.1 Aside from the characteristics resins must have to develop the required strength and other physical properties in the cured form, the most important characteristics during processing and cure are related to viscosity and development of cure. Viscosity requirements vary from 500 cps for continuous impregnation to approximately 1500 cps for wet pack impregnation or 50,000 cps for bank application on decorative laminates.

27.023.2 In developing cure it is important to use a resin which will maintain uniform gel time and exotherm characteristics since the curing zones in which these occur are critical. Resin with moderate exotherms is also desirable to reduce runaway cures which result in blisters and other defects. Moderate shrinkage during cure is desirable to control warping and wavy patterns caused by the texture of the reinforcing web.

27.024 Reinforcement. Applicable reinforcements include materials such as paper, glass fabric, various natural and synthetic fabrics and non-woven webs or mats made up of single types or blends of fibers.

27.025 Premix. Not applicable.

27.026 Prepreg. Continuous press molding can be adapted to use prepreg materials by omitting the impregnation stage and feeding the prepreg directly to the combining rollers. However, certain advantages are lost if this is done. It is not too prevalently used in industry although it may be more widespread in the future.

27.027 Precured. Not applicable.

27.028 Other. Carrier sheets are required to transport the material after leaving impregnation and through the remainder of the process. These carrier sheets are most frequently plain transparent cellophane since the shrinking which occurs in heated cellophane provides tension that assures a perfectly smooth surface. Other carrier sheets sometimes used include pigmented cellophane (for semi-gloss surface), coated paper, polyvinyl alcohol, cellulose acetate (crinkle finish), polyester film and metal belts.

27.03 Equipment Used

27.031 Lay-up. In this process, lay-up actually consists of bringing together the correct number of plies of material fresh from the impregnation bath. This is automatically achieved by use of appropriate rollers and travel built into the basic equipment.

27.032 Molds. Not applicable.

27.033 Press. Pressure is applied by a pair of heavy combining rolls set to produce a predetermined thickness of laminate. Side gates are associated with the rolls to maintain the formation of a resin bead along the edges of the laminate.

27.034 Oven. The curing oven may be vertical or horizontal 50 to 100 feet in length divided into zones. Heat is generally supplied by circulating hot air or direct-fired gas burners. Auxiliary heating by infrared lamps is sometimes used. The oven zones are set up along the following general lines although this will vary depending on the specific type of laminate being produced. Temperatures indicated may not be suitable for all types of laminates.

1. Preheat Section: Range from 220 to 250F to bring laminate up to cure temperature quickly.

2. Gelation Section: Range from 180 to 220F, temperature control in this zone being extremely critical to avoid runaway of curing reaction.

3. Exotherm Section: Usually no heat is supplied in this section since the curing resin is reaching its peak exotherm. Sometimes venting must be provided to control heat build up.

4. Finish Section: Range from 230 to 260F to finish curing of laminate.

27.035 Other. The coating machines are employed in continuous laminating to impregnate the reinforcement with resin. These are of the high-speed type and are equipped with automatic electronic controls to maintain the precise speed of travel required for the coated materials and the correct amount of heat required for each grade of material and type of resin used.

27.04 Process Description. Since this process does not follow the sequence format used in other process writeups, the following is organized by "stages" in the operation.

27.041 Impregnation

27.041.1 Prior to the actual impregnation or saturation of the base material with resin, it is necessary to follow strict rules of storage for both the resin and the reinforcement. Depending on the manufacturer's facilities, the resins may be either purchased or, if feasible, produced on the premises. Since resins in their ordinary state are essentially solid materials (either powdered or in pellet form) they must first be dissolved with alcohol or other solvent to form a "varnish" or "syrup".

Resin solutions must be prepared in fresh batches and in quantities only for immediate use, as the solvent evaporates to a certain extent, thereby changing the impregnating quality of the resin and consequently the characteristics of the end product. "Varnish" batched for a particular coating job should be kept in airtight drums or in large blending or storage tanks, preferably in constant-temperature or airconditioned rooms provided with approved fire-protection facilities.

Certain grades of paper, glass, and other base materials should also be stored under controlled conditions of moisture and temperature to prevent dimensional changes, water absorption, and other preimpregnation changes that will affect the finished product.

27.041.2 Impregnation of the base material is accomplished by passing the plies through a resin bath for a period of time sufficient to saturate the fibers completely. When a dense paper or closely woven fabric is being used, the time period must be sufficient to assure an adequate coating of resin to obtain complete saturation during storage in roll form. In this type of wetpack storage, the roll must be slowly rotated to prevent draining within the roll.

When loosely bonded fibers, such as glass mat, are impregnated, special procedures, such as supports in the resin bath, vertical impregnation, or laying the mat down onto a film of resin, must be used to prevent the mat from separating. Regardless of the procedure, impregnation must be complete, since trapped air will show up in the end product as blisters, delamination and surface defects.

27.042 Combination

27.042.1 After the plies of reinforcement have been completely impregnated, they are combined and sandwiched between carrier sheets which serve to carry the laminate construction through the curing operation and to exclude air from the curing resin. These carrier sheets are frequently cellophane although other materials may be used as indicated in Section 27.028.

27.042.2 The plies of reinforcement and carrier sheets are brought together at heavy combining rolls which are accurately set to regulate the thickness of the laminate. Excess resin in the reinforcement is squeezed out at these rolls and maintained as a slight bank to assure that no air bubbles travel into the laminate. Side gates conforming to the contour of the rolls allow a resin bead to form along the edges of the laminate. Any excess resin is returned to the impregnation tanks.

27.042.3 When additional wear resistance is required, as in the case of decorative laminates, the roll gap is set at more than the combined thickness of the plies and a high viscosity (approximately 50,000 cps) resin bank is maintained between the top ply and the cover sheet.

27.042.4 After passing the combining rolls, the cellophane is generally clamped on the edges by some mechanism to hold the sheet under tension sideways as the sheet passes through the curing oven. This device is usually a textile center frame or a similar mechanism. In some equipment, tension is developed by passing the cellophane encased laminate over a heated convex platten avoiding the necessity of edge clamps.

27.043 Curing. The curing section of a continuous laminator consists of a circulating hot air or direct-fired gas oven which is divided into zones as indicated in Section 27.034. Most commercial laminating ovens operate in the range of 5 to 12 feet per minute of laminate travel.

27.044 Sizing. After curing, the laminate is edge-trimmed to remove the resin bead and produce the desired width. Trimming is accomplished with rotary disc shears, saws or abrasive wheels depending on the thickness of the laminate and the type of reinforcing material. The carrier sheets are usually removed from one or both sides and the laminate cut to length. Sometimes thin laminates are wound on storage rolls in lengths up to 300 feet. When the laminate is used for applications involving bonding to other materials, it is sanded on one side to improve adhesion.

27.05 <u>Finishing</u>. It is not one of the objectives of this first edition to cover this topic fully.

27.051 Trimming

27.052 Machining

27.053 Surfacing. It is important to realize that virtually any surface texture or configuration may be obtained with continuous pressure molding.

27.054 Coloring. The final molding can be painted with any of the usual surface coating finishes after all traces of carrier sheets have been removed. It is often worthwhile to incorporate a pigment in the resin, however too much pigmentation may result in an inferior molding.

27.055 Attachments

1.0 INTRODUCTION

1.01 Purpose of Manual

1.011 The purpose of this Manual is to present various test and quality control methods as they are used in the reinforced plastics industry. These methods are described in sufficient detail to give a good understanding of the test and its purpose. Additional details not included may be found by referring to the original source.

1.012 Most of the test methods used to obtain data presented in other Manuals of the Handbook are included in this Manual.

1.013 The test methods are cross-referenced to other Manuals by use of a code number system which identifies the property category and the assigned test identification number. For example, test method code number T6.011 has the following significance:

T	= Test Code Number
6.	= Property Category: mechanical, thermal, etc.
.01	= Type of test: tension, conductivity, etc.
.001	= Sequential identification number (first method described in this case)

1.014 Due to the significance and importance of LP-406 and ASTM test procedures, the code numbers for these carry a suffix of initials "LP" or "ASTM". Hence, if the example in section 1.013 above were for an ASTM test method, the code number used in cross-referencing would be T6.011 ASTM.

1.015 This Manual also presents summaries of Quality Control procedures. For distinction, these are designated with the prefix initial "Q" in the code number instead of the "T" used for test methods.

1.016 Certain organizations (ASTM for example) incorporate "Standard Test Procedures" which may be referenced to individual test method descriptions in their published works. To avoid repetition and excessive length, the same procedure is followed in this Manual. Section S10.0, "Summary of Standard Test Procedures", includes procedures common to several or more test methods described in Sections 2.0 thru 9.0. Paragraph cross-referencing within Manual IG is employed here as being sufficient. The prefix initial "S" is used in the code number for these Sections.

1.02 Contents of Manual IG

1.021 This Manual is divided into Sections as follows:

Section No.	Subject
1.0	INTRODUCTION
2.0	TEST METHODS - PHYSICAL PROPERTIES
2.01	Composition - Resins
2.02	Composition - Reinforcements
2.03	Composition - Material Systems
2.04	Resin Content
2.05	Density
2.06	Moisture Transmission
2.07	Water Absorption
3.0	TEST METHODS - CHEMICAL PROPERTIES
3.01	Flammability
3.02	Products of Combustion
3.03	Toxicity
3.04	Environmental Resistance
3.05	Corrosion Resistance
3.06	Reagent Resistance
4.0	TEST METHODS - THERMAL PROPERTIES
4.01	Heat Distortion
4.02	Thermal Conductivity
4.03	Thermal Expansion
4.04	Diffusivity
4.05	Emissivity
4.06	Thermal Shock
4.07	Ablation
5.0	TEST METHODS - ELECTRICAL PROPERTIES
5.01	Resistivity
5.02	Conductivity
5.03	Dielectric Constant and Loss Tangent
5.04	Microwave
5.05	Magnetic
6.0	TEST METHODS - MECHANICAL PROPERTIES
6.01	Tension
6.02	Compression
6.03	Flexure
6.04	Shear
6.05	Bearing
6.06	Creep and Creep Rupture
6.07	Fatigue
6.08	Elastic
6.09	Hoop Tension
6.10	Hardness
6.11	Impact
6.12	Bond
6.13	Shock Loading
7.0	TEST METHODS - MISCELLANEOUS PROPERTIES
10.0	SUMMARY OF STANDARD TEST PROCEDURES
20.0*	QUALITY CONTROL - MATERIAL PRODUCTION
21.0*	QUALITY CONTROL - MATERIAL RECEPTION
22.0*	QUALITY CONTROL - FABRICATION
23.0*	QUALITY CONTROL - FINISHED PRODUCT

*These subject areas are planned for future addition to this Manual.

1.022 Each Section describing a Test Method is subdivided as follows, using Method T6.011 as an example.

6.0	TEST METHODS - MECHANICAL PROPERTIES
6.01	Tension Tests
6.011	Test T6.011
6.011.1	Source
6.011.2	Specimen
6.011.3	Conditions
6.011.4	Procedure - Preliminary
6.011.5	Procedure - Testing
6.011.6	Observations
6.011.7	Report
6.011.8	Test Equipment
6.011.9	Measuring and Recording Equipment

1.023 It will be noted that for each test method one paragraph number will always indicate the same subject. This will facilitate the use of this Manual and the cross referencing to other Manuals.

1.024 For complete Table of Contents for the entire Handbook, see Manual IA.

1.03 Abbreviations and Glossary

1.031 For complete listing of all abbreviations and definitions used throughout the Handbook, see Manual IA.

1.04 Information Sources

1.041 Each test method and quality control procedure is source referenced in their respective write-ups.

1.042 A complete sources index is given in Manual IA.

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.10 Hardness Tests

6.104 Test T6.104 LP

6.104.1 Source. LP-406b Federal Specification for Plastics, Organic: General Specifications, Test Methods; Method 1081.1: Rockwell Indentation Hardness Test.

6.104.2 Specimen. Minimum specimen thickness is to be 1/4 in. unless it can be verified that hardness values are unaffected when thinner specimens are used. The specimen should be 1 in. square if cut from sheet material and at least 1 square inch if from other shapes. The minimum dimensions should be greater than 1/2 in. Specimens may be composites of several thin sections stacked closely with complete contact between layers.

6.104.3 Conditions. None specified.

6.104.4 Procedure - Preliminary. To insure that the major load is being applied to the specimen, additional indentation should be indicated when hand pressure is applied to the weight pan. If the additional indentation does not occur, the load is too great and a lower scale should be chosen. For hard materials, a scale of 150 divisions shall not be exceeded, while for soft materials, 250 divisions should not be exceeded. The M scale should be selected first. If 150 divisions are exceeded within 15 seconds after applying the load, the L scale should be used. If materials are too hard for the M scale, and the readings are in excess of 115, the E scale should be selected.

6.104.5 Procedure - Testing. The loads, both major and minor, to be applied for each scale are given in Table 6.104.5. The dash pot on the tester should be adjusted to complete its travel in 4 to 5 sec. when a 100 kg major load is applied. The time for the mechanism to come to a stop should be 5 to 15 sec. The major load is to be removed 15 sec. after the handle is tripped and the Rockwell reading recorded to the nearest full division.

TABLE 6.104.5

Rockwell Hardness Scale	Minor load kg	Major load kg	Penetrator, ball, in
R (least hard)	10	60	1/2
L - - - - - -	10	60	1/4
M - - - - - -	10	100	1/4
E (most hard)	10	100	1/8

6.104.6 Observations. Subtract the number of times the needle passes through zero upon application of the major load from the number of times it passes through zero on removal of the load. If this number is zero, the reading should be recorded as over 100. If this number is 1, the reading should be recorded between zero and 100. If this number is 2, the reading should be recorded as the scale indication less 100.

6.104.7 Report. The number of specimens and their thicknesses, the Rockwell hardness numbers and the scale used, should be reported.

6.104.8 Test Equipment. A standard Rockwell hardness tester shall be used.

6.104.9 Measuring and Recording Equipment. Part of standard test equipment.

4 TEST METHODS - THERMAL PROPERTIES

4.01 Heat Distortion Tests

4.011 Test T4.011 ASTM

4.011.1 Source. ASTM D648-56, Deflection Temperature of Plastics Under Load.

4.011.2 Specimen. Dimensions of the specimens should be 5 by 1/2 by any thickness from 1/8 to 1/2 in. Molding procedures are important but are not designated.

4.011.3 Conditions. Conditioning of test specimens should conform to ASTM D618. See Section S10.01.

4.011.4 Procedure - Preliminary. The apparatus is to be designed to permit measurement of deflections at the mid-point of the specimen to 0.005 in. The specimen is to be loaded on the flat. If the specimen is 1/2 by 1/2 in., the direction of loading should be perpendicular to the direction of the molding pressure. The load to be applied (See 4.011.5) is to be calculated by the following equation.

$$P = \frac{2}{3}\frac{Sbd^2}{1}$$

where: S = Maximum fiber stress in psi

b = width of specimen in inches

d = depth of specimen in inches

1 = length between supports in inches

p = load in pounds

4.011.5 Procedure - Testing. Temperature of the immersion bath should be 23 $\pm$ 1C at the start of testing unless it is known that error is not introduced by higher starting temperatures. The fiber stress at this time should be 264psi $\pm$ 2 1/2%. The load should be allowed to act for 5 minutes prior to setting the zero scale for deflections. The temperature is then elevated at the rate of 2 $\pm$ 0.2C per minute. When 0.010 in. deflection is reached, the temperature is recorded as the deflection temperature. This procedure is to be repeated at 66psi $\pm$ 2 1/2% and the deflection temperature again recorded.

4.011.6 Observations. At least two specimens should be tested. The test temperatures at which the 0.010 in. deflection is reached should be recorded.

4.011.7 Report. Dimensions of the specimen, specimen material, deflection temperatures, fiber stresses, immersion medium and heating rate should be reported. Any unusual characteristics or conditions are to be reported also.

4.011.8 Test Equipment. The apparatus should be constructed as shown in Fig. 4.011.8. The supports are to be 4 in. apart and should have 1/8 in. radius by at least 1/2 in. long bearing surfaces. The immersion bath should be chosen for its heat-transfer properties, and should be stirred during the test. Weights of suitable size to achieve the 66 and 264 psi $\pm$ 2 1/2% specimen stresses required in the test should be available.

4.011.9 Measuring and Recording Equipment. Dial gages are to be placed under the weight pan. The spring load of these is to be subtracted from the weight applied to the specimen. Thermometers to suit the range of the test temperatures required are to meet ASTM standard specification E-1.

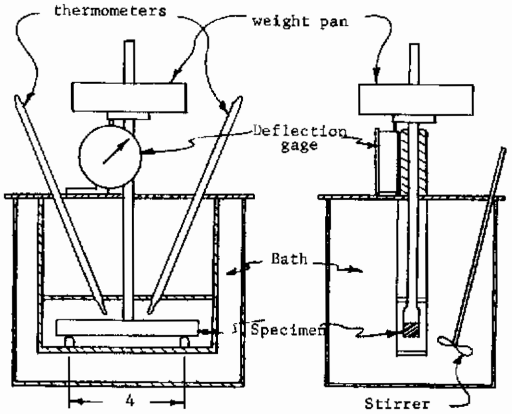


FIG. 4.011.8 TEST EQUIPMENT

4. TEST METHODS - THERMAL PROPERTIES

4.01 Heat Distortion Tests

4.012 Test T4.012 LP.

4.012.1 Source. LP-406b Federal Specification for Plastics, Organic: General Specifications, Test Methods; Method 2.011.1: Heat Distortion Temperature. (Note: Although not identical, this method conforms in general to ASTM D648-56; See T4.011 ASTM.)

4.012.2 Specimen
a. Molded specimens shall be 5 x 1/2 x 1/2 or 1/4 in. thick.. They shall be loaded in a direction perpendicular to the direction of molding pressure.
b. Sheet specimens shall be 5 x 1/2 x the sheet thickness of from 1/8 to 1/2 in.

4.012.3 Conditions. The specimen should be conditioned at 23 ± 1.1C for 5 minutes.

4.012.4 Procedure - Preliminary. The molded specimens are to be placed in the apparatus so that the thickness of the mold (or the thickness of the sheet) is the width of the beam, unless otherwise specified. The load to be applied to the specimen is to be calculated by the following equation.

$$P = 44bd^2$$

where: P = load in pounds

b = width of specimen in inches

d = depth of specimen in inches

The weight of the loading rod and spring load in the dial gage are to be considered as part of the force P.

4.012.5 Procedure - Testing. Temperature at the beginning of test should be 23 ± 1.1C and subsequently is to be increased at a rate of 2 ± 0.2C per minute. A load producing a fiber stress of 264 ± 6.6 psi in the specimen is to be applied and allowed to stand on the specimen for 5 minutes prior to setting the zero scale for deflections and elevating the temperature. The temperature at which deflection of 0.010 in. is reached is the heat distortion temperature.

4.012.6 Observations. Deflections are to be recorded at each 5C of temperature rise. The heat distortion temperature is defined as the temperature at which a deflection of 0.010 in. is reached at the mid-span of the specimen.

4.012.7 Report. A temperature-deflection curve should be plotted with the abscissa as temperature and the ordinate as deflection. Unusual characteristics of the specimen should be reported.

4.012.8 Test Equipment. The apparatus should be constructed similar that indicated for ASTM D648-56 (See Fig. 4.011.8 for T4.011 ASTM). The steel supports are to be 4 in. apart and shall have 1/8 in. radius by at least 1/2 in. long bearing surface. The weight shaft should be at least the width of the test specimen and have the same thermal coefficient of linear expansion as the rods used to attack the loading frame to the top plate of the test apparatus. Even though the materials are the same, a correction factor is to be correlated for the range in which tests are to be run. The immersion liquid to be used for transfer of heat to the specimen should not affect the rigidity of the specimen and should be stirred during testing. Weights of suitable size to achieve the 264 ± 6.6 psi specimen stress required in the test should be available.

4.012.9 Measuring and Recording Equipment. A dial gage is to be used to measure deflection.

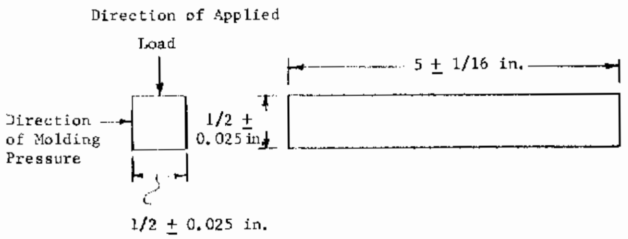


FIG. 4.012.2 HEAT DISTORTION SPECIMEN

4. TEST METHODS - THERMAL PROPERTIES

4.01 Heat Distortion Tests

4.013 Test 4.013 LP

4.013.1 Source. LP-406b Federal Specification for Plastics, Organic: General Specifications, Test Methods; Method 6061: Hot Oil Bath Test.

4.013.2 Specimen. Specimens as described in LP-406b Method 2011.1 (T4.012, Section 4.012.2 are suggested; however, any convenient size of specimen may be used.

4.013.3 Conditions. Specimens should be soaked in an oil immersion bath for 1 hr. prior to testing at the heat distortion temperature.

4.013.4 Procedure - Preliminary. Careful examination is to be made of the specimen prior to conditioning. The inspector is to take cognizance of the surface finish, color and, particularly, the dimensions and shape of the specimen.

4.013.5 Procedure - Testing. After conditioning, the specimen is to be wiped dry and cooled to 20 to 25C. Again, inspections similar to those described in 4.013.4 are to be carried out. The oil bath is to be stirred during the condition period.

4.013.6 Observations. See 4.013.4 and 4.013.5.

4.013.7 Report. The report is to include changes in appearance, color, surface finish, evidence of warping, splitting or softening, and changes in the original dimensions.

4.013.8 Test Equipment. The test bath should be large enough to permit simultaneous testing of all samples from the same lot. A propeller is to be provided to achieve continuous stirring of the immersion fluid throughout the test. Accurate adjustment of the temperature should also be provided.

4.013.9 Measuring and Recording Equipment. A thermometer of sufficient accuracy is to be placed in the immersion bath.

4. TEST METHODS - THERMAL PROPERTIES

4.02 Thermal Conductivity Tests

4.021 Test 4.021 ASTM

4.021.1 Source. ASTM C 177-45, Thermal Conductivity of Materials by Means of the Guarded Hot Plate.

4.021.2 Specimen. Two samples should be selected, each to fit entirely over the heating unit. Thickness should be determined as indicated in Table 4.021.2. See also Fig. 4.021.8.

TABLE 4.021.2

Maximum thickness of specimen in	Minimum linear dimensions of guarded hot plate (square or round) in	
	Central Section	Guard Section
1	4	1 1/2
1 1/2	8	2 1/4
2	12	3
4	12	6

Minimum thickness is to be limited by the ability to determine accurately the conductivity. The surfaces of the specimen should be sanded smooth to obtain good contact with the heater. The specimen should be dried at 215F if it is unharmed at this temperature, until no reduction in weight is indicated. If it is harmed by 215F, it should be placed in a desiccator and dried at 120 to 140F.

4.021.3 Conditions. The test is to be used only over the range from -50 to 1400F for extreme temperatures and 0 to 1200F for mean temperatures.

4.021.4 Procedure - Preliminary. None specified.

4.021.5 Procedure - Testing. Test temperatures are to be those at which the specimen is to be used and the temperature drop across the specimen is to be at least 40F. Tests are to be run at mean temperatures differing by at least 30F. The dew-point is not to be higher than the coolest part of the surface. When thermocouples are mounted on the hot and cold plates to determine the temperature difference, the distance between the hot and cold plates is to be considered in the thickness of the specimen. When thermocouples are mounted on the specimen, the distance between the hot and cold plates less the two thicknesses of blotting or asbestos mounting paper is to be considered as the specimen thickness. After a steady state is reached, observations should be made at not more than one hour intervals. The temperature drops for the two test specimens shall not differ by more than 1 per cent, over a 5 hour period. The specimen is to be weighed at the end of the test.

4.021.6 Observations. At least 3 specimens should be tested. The temperatures at both surfaces of the specimen, its mean temperature and the moisture during testing should be recorded. The weight of the specimen should be measured before drying, after drying but before testing, and after testing. The exact dimensions of the specimen are to be recorded. The thermal input is to be reported in BTU per hr ft^2.

4.021.7 Report. Density and other items are to be calculated by the following equations.

a. $D = \frac{A}{B}$

where: D = density in lb/in^3
A = weight of sample after drying in pounds
B = Volume of sample after drying in cubic inches

b. $M = \frac{C-A}{B}$

where: M = moisture in sample as received in lb/in^3
C = weight of sample as received in pounds

Weight change during testing.

c. $R = (G-F) \times \frac{A}{F} \times \frac{1}{B}$

where: R = moisture regained during testing lb/in^3
G = weight of specimen after testing in pounds
F = weight of specimen prior to testing in pounds

Thermal conductivity is to be computed as follows:

$$k = \frac{QL}{A_t(T_1-T_2)} = \frac{qL}{A(T_1-T_2)}$$

where: k = thermal conductivity
Q = total quantity of heat
t = time
L = thickness of the specimen
A = area of specimen normal to the heat flow
T_1 = temperature of the hot surface
T_2 = temperature of the cold surface
q = quantity of heat per unit time

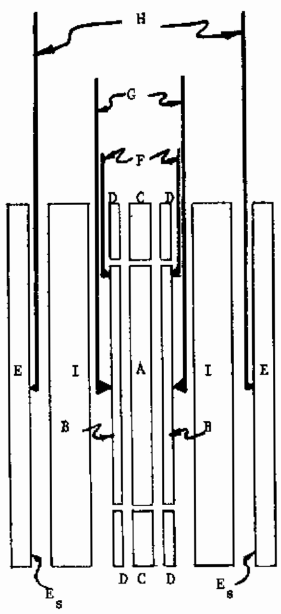
Thermal conductance is to be computed as follows:

$$C = \frac{1}{R} = \frac{q}{T_1 - T_2}$$

C = thermal conductance, heat transferred per unit time per degree
R = thermal resistance

The name of the material and thermal conductivity should be reported, in addition to those facts required in section 4.021.6. A conductivity vs mean temperature plot should be produced from the mean values determined from the three samples tested.

4.021.8 Test Equipment. Figure 4.021.8 is a sketch of the apparatus to be used for this test. No detailed requirements are given for the construction of this unit.



A - Central Heater
B - Central Surface Plates
C - Guard Heater
D - Guard Surface Plates
E - Cooling Units
E_s - Cooling Unit Surface Plates
F - Differential Thermocouples
G - Heating Unit Surface Thermocouples
H - Cooling Unit Surface Thermocouples
I - Test Specimens

FIG 4.021.8 TEST APPARATUS

4.021.9 Measuring and Recording Equipment. Thermocouples are to be used to measure the surface temperatures. The potentiometer is to have a sensitivity of at least 5 micro volts. The heating element is to have regulation to ± 1 per cent, if it is automatic. If the regulator is manually adjustable, the maximum temperature difference between the center and guard surface plates over the 5 hour interval should be less than 0.75 per cent of the average drop through the two halves of the specimen.

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.01 Tension Tests

6.011 Test T6.011 ASTM

6.011.1 Source. ASTM D638- 60T, Tensile Properties of Plastics

6.011.2 Specimen.

a. Specimen for Plastic Sheet, Plate and Molding, Fig. 6.011.2a. These specimens shall be fabricated by machining from sheets, plates, etc., or by molding.
b. Specimen for Plastic Tubes, Fig. 6.011.2b.
c. Specimen for Plastic Rod, Fig. 6.011.2c.
d. All specimens should be free of flaws, scratches and machining marks. Where these do occur they should be removed with No. 00 abrasive paper stroked parallel to the tensile axis of the specimen.
e. Gage marks should be made by some means other than indentation.
f. The Figures above give basic specimen dimensions. Details on tolerences, etc., will be found in original source.

6.011.3 Conditions. Conditioning of test specimens should conform to ASTM D-618 for purposes of obtaining reproducible results. See Section S10.01. No environmental conditions are specified by source.

6.011.4 Procedure - Preliminary. The grips are to be spaced apart as shown in the Fig. 6.011.2 illustrating the specimens and the axis of the grips and specimen are to be aligned such that no moment can be developed in the specimen. With the specimen accurately placed, the grips are to be tightened firmly, but not to pressures sufficient to crush the gripped portion of the specimen.

6.011.5 Procedure - Testing. The speed of testing shall be one of those shown in Table 6.011.5. Unless otherwise specified, Speed B shall be used. When determining the

TABLE 6.011.5

Source	ASTM D638-60T
Speed Designation	Test Speed in/min
A	0.05
B	0.2 to 0.25
C	2
D	20

Elastic Modulus, Speed A shall be used for laminated thermosetting plastics, and Speed B for others. Hence, different specimens for strength and modulus determinations may be necessary in certain cases.

6.011.6 Observations.

a. The number of specimens necessary to substantiate the finding is five. If the material has a possibility of exhibiting anisotropic properties, ten specimens should be taken, 5 parallel and 5 at 90° to the principal axis. If reasons, such as flaws not ordinarily found in the material, result in errors, additional specimens should be tested.
b. To determine the modulus of elasticity a record of loads and deformation should be kept. Record the elapsed time between start of test and when strain is 0.02. Also record the load and elongation at failure. From this data, tensile strength, percentage elongation, mean rate of stress, mean rate of strain, and elastic modulus can be determined.

6.011.7 Report. Not specified by Source.

6.011.8 Test Equipment. A constant strain testing machine which is accurate to ± 1 per cent of the indicated load value shall be used.

6.011.9 Measuring and Recording Equipment.

a. The strain indicated should be accurate to ± 1 percent of the measured value.
b. Micrometers should read to 0.001 in or less.

SPECIMEN DIMENSIONS - IN

Type I (a)				
T(b)	C	W	L	E(c)
≤ 1/4	0.750	0.500	8 1/4	4 1/2
> 1/4 ≤ 1/2	1.125	0.750	9 3/4	4 1/2
> 1/2 ≤ 1	1.500	1.000	12	5 1/4
Type II				
≤ 1/4	0.750	0.250	9 3/8	5 1/4
> 1/4 ≤ 1/2	1.125	0.375	10 1/8	5 1/4

(a) Shall be used wherever possible
(b) Shall be 0.125 wherever possible if T > 1 in, machine to 1.000
(c) Distance between grips

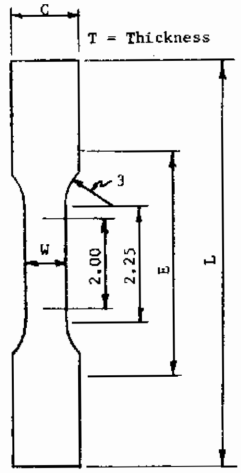


FIG. 6.011.2a SPECIMEN FOR PLASTIC SHEET, PLATE & MOLDING

SPECIMEN DIMENSIONS - IN

T Nom.	L Calc.	L Std.	E(a) Min.
1/32	13.00	15	6.80
3/64	13.92	15	6.92
1/16	14.02	15	7.02
3/32	14.20	15	7.20
1/8	14.34	15	7.34
3/16	14.58	15	7.58
1/4	14.79	15.75	7.79
5/16	14.96	15.75	7.96
3/8	15.12	15.75	8.12
7/16	15.27	15.75	8.27
1/2	15.40	16.5	8.40

(a) Distance between grips
(b) Standard grip length = 3 1/2 in

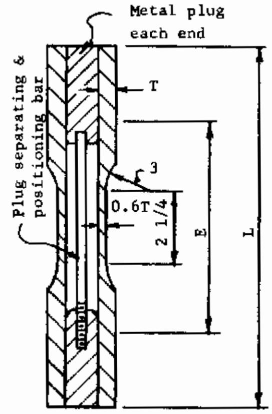


FIG. 6.011.2b SPECIMEN FOR PLASTIC TUBE

SPECIMEN DIMENSIONS - IN

D Nom.	L Calc.	L Std.	E(a) Min.
1/8	14.02	15	7.02
3/16	14.20	15	7.20
1/4	14.34	15	7.34
3/8	14.58	15	7.58
1/2	14.79	15.75	7.79
5/8	14.96	15.75	7.96
3/4	15.12	15.75	8.12
7/8	15.27	15.75	8.27
1	15.40	16.5	8.40
1 1/4	15.65	16.5	8.65
1 1/2	15.87	16.5	8.87
1 3/4	16.06	16.5	9.06
2	16.24	17	9.24

(a) Distance between grips
(b) Standard grip length = 3 1/2 in

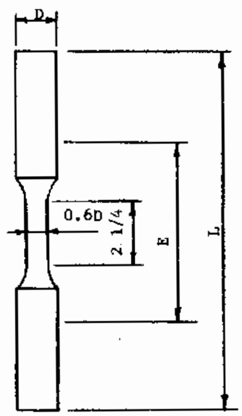


FIG. 6.011.2c SPECIMEN FOR PLASTIC ROD

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.01 Tension Tests

6.012 Test T6.012 ASTM

6.012.1 Source. ASTM D1708-59T, Tensile Properties of Plastics By Use of Microtensile Specimens.

6.012.2 Specimen. The shape of specimen shown in Fig. 6.012.2 is to be used when the thickness of the sheet is less than 1/8" and only when the amount of material available is limited. Specimen shall be prepared by die-cutting.

6.012.3 Conditions. Conditioning of test specimens should conform to ASTM D-618 for purposes of obtaining reproducible results. See Section S10.01. No environmental conditions are specified by source.

6.012.4 Procedure - Preliminary. The grips are to be 0.900 ± 0.010 in apart and the axis of the grips and specimen are to be aligned such that no moment can be developed in the specimen. With the specimen accurately placed, the grips are to be tightened firmly, but not to pressures sufficient to crush the tabs.

6.012.5 Procedure - Testing. The speed of testing shall be one of those shown in Table 6.012.5. If a specific testing speed is not given to satisfy requirements of the use, Speed B, in the table should be used. These speeds produce rates of strain comparable to those specified in ASTM D638-60T (See Sect. 6.011.5).

6.012.6 Observations.

TABLE 6.012.5

Source	ASTM D1708-59T
Speed Designation	Test Speed in/min
A	0.01
B	0.04 to 0.05
C	0.4 to 0.5
D	4 to 5

a. The number of specimens necessary to substantiate the finding is five. If the material has a possibility of exibiting anisotropic properties, ten specimens should be taken, 5 parallel to and 5 at 90° to the principal axis. If reasons, such as flaws not ordinarily found in the material, result in errors, additional specimens should be tested.

b. A record of load and elongation should be made throughout the test in order to calculate mechanical properties of the material. From this data, the yield strength, ultimate strength, elastic modulus and ductility can be computed.

6.012.7 Report. Not specified by source.

6.012.8 Test Equipment. It is best to use rubber faced grips for thin specimens, but serrated grips can be used if care is taken. Self-tightening grips are not satisfactory.

6.012.9 Measuring and Recording Equipment.

a. The distance between the fixed and movable heads of the testing machine is to be the elongation of the specimen. An accuracy of ± 1% should be met by the measuring device and deformation of testing apparatus should be less than 1% of the total elongation of the specimen.

b. Micrometers, should read to 0.0001 in or less.

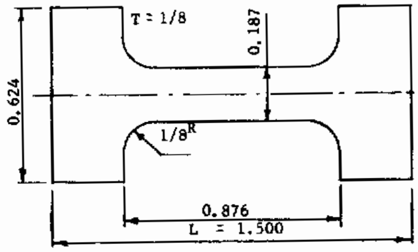


FIG. 6.012.2 MICROTENSILE SPECIMEN

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.01 Tension Tests

6.013 Test T6.013 LP

6.013.1 Source. LP-406b Federal Specification for Plastics, Organic: General Specifications, Test Methods; Method 1011: Tensile Properties of Plastics. (Note: Although not identical, this method conforms in general to ASTM D638-60T; See T6.011 ASTM.)

6.013.2 Specimen.

a. Specimen for Plastic Sheet, Plate and Molding, Fig. 6.013.2a.

b. Specimen for Plastic Tubes, Fig. 6.01.2b. Where wall thickness exceeds 1/8 inch, it shall be reduced by 1/32 inch over a length of 2 1/4 inches in the middle of the specimen length. Transition to the reduced section shall be by fillets with 3 inch radius.

c. Specimens for Plastic Rod shall be 12 inches long. Where the diameter exceeds 1/4 inch, it shall be reduced by 1/32 inch over a length of 2 1/4 inches at the middle of the specimen length. Transition to the reduced section shall be by fillets with 3 inch radius.

d. Machined surfaces shall be finished with No. 000 emery paper.

e. Gage marks shall be made by some means other than indentation.

6.013.3 Conditions. Conditioning of test specimens shall conform to LP-406 General Requirements for purposes of obtaining reproducible results. See Section S10.02. No environmental conditions are specified by source.

6.013.4 Procedure - Preliminary. The grips are to be spaced apart as shown in the Fig. 6.013.2. The use of coarse abrasive paper or cloth in the grips with the abrasive side next to the specimen is recommended to reduce slipping and failure in the grips. Grips shall be self aligning.

6.013.5 Procedure - Testing. A head travel speed of 0.20 to 0.25 in/min shall be used to load the specimen if load-deformation data are being taken, the speed shall be 0.05 in/min maximum.

6.013.6 Observations.

a. The number of specimens necessary to substantiate the finding shall be in accordance with LP-406 General Requirements. See Section S10.02.

b. Data should be obtained to compute stress, strain, elastic modulus, proportional limit, and yield ultimate strengths.

6.013.7 Report. The report shall conform to the LP-406 General Requirements. See Section S10.02.

6.013.8 Test Equipment. Any standard tensile testing machine having an accuracy of ± 1 percent of the measured value shall be used.

6.013.9 Measuring and Recording Equipment. Strain gages accurately indicating extensions corresponding to 0.0001 inch per inch strain shall be used.

SPECIMEN DIMENSIONS - IN

T(b)	C	W	L	E(c)
TYPE I (a)				
≤ 1/4	3/4	0.500	8 1/2	4 1/4
> 1/4 ≤ 1/2	1 1/8	0.750	9 3/4	4 1/2
> 1/2 ≤ 1	1 1/2	1.000	12	5 1/4
TYPE II				
≤ 1/4	3/4	0.250	9 3/8	5 1/4
> 1/4 ≤ 1/2	1 1/8	0.375	10 1/8	5 1/4

(a) Shall be used wherever possible
(b) Shall be 0.125 wherever possible for molded specimens
(c) Distance between grips

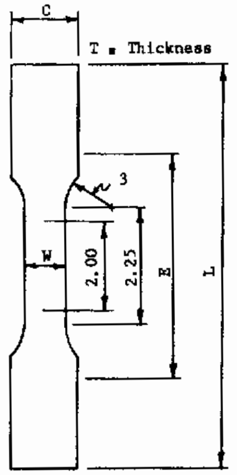


FIG. 6.013.2a SPECIMEN FOR PLASTIC SHEET, PLATE & MOLDING

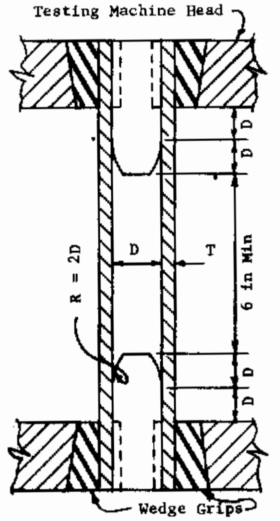


FIG. 6.013.2b SPECIMEN FOR PLASTIC TUBES

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.02 Compression Tests

6.021 Test T6.021 ASTM

6.021.1 Source. ASTM D695-54, Test for Compressive Properties of Rigid Plastics.

6.021.2 Specimen.

a. The standard test speciment shall be in the form of a right cylinder or prism whose length is twice its principal width or diameter and whose ends are parallel within 0.005 in. Preferred specimen sizes are 1/2 x 1/2 x 1 inch for prisms and 1/2 inch diameter by 1 inch for cylinders. The specimen may be machined from stock or molded.

b. To determine the elastic modulus and yield strength, specimens with a slenderness ratio of 11 to 15 shall be used.

c. Rod specimens shall have the same diameter, up to 1 inch, as the stock material and lengths as shown in Table 6.021.2c. For rod material over 1 inch diameter standard 1/2 x 1/2 x 1 inch prismoidal specimens shall be cut to be representative of the rod cross-section.

d. For tubes, a specimen with diameter of the tube x 1 inch in length shall be used. To determine the crushing-load of tubes, the same specimen shape is to be loaded at 90° to the longitudinal axis.

e. To test sheet material less than 1 inch thick, a pile-up of sheets 1 inch square with sufficient layers to produce a minimum height of 1 inch shall be used. Considerable care is necessary during testing to avoid buckling.

6.021.3 Conditions. Conditioning of test specimens shall conform to ASTM D618 for purposes of obtaining reproducible results. See Section S10.06. No environmental conditions are specified by source.

6.021.4 Procedure - Preliminary. The specimen shall be carefully placed in testing machine or compression tool to assure concentricity of axes. See Fig. 6.021.8b for a schematic of a typical compression tool. The compression tool framework shall be very stiff and shall hold the plunger perpendicular.

6.021.5 Procedure - Testing. The speed of testing shall be 0.05 in/min below the yield point. Rates of 0.20 to 0.25 in/min may be used beyond this point.

6.021.6 Observations.

a. The number of specimens necessary to substantiate the finding is five. If the material has a possibility of exhibiting anisotropic properties, ten specimens shall be taken, 5 parallel to and 5 perpendicular to the principal axis. If reasons, such as flaws not ordinarily found in the material, result in errors, additional specimens shall be tested.

b. A record of load and elongation should be made throughout the test in order to calculate mechanical properties of the material. From this data, the yield strength, compressive strength, elastic modulus, and deformation beyond yield can be computed.

6.021.7 Report. The report shall include complete identification of material, preparation of test specimen (with dimensions), conditions of test, rates of stress and strain, compressive strength (with deviations), yield strength, ductility, toughness and elastic modulus.

6.021.8 Test Equipment

a. A constant strain testing machine which is accurate to ± 1 percent of the indicated value shall be used.

b. A compression tool, such as shown in Fig. 6.021.8b, may be used.

6.021.9 Measuring and Recording Equipment

a. Measurements of longitudinal deformations shall be accurate to ± 0.001 inch.

b. Micrometers shall read to 0.001 inch or less.

TABLE 6.021.2c ROD SPECIMEN DIMENSIONS

Diameter inch	Length inch	Slenderness Ratio
1/8 to 1/4	1/2	16 to 8
1/4 to 1/2	1	16 to 8
1/2 to 1	2	16 to 8

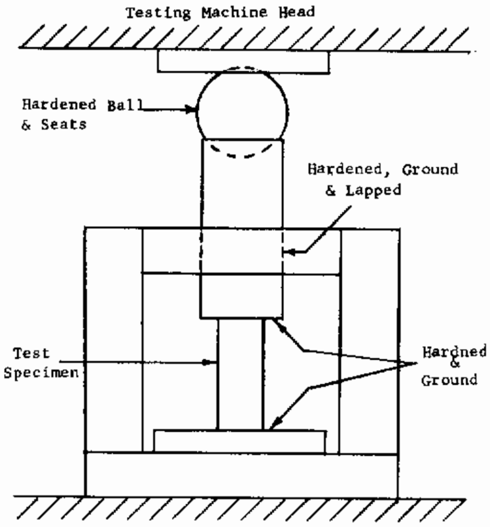


Fig. 6.021.8b TESTING MACHINE HEAD

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.02 Compression Tests

6.022 Test T6.022 LP

6.022.1 Source. LP-406b Federal Specification for Plastics, Organic: General Specifications, Test Methods; Method 1021.1: Compressive Properties of Rigid Plastics. (Note: Although not identical, this method conforms in general to ASTM D695-54; See T6.021 ASTM.)

6.022.2 Specimen.

a. The standard test specimen shall be in the form of a right cylinder or prism whose length is twice its principal width or diameter and whose ends are parallel within 0.005 in. Preferred specimen sizes are 1/2 x 1/2 x 1 inch for prisms and 1/2 inch diameter by 1 inch for cylinders. The specimen may be machined from stock or molded.

b. To determine the elastic modulus and yield strength, specimens with a slenderness ratio of 11 to 15 shall be used.

c. Rod specimens shall have the same diameter, up to 1 inch, as the stock material and lengths as shown in Table 6.021.2c. For rod material over 1 inch diameter standard 1/2 x 1/2 x 1 inch prismoidal specimens shall be cut to be representative of the rod cross-section.

d. For tubes, a specimen with diameter of the tube x 1 inch in length shall be used. To determine the crushing-load of tubes, the same specimen shape is to be loaded at 90° to the longitudinal axis.

Diameter inch	Length inch	Slenderness Ratio
1/8 to 1/4	1/2	16 to 8
1/4 to 1/2	1	16 to 8
1/2 to 1	2	16 to 8

e. To test sheet material from 1/4 to 1 inch thick in the direction perpendicular to the plane of the sheet, a pile-up of sheets 1 inch square with sufficient layers to produce a minimum height of 1 inch shall be used.

f. Thin sheets 1/4 inch or less in thickness shall be tested in the direction parallel to the plane of the sheet using a suitable supporting jig as shown in Fig. 6.022.8c. This specimen shall be 1/2 inch x sheet thickness x a length equal to that of the jig plus 1 to 2 times the specimen thickness. The specimen ends shall be machined parallel to each other and perpendicular to the adjacent faces.

6.022.3 Conditions. Conditioning of test specimens shall conform to LP-406 General Requirements for purposes of obtaining reproducible results. See Section S10.02. No environmental conditions are specified by source.

6.022.4 Procedure - Preliminary. Spherical seats shall be employed and the use of a special compression tool is desirable. A supporting jig for thin sheet specimens, as shown in Fig. 6.022.8c, shall be used.

6.022.5 Procedure - Testing. The speed of testing shall be 0.05 in/min below the yield point. Rates of 0.20 to 0.25 in/min may be used beyond this point.

6.022.6 Observations.

a. The number of specimens necessary to substantiate the finding shall be in accordance with LP-406 General Requirements. See Section S10.02.

b. A record of load and elongation should be made throughout the test in order to calculate mechanical properties of the material. From this data, the yield strength, compressive strength, elastic modulus, and deformation beyond yield can be computed.

6.022.7 Report. The report shall conform to the LP-406 General Requirements. See Section S10.02.

6.022.8 Test Equipment.

a. A suitable compressive testing machine having an accuracy of ± 1 per cent of the measured value shall be used.

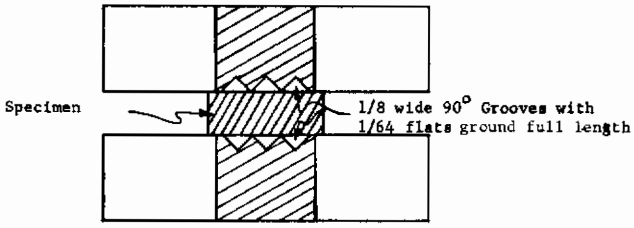
b. A compression tool, such as shown in Fig. 6.021.8b of test method T6.021 ASTM, may be used.

c. A special supporting jig for thin sheet specimens is shown in Fig. 6.022.8c. This jig shall be made of cold rolled steel.

6.022.9 Measuring and Recording Equipment.

a. Strain gage or gages shall be mounted directly on the specimen. Measuring of head travel is not acceptable.

b. Specimen dimensions shall be measured to the nearest 0.001 inch.



SECTION A-A

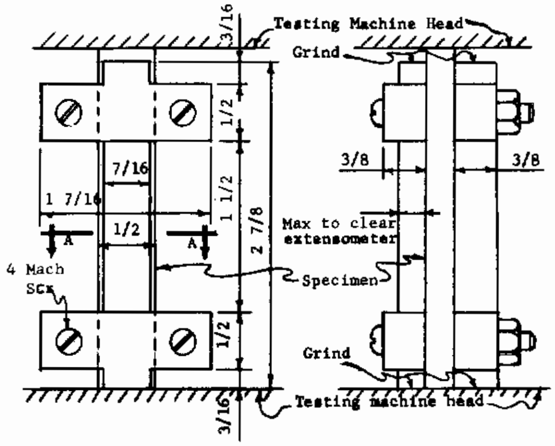


Fig. 6.022.8c DETAIL OF SUPPORTING JIG FOR THIN SHEET SPECIMENS

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.03 Flexure Tests

6.031 Test T6.031 ASTM

6.031.1 Source. ASTM D790-58T, Flexural Properties of Plastics.

6.031.2 Specimen. The shape may be as selected by the investigator and may be cut from sheets or molded. General specifications for specimen are as follows:

a. For materials with thickness greater than 1/16 inch, the thickness of the sheet is to be used as the depth of the test specimen when flat strength is desired. If the test is to determine the strength when the load is applied on the edge, the width of the specimen will be the sheet thickness, and the depth of the specimen should not exceed this. The depth of the span is to be 1/16 of the length or less and the width should not be greater than 1/4 the length. Ten per cent overhang allowance at each end should be included in the length, but in no case is this to be less than 1/4 inch.

b. For materials with thickness less than 1/16 inch, the test specimen dimensions should be 2 inches long by 1/2 inch wide. These are to be tested over a 1 inch span length.

c. Laminated thermosetting materials and sheet and plate materials used for electrical insulation, including vulcanized fibre and glass-bonded-mica shall be tested as indicated in Table 6.031.2c. All specimen are to be machined and those with glass or nylon bases having thickness greater than 1/2 inch shall be reduced to 1/2 inch in thickness.

d. Molded materials should have test specimen dimensions of 5 x 1/2 x 1/4 inch and be tested flat on a 4 inch span.

TABLE 6.031.2c

Nominal Thickness in	Specimen Width in	Length in	Test Span in	Crosshead Speed in/min
1/32	1	2 1/2	5/8	0.02
1/16	1	3	1	0.03
3/32	1	3 1/2	1 1/2	0.04
1/8	1	4	3	0.05
3/16	1/2	5	3	0.08
1/4	1/2	6	4	0.11
3/8	1/2	8	6	0.16
1/2	1/2	10	8	0.21
3/4	3/4	14	12	0.32
1	1	18	16	0.43

6.031.3 Conditions. Conditioning of test specimens should conform to ASTM D-618 for purposes of obtaining reproducible results. See Section 10.01 ASTM. All specimens shall be tested in a standard laboratory atmosphere.

6.031.4 Procedure - Preliminary. At least 10 per cent of the specimen shall over-hang each end of the support structure. But in no case can this overhang be less than 1/4 inch at each end. The spans are to be determined to the nearest 1 per cent. The axes of loading nose and the specimen supports must be parallel and the loading nose placed at the midpoint of the beam span.

6.031.5 Procedure - Testing. The crosshead speed should be computed as follows.

a. If Procedure A is used:

$$N = \frac{zL^2}{6d}$$

where: N = crosshead speed, in/min
L = Span length, in
d = depth of beam, in
z = strain rate at the outer fiber and is equal to 0.01 in/in/min

b. If Procedure B is used the crosshead speed should be 0.10 in/in/min. This method should be used for the more flexible materials.

6.031.6 Observations.

a. The number of specimens necessary to substantiate the finding is five. If the material has a possibility of exhibiting aeolotropic properties, ten specimens should be taken, 5 parallel to and 5 at 90° to the principal axis. If reasons, such as flaws not ordinarily found in the material, result in errors, additional specimens should be tested. Both flat and on edge specimen positions are recommended.

b. The applied load and the deflection at this load should be taken simultaneously during the test. This should be done until the outer fiber is strained to 0.05 in/in as defined by the following equation:

$$D = \frac{rL^2}{6d}$$

where: D = deflection
r = strain
L = span
d = depth of beam

c. All dimensions of the specimen and the constituent materials should be indicated.

6.031.7 Report. The maximum fiber stress shall be reported as computed by the following equation:

$$S = \frac{3PL}{2bd^2}$$

where: S = stress, psi
P = load, pounds
L = length, in
b = width, in
d = depth, in

The flexural strength or stress at cracking load, flexural yield strength, flexural offset yield strength, stress at a given strain, maximum strain, and modulus of elasticity (by both tangent and secant modulus methods) should be reported.

6.031.8 Test Equipment. A constant strain testing apparatus which is accurate to $\pm$ 1 per cent shall be used. The nose and support members should have cylindrical surfaces with radii of 1/8 inch min and 1 1/2 times the thickness of the specimen max. The maximum value is to be used when excessive indentation occurs.

6.031.9 Measuring and recording equipment. None given.

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.03 <u>Flexure Tests</u>

6.032 Test T6.032 LP

6.032.1 Source. LP-406b, Federal Specification for Plastics, Organic: General specifications, Test Methods; Method 1031: Flexural Properties of Plastics.

6.032.2 Specimen.

a. Sheet materials. For testing in a flat position, the thickness of the sheet should be the depth of the specimen. The span length should be at least 16 times the depth and at least a one inch over-hang should be allowed at each end. The width of the specimen should be at least 1/2 inch. For testing sheet specimens on edge, the thickness of the sheet should be the width of the specimen. The depth should not be greater than the width and the span to depth ratio should be at least 16.

b. Molded materials. The specimen can be 5 x 1/2 x 1/2 inch or 5 x 1/2 x 1/4 inch and have a span length of 4 inches. The latter of these is preferred since it has a span to depth ratio of 16.

c. All width and depth dimensions shall be taken to the nearest 0.001 inch, while length dimensions should be to the nearest 0.01 inch.

6.032.3 Conditions. None given.

6.032.4 Procedure-Preliminary. None given.

6.032.5 Procedure - Testing. Testing head movement should be in the range of 0.20 to 0.25 inches. The rate of fiber strain should be less than 0.01 in/in/min at the extreme fiber for load-deflection data purposes. The head travel speed is to be calculated by the following equation:

$$N = \frac{ZL^2}{6d}$$

where: N = travel rate, in/min
L = span length, in
d = depth of beam, in
Z = limit rate of fiber strain in inches per inch of outerfiber per minute, to be 0.01. Past the point of recording deflection, the head travel can be increased to 0.20 to 0.25 inches per minute.

6.032.6 Observations. The dimensions, general properties and proportions of the material, direction and type of loading, relation of direction of load to molding pressure, to laminate and to grain of material, load and deflection data, rate of loading and strain rate and location and type of failure which has resulted from the loading, all shall be observed.

6.032.7 Report. A load deflection curve should be plotted showing the proper travel limit, flexural strength, modulus of elasticity and maximum fiber strength.

a. The modulus of elasticity is to be computed by the equation:

$$E_F = \frac{L^3}{4bd^3} \times \frac{P}{Y}$$

where: E_F = modulus of elasticity in bending, psi
L = span length, in
b = width of beam, in
d = depth of beam, in
$\frac{P}{Y}$ = slope of straight line portion of load deflection curve, lb/in

b. The flexural and maximum strengths are to be computed by:

$$S = \frac{3PL}{2bd^3}$$

where: P = load, pounds
L = span length, in
b = width of beam, in
d = depth of beam, in

6.032.8 Test Equipment. Any suitable flexural testing machine can be used. Loading and support edges should have 1/8 inch radius noses. For excessive deformations, the nose radius should be 1 1/2 times the specimen depth.

6.032.9 Measuring and recording equipment. None given.

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.03 Flexure Tests

6.033 Test T6.033

6.033.1 Source. FPL Report No. 1807, "Effect of Span Depth Ratio and Thickness On The Mechanical Properties Of A Typical Glass Fabric - Base Plastic Laminate As Determined By Bending Tests."

6.033.2 Specimen. The ratio of width to depth for each specimen was approximately 2, except for those 1/16 inch laminates which were 1/2 inch wide. The span/depth ratios were as indicated in Table 6.033.2. Other than this the specimens met the specification of T6.032 ASTM.

TABLE 6.033.2

Thickness in	plies	Span/depth Ratio
1/16	7	16, 20, 30
1/4	25	12, 16, 20, 26, 32, 38
1/2	50	12, 16, 30

6.033.3 Conditions. None given.

6.033.4 Procedure - Preliminary. None given.

6.033.5 Procedure - Testing. See T6.032 ASTM.

6.033.6 Observations. See T6.032 ASTM.

6.033.7 Report. See T6.032 ASTM.

6.033.8 Test Equipment. See T6.032 ASTM.

6.033.9 Measuring and Recording Equipment. None given.

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.03 Flexure Tests

6.035 Test T6.035

6.035.1 Source. "Improved NoL Ring Test Method For Parallel Glass Roving Reinforced Plastics - Evaluation of Chemical Finishes."

6.035.2 Specimen. Specimens are to be cut from a 6 inch diameter by 1/4 inch wide by 1/8 inch thick ring. The span to depth ratio should be 16 to 1.

6.035.3 Conditions. Specimens were tested dry and after varying periods of being immersed in boiling water.

6.035.4 Procedure - Preliminary. None given.

6.035.5 Procedure - Testing. Testing head speed should be 0.05 in/min.

6.035.6 Observations. The conditions and pre-conditioning of the specimen, constituents of the specimen, loading rate, failure load, specimen length, width, and thickness should be given. Five specimens are to be tested.

6.035.7 Report. The ultimate flexural strength is to be computed by the following equation;

$$\sigma_{FU} \quad \frac{3PL}{2bd^2} .$$

Both stress and strain values are to be recorded in order that a modulus can be determined.

6.035.8 Test Equipment. Tests were conducted on a universal testing machine.

6.035.9 Measuring and Recording Equipment. None given.

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.04 Shear Tests

6.041 Test T6.041 ASTM

6.041.1 Source. ASTM D732-46, Shear Strength of Plastics.

6.041.2 Specimen. The specimen shall be 2 inches square or 2 inches in diameter and can be molded or cut from sheet material. The thickness may vary from 0.005 inch to 0.500. The specimen should have parallel faces and a 7/16 inch hole drilled through its center.

6.041.3 Conditions. Conditioning of test specimens should conform to ASTM D-618, except that the conditioning practice described as Method D, Procedure B shall be modified to allow testing once the specimen has reached room temperature. For Procedure A or B, Method D, the test should be run at 23 ± 1C. If procedure A, Method D, is used, the relative humidity should be kept at 50± 2 per cent.

6.041.4 Procedure - Preliminary. Specimen should be placed over the holding pin and after positioning, the bolt is tightened. The pin and punch assembly is then placed on the body of the tool and the bolts tightened. See Fig. 6.041.8.

6.041.5 Procedure - Testing. Crosshead speed should be 0.05 inch per minute.

6.041.6 Observations. Five specimens should be used. The maximum load which is required to drive the moving portion of specimen completely clear of the stationary part is the punching shear.

6.041.7 Report. Complete identification of specimen including material, manufacturer, dimensions, previous history, method of test as well as environmental conditions and conditioning procedure should be given. Punch diameter, maximum load and calculated shear strength, in psi on the basis of shear area of the punched section should be reported.

6.041.8 Test Equipment. A constant strain testing machine should be used. The weighing mechanism should be free of inertial drag and be accurate to ± 1 per cent of the indicated value. A shear tool similar to the one shown in Fig. 6.041.8 should be used.

6.041.9 Measuring and Recording Equipment. None given.

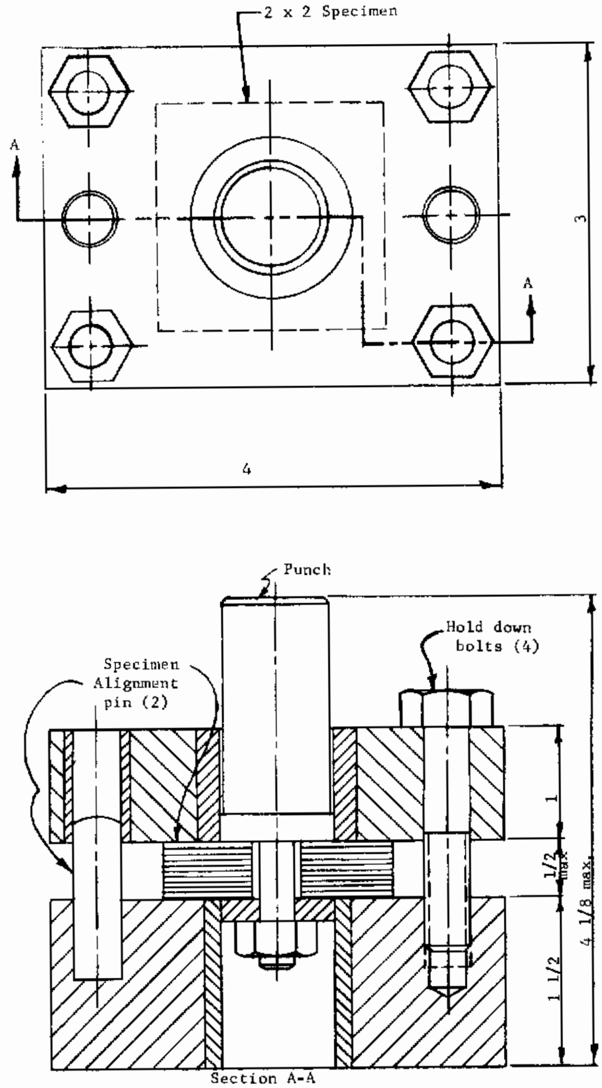


FIG. 6.041.8 TYPICAL PUNCH SHEAR TOOL

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.04 Shear Tests

6.042 Test T6.042LP.

6.042.1 Source. LP-406b Federal Specification for Plastics, Organic: General Specifications, Test Methods: Method 1041: Shear Strength (Double Shear).

6.042.2 Specimen.

a. For thermosetting materials, test cylinders are to be 1/2 inch in diameter, however, diameters of 3/8 and 1/4 inch can be used. The length of the cylinder is to be at least 3 times its diameter. Rectangular specimens are to be suitable for a Johnson-type shear tool.

b. For thermoplastic materials only rectangular specimens are acceptable. Sizes of 3 inches by 1/2 to 1 inch by 1/8 inch or less should be used. If the material is over 1/8 inch thick, machining will be required before a specimen can be acceptable.

6.042.3 Conditions. None given.

6.042.4 Procedure - Preliminary. None given.

6.042.5 Procedure - Testing. Range of head travel under load shall be from 0.015 to 0.025 in/min.

6.042.6 Observations. None given.

6.042.7 Report. This should include the information given in Section 10.02 LP as well as the type of jig and loading used.

6.042.8 Test Equipment. A standard tension testing machine is to be used with a three-plate jig or a Johnson-type Shear Tool.

6.042.9 Measuring and Recording Equipment. None given.

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.04 Shear Tests

6.043 Test T6.043.

6.043.1 Source. FPL Report No. 1821, "Mechanical Properties of Cross-Laminated and Composite Glass-Fabric-Base-Plastic Laminates."

6.043.2 Specimen. The shape of the test specimen is somewhat comparable to that of a formec cross. The center portion common to the 4 arms of the cross is a 3 inch square such that in the center loaded section two edges are parallel to the warp direction. The jigs for applying shear loads to the square center portion are bonded and bolted to the arms of the cross. The reader is referred to the source for illustrations of this.

6.043.3 Conditions. Preconditioning was done at 75F and 50% RH. During testing no control of temperature and humidity was attempted.

6.043.4 Procedure - Preliminary. Specimen placement is such that loads are transmitted through rollers of the jig through the 4 arms of the cross and thence along the edges of the 3 inch square resulting in a case approaching pure shear.

6.043.5 Procedure - Testing. Loads were applied at the rate of 0.01 in/min of head travel.

6.043.6 Observations. A minimum of 2 specimens were tested. The thickness, number of plies, constituent and mechanical properties of each individual ply should be observed. The applied strains and loads should be recorded.

6.043.7 Report. The property of the of the laminate was determined bv the following equation:

$$F_a = \frac{1}{A} \sum_{i=1}^{i=n} F_i A_i$$

where:

F_a = Property of the laminate
A_a = Area of the laminate
F_i = Property of the i^{th} ply of the laminate
A_i = Area of the i^{th} ply

6.043.8 Test Equipment. The "panel shear apparatus" described in the source was used with a constant strain loading apparatus.

6.043.9 Measuring and Recording Equipment. Strains were measured over a 1 inch gage length with a Tuckermon Strain Aparatus.

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.04 Shear Tests

6.044 Tests T6.044

6.044.1 Source. Boeing T6-1814, "Panel Shear Testing of Thin Epoxy Hetanhydride Laminates".

6.044.2 Specimen. The specimens used were approximately 5.75 in x 3.00 in x 0.05 in thick. For high tools, the size was 5.75 in x 2.00 in x thickness.

6.044.3 Conditions. None given.

6.044.4 Procedure - Preliminary. The fixture was bonded to the specimen with type 2 adhesive with a cure pressure of 30 psi in a heated atmosphere.

6.044.5 Procedure - Testing. Panels were tested at 0° and 45° to the direction of warp. Specimens were strained at the rate of 0.025 in/min.

6.044.6 Observations. The make up of the laminate and total load to fail the specimen should be given.

6.044.7 Report. The shear strength is expressed by the following equation:

$$\sigma_{su} = P/A$$

where: P = Total load, pounds
A = Total area, sq. in.

6.044.8 Test Equipment. A special jig to hold the specimen was developed and is shown in Figure 6.044.8. This figure also shows how the specimen is placed into the jig and frame assembly.

6.044.9 Measuring and Recording Equipment. None given.

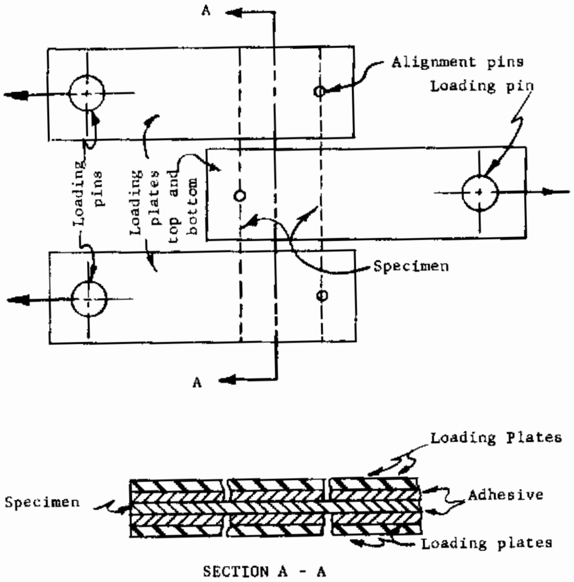


FIG 6.044.8 BOEING SHEAR APPARATUS

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.04 Shear Tests

6.045 Test T6.045.

6.045.1 Source. NAVORD Report 6153, "Improved NOL Ring Test Method for Parallel Glass Roving Reinforced Plastics; Evaluation of Chemical Finishes".

6.045.2 Specimen. The specimens were removed from a 6" diameter x 1/4" wide x 1/8" thick ring. They were 0.635 ± 0.002 inch long as measured along the chord of the convex side.

6.045.3 Conditions. Dry tests were run after 4 days conditioning at 23C and 50% RH. Specimens subjected to wet test conditions were boiled the prescribed length of time and placed in water at 23C for at least 15 minutes before testing.

6.045.4 Procedure - Preliminary. The specimen is to be placed with convex side up on well lubricated sliding supports in a horizontal shear jig as illustrated in the source.

6.045.5 Procedure - Testing. Rate of loading was 0.05 inch per minute.

6.045.6 Observations. No indication of the number of specimens required is given. The breaking load (P), width (b) and thickness (t) of specimen are required as well as the description of the material tested.

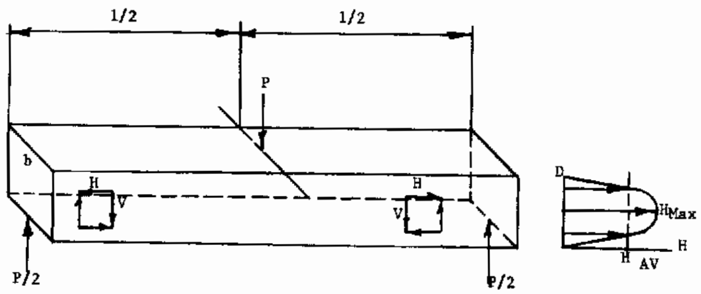
6.045.7 Report. Shear strength should be computed assuming the specimen to be as shown in Fig. 6.045.7, by the following equation:

$$\text{Horizontal shear} = \frac{0.75P}{bd}$$

where P, b and d are as defined in 6.045.6.

6.045.8 Test Equipment. A jig for holding and aligning the specimen was used. No identification of the apparatus for the application of load onto the jig is indicated.

6.045.9 Measuring and Recording Equipment. None given.



$$V = H_{Av} = \frac{2}{3}$$

$$H_{av} = V = \frac{P}{2} \cdot \frac{1}{bd}$$

$$H_{max} = \frac{3}{2}V = \frac{3}{4} \cdot \frac{P}{bd}$$

FIG. 6.045.7 HORIZONTAL SHEAR IN A BEAM

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.06 Creep and Creep Rupture Tests

6.061 Test T6.061 ASTM

6.061.1 Source. ASTM D674-56, Long-time Creep or Stress - Relaxation Tests of Plastics under Tension or Compression Loads at Different Temperatures.

6.061.2 Specimen. Tension specimens should conform to ASTM D638 (See T6.011 ASTM). Compression specimens should conform to ASTM D695 (See T6.021 ASTM) except that the slenderness ratio, L/r, should be between 11 and 15.

6.061.3 Conditions. The test environment should be held at constant temperature which should not vary over the length of the specimen. For a five inch length acceptable variations are as follows:

Test Temp Range - F	Acceptable Variation
-50 to 300	$\pm$ 1
300 to 500	$\pm$ 2
800 to 1200	$\pm$ 3

The specimen should be isolated from vibration. Preconditioning should be done as described in ASTM D618 (See S10.01 ASTM) and, in addition, dimensional stability should be obtained for constant temperature and relative humidity for 48 hours prior to testing.

6.061.4 Procedure - Preliminary. The grips and gripping technique should be designed to minimize eccentric loading of the specimen.

6.061.5 Procedure - Testing. Specimen should be tested to failure at times of less than 10 hours and up to 1000 hours. Loads should be accurate to within 1 per-cent. Either a constant stress or constant load procedure is acceptable.

6.061.6 Observations. Suggested time intervals for both creep and relaxation strain and stress measurements are 0.1, 0.2, 0.5, 0.7, 1, 2, 3, 5, 7, 10, and 20 hours; then every 24 hours to 500 hours; and every 48 hours to 1000 hours. Four (4) specimens should be run at each temperature.

6.061.7 Report. A description of the materials, preconditioning, specimen dimensions and equipment should be presented. Curves for total creep as a function of total strain should be plotted on rectangular or log-log coordinates. Parameters of temperature and humidity should be included.

6.061.8 Test Equipment. Dead weights are to be applied directly to the creep specimen or through levers if the vibration is small. If a relaxation is to be measured, a screw-type load adjustment that is actuated by the strain in the specimen should be used.

6.061.9 Measuring and Recording Equipment. Strain should be measured to the nearest 0.001 in. if the total strain is above 50 per cent. Extensometers should be made of stable materials.

6.0 TEST METHOD - MECHANICAL PROPERTIES

6.06 Creep and Creep Rupture Tests

6.062 Test T6.062 LP

6.062.1 Source. LP-406b. Federal Specification for Plastics, Organic: General Specifications, Test Methods; Method 1063.1, Tensile Time-Fracture and Creep.

6.062.2 Specimen. Specimens should conform to LP-406b Method 1011 (See T6.013 LP).

6.062.3 Conditions. None specified.

6.062.4 Procedure - Preliminary. Load should be applied by a dead weight or lever system. Load should be placed without producing impact on specimen.

6.062.5 Procedure - Testing. Test should be at least 1000 hours in duration and all tests should begin simultaneously. Initial elongation is defined as consisting of elastic elongation plus the creep during the first 60 seconds of loading.

6.062.6 Observations. Time and elongation are to be recorded at intervals. Tensile strength of the specimen is to be obtained as specified under LP-406b Method 1011.

6.062.7 Report. Stress and strain are to be presented as functions of time to failure. Time is to be plotted as the abscissa.

6.062.8 Test Equipment.

6.062.9 Measuring and Recording Equipment.

6.0 TEST METHOD - MECHANICAL PROPERTIES

6.06 Creep and Creep Rupture Tests

6.063 Test T6.063

6.063.1 Source. Wright Air Development Center Technical Report 53-491 High Temperature Creep - Rupture Properties of Glass Fabric Laminates.

6.063.2 Specimen
a. Tension, See Fig. 3.063.2a.
b. Compression, 1 x 1/4 x 1/4

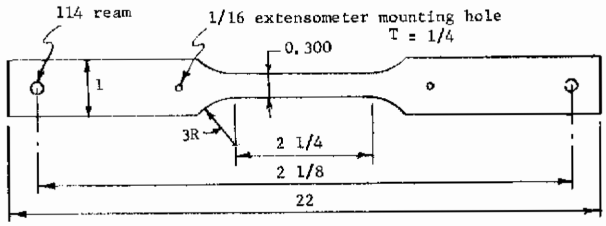


FIG. 3.063.2a SPECIMEN FOR CREEP TESTS IN TENSION

6.063.3 Conditions. Both tension and compression tests were conducted at 80 and 500F. Relative humidity varied between 30 and 76 percent and was not controlled.

6.063.4 Procedure - Preliminary
a. Tension specimens were aligned and loaded through a 1/4 inch pin inserted in each end.
b. Compression specimens were seated on hemispheres at each end in an attempt to achieve self-alignment.

6.063.5 Procedure - Testing. Tests were designed to produce rupture at times which varied between 0.10 and 1000 hours.

6.063.6 Observations. Time and elongation were recorded at intervals. Strength tests were conducted on panels in flexure for comparison purposes.

6.063.7 Report. Composition and specific data for each specimen should be recorded. Time and elongations are to be indicated. Deformation in percent should be plotted as a function of time with time being the abscissa.

6.063.8 Test Equipment. An electric furnace was used to obtain the 300 and 500F temperatures and it was controlled to ± 2F.

6.063.9 Measuring and Recording Equipment. Deformations were recorded with a platinum strip extensometer. These were polished and scribed to obtain an original length. A microscope accurate to 0.00005 in. was used to measure the change of position of the scribed marks.

6.0 TEST METHODS

6.07 Fatigue Tests

6.071 Test T6.071 ASTM

6.071.1 Source. ASTM D671-51T, Repeated Flexural Stress (Fatigue) of Plastics.

6.071.2 Specimen.

a. Unnotched specimen, Fig. 6.071.2a, shall have a critical section 0.30 x 0.30 inch or 0.30 by the sheet thickness where same is less than 0.30. The 2 in radius is to be carefully milled and finished. Final finishing shall be with No. 00 emery paper in the direction of the specimen length.

b. Standard V-notch specimen, Fig. 6.071.2b, shall have a transverse notch on one side only as shown.

c. Drilled hole specimen, Fig. 6.071.2c, shall be used for their sheet material in lieu of the V-notch specimen. Burrs shall be removed after drilling the polished specimen, but no attempt shall be made to smooth the inside of the hole.

6.071.3 Condition. All specimens are to be preconditioned for 14 hours. Conditioning of specimens should conform to ASTM D-618 for purpose of obtaining reproducible results. See Section S10.01 ASTM. Tests shall be conducted in still air (velocity less than 50 feet per minute).

6.071.4 Procedure - Preliminary. The vice holding the specimen shall be carefully positioned to assure the proper maximum and minimum stress values. In some cases it may be necessary to use rubber gaskets in the specimen holder and the Dynamometer to prevent failure in the grips.

6.071.5 Procedure - Testing. The temperature of the specimen is to be measured by a thermocouple attached with cellulose tape 1/8 inch wide. The speed of testing should be 1720 $\pm$ 25 cycles per minute.

6.071.6 Observations. The deflection and load on the specimen shall be recorded at 0, 12 and 24 hours. The number of cycles to failure is to be recorded and the type of classified as follows:

a. Rapid progress of a spreading crack,
b. Rapid cracking and then progress to failure, or
c. Overheating and softening of the specimen.

A sufficient number of specimens shall be run to show that the S-N curve is asymtotic.

6.071.7 Report. No corrections shall be made for the stress values at the minimum section, away from the minimum section, for the position of maximum stress or a change in dynamometer reading. A standard S-N plot on semi-log paper shall be used to present the data. If specimens do not fail, this is to be indicated by arrows directed toward increasing number of cycles.

6.071.8 Test Equipment. A fatigue testing machine of the fixed-cantilever, repeated constant deflection type shall be used. A balanced specimen holder such that the center of percussion of the oscillating portion of the specimen and holder shall be at the wrist pin. Suggested details for the holder are given in the source.

6.071.9 Measuring and Recording Equipment. A flex-beam type dynometer to measure load on the specimen shall be calibrated with known dead weight. A cycle counter shall be used in such a way that it will stop upon failure of the specimen.

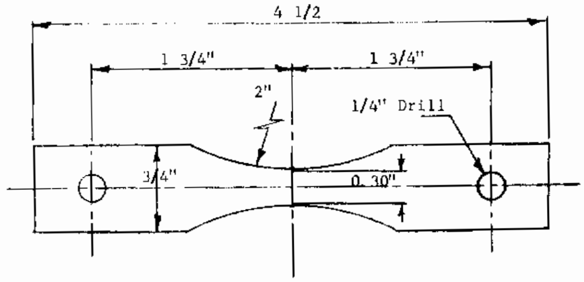


FIG. 6.071.2a UNNOTCHED SPECIMEN

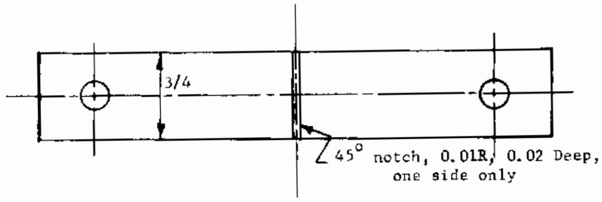


FIG. 6.071.2b STANDARD V-NOTCH SPECIMEN

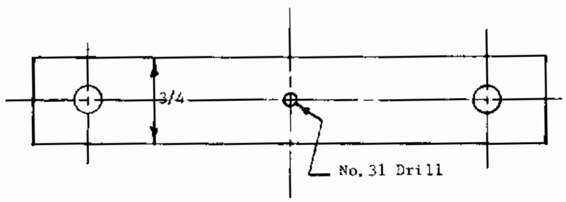


FIG. 6.071.2c DRILLED HOLE SPECIMEN

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.07 Fatigue Tests

6.072 Test T6.072 LP

6.072.1 Source. LP 406b, Federal Specification for Plastics Organic: General Specifications, Test Methods; Method 1061: Constant-Strain Flexural Fatigue Strength.

6.072.2 Specimen. Dimension of test specimens should conform to those shown in Fig. 6.072.2 and the thickness should be 1/8 inch. The edges of specimens which are machined from thermoplastics should be polished with a compound. Other materials should be finished with fine sandpaper or emery cloth.

6.072.3 Conditions. None given.

6.072.4 Procedure - Preliminary. None given.

6.072.5 Procedure - Testing. Specimen should be cycled 1725 times per minute.

6.072.6 Observations. These should include all data described under T6.013 LP. The flexural fatigue strength at 10×10^6 cycles, the stress to which each specimen is subjected and the number of cycles to failure shall be observed.

6.072.7 Report. Data are to be presented on a standard semi-log S-N plot.

6.072.8 Equipment. A Krouse-type fatigue testing machine should be used.

6.072.9 Measuring and Recording Equipment. None given.

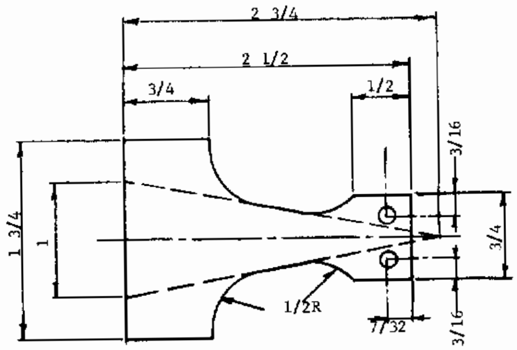


FIG. 6.072.2 KROUSE-TYPE FATIGUE SPECIMEN

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.07 Fatigue Tests

6.073 Test T6.073 LP.

6.073.1 Source. LP-406b, Federal Specification for Plastic Organic: General Specifications, Test Methods; Method 1062: Constant-Stress Flexural Fatigue Strength.

6.073.2 Specimen. The shape of the unnotched or notched specimen should be as shown in Fig. 6.073.2 a and b respectively. Thermoplastic specimens should be polished with a compound. Other materials should be finished with fine sand paper or emery cloth.

6.073.3 Conditions.

6.073.4 Procedure-Preliminary. None given.

6.073.5 Procedure - Testing. Operating speed should be 3,450 or 10,000 revolutions per minute.

6.073.6 Observations. These should include all data described under T6.013 LP. In addition, the flexural fatigue strength in psi at 10 x 10^6 cycles, the stress to which each specimen has been subjected and the number of cycles to failure, and the type of specimen shall be recorded.

6.073.7 Report. The data are to be presented on a standard semi-log S-N plot.

6.073.8 Test Equipment. A O.R.R. Moore-type rotating beam fatigue testing machine should be used.

6.073.9 Measuring and Recording Equipment. None given.

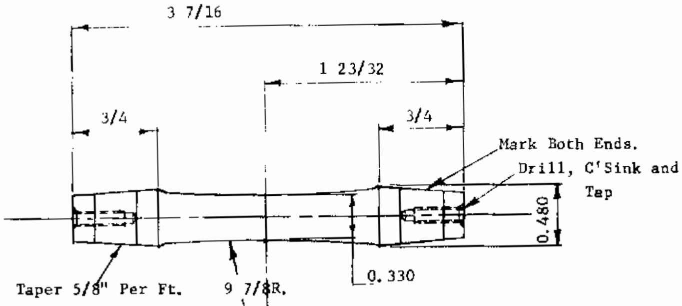


FIG 6.073.2a UNNOTCHED SPECIMEN

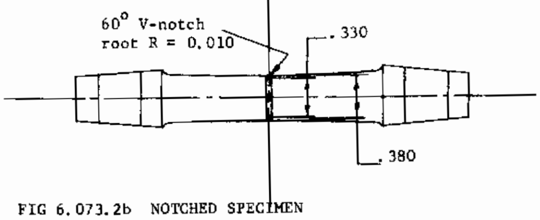


FIG 6.073.2b NOTCHED SPECIMEN

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.07 Fatigue Tests

6.074 Test T6.074

6.074.1 Source. F.P.L. Report No. 1823, "Fatigue Tests of Glass-Fabric - Base Laminates Subjected to Axial Loading."

6.074.2 Specimen. The specimen was designed for tension and compression use and is shown in Fig. 6.074.2. The unsupported length was 2 1/4 inches. A notched specimen was produced by placing a 1/8 inch circular hole at the center of the specimen and perpendicular to the laminates. Specimens were cut from the panel with a carborundum saw at 0^o and 45^o to the direction of warp, and were finished with an emery wheel. No burrs were allowed at the notch, however, no polishing was done.

6.074.3 Conditions. Tests were run under three sets of conditions as follows:

a. Standard (75F and 50 RH),
b. Standard plus cooling air,
c. Preconditioned 30 days at 100F and 100 RH and tested at 75F and 98 RH in cooling air.

6.074.4 Procedure - Preliminary. Notched and unnotched specimens were clamped at the ends to give an axial stress at the above test conditions. The length between clamps was 2 1/4 inches.

6.074.5 Procedure - Testing. Tension and compression repeated loads were applied at the rate of 1900 cycles per minute. These had a mean stress of zero, about 20% of the maximum stress and about 50% of the ultimate notched strength. Static tensile loads were applied at 0.035 inch per minute, while static compressive loads were applied at the rate of 0.012 inch per minute.

6.074.6 Observations. Three static tensile tests and three static compressive tests were run. No indication of the minimum number of fatigue tests is given.

6.074.7 Report. The static ultimate strength and modulus of elasticity in tension and compression, should be reported for the physical constituents of the material. Data are to be presented as alternating stress as a function of the logarithm of the number of cycles to failure (Standard S-N plot).

6.074.8 Test Equipment. A fatigue loading machine of the rotating cam type with a capacity of 10,000 pounds was used. A fan was used to force air around specimens where conditions dictated.

6.074.9 Measuring and Recording Equipment. Loads were measured on a calibrated flexure plate through electric resistance strain gages. Data were taken from a wheatstone bridge and an oscillograph.

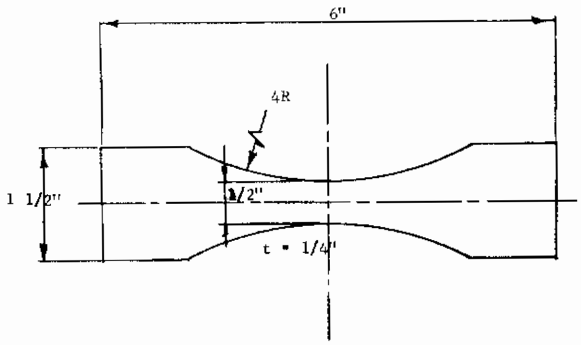


FIG. 6.074.2 FATIGUE SPECIMEN

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.07 Fatigue Tests

6.075 Test T6.075

6.075.1 Source. SPI 12th ANTEC, Section 12-C pp. 1-8, 1957. Accelerated Fatigue of Reinforced Plastics.

6.075.2 Specimen. Rods were machined radially to a minimum diameter according to ASTM specifications (STP-93). Sheet specimens of 13 plies of heat treated glass cloth, prepared to ASTM D638-52T specifications were used.

6.075.3 Conditions. None given.

6.075.4 Procedure - Preliminary. None given.

6.075.5 Procedure - Testing. Stress levels were increased as the test was being conducted. Care was taken to adjust the rate of increase properly. Testing speed was 1,900 cycles per minute. No ultimate loading rate is suggested.

6.075.6 Observations. It is necessary to observe and record the loading rate and mean stress endurance limit.

6.075.7 Report. Stress was presented as a function of the square root of the loading rate.

6.075.8 Test Equipment. A Sontagg SF-1-U Universal Fatigue Machine for holding round and flat specimens was used, with an adapter for varying the stress level while the machine was in operation.

6.075.9 Measuring and Recording Equipment. Loads were measured with a SR4 load-cell after amplification in an oscilloscope. Accuracy of this unit is the smaller of $\pm$ 2% or $\pm$ 4 pounds.

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.08 Elastic Modulus Tests

6.081 Test T6.081 ASTM

6.081.1 Source. Young's Modulus in Flexure of Natural and Synthetic Elastomers at Normal and Subnormal Temperatures ASTM D797-58.

6.081.2 Specimen. The specimen should be cut from molded sheets or molded to size. They are to be rectangular in cross-section and have the longitudinal axis parallel to the calendar grain, unless the effect of the grain is to be evaluated. The thickness of the specimen is to be selected such that a weight of not more than 2.5 pounds will give the required deflection indicated under 6.081.5. Dimension are as follows:

Width	1.00" ± 0.01"
Thickness	0.250" ± 0.002"
Length	2.50" ± 0.025"

6.081.3 Conditions. Subnormal temperatures are to be achieved in a covering chamber and maintained at ± 1.0F. This should be automatically regulated and held uniform throughout by a fan. Standard tests are to be run at 73F after allowing the specimen to stand for 15 minutes. Tests are to be repeated at 32F, -40F, -67F, and lower if possible.

6.081.4 Procedure - Preliminary. An aligning mechanism shall be used in placing the specimen under the loading foot. Retaining pins should be placed at each end and side of the specimen.

6.081.5 Procedure - Testing. The initial load is to be 0.09 to 0.11 lb. at the center of the specimen to obtain a known deflection and weight position. The weight pan is then loaded until a deflection of between 0.010 and 0.025 is obtained. Remove the weights and allow the specimen to rebound for 10 seconds before recording the deflection. Reapply the load and allow 15 seconds before reading the deflection. Crystallization of the material should be checked.

6.081.6 Observations. No indication is given as to the number of specimens to be tested. For each test the dimensions of the specimen, distance between supports, initial and second dial indicator readings, and applied load should be noted. A complete set of information about the material should be included with each specimen.

6.081.7 Report. The data are to be shown as Young's modulus as a function of the test temperature. Young's modulus is to be computed by the use of the following equation.

$$E = \frac{Ll^3}{4wt^3 (R_2 - R_1)}$$

where E = Young's Modulus
L = Load in pounds, added in the weight pan.
l = distance between supports, in inches.
w = Width of specimen R_1 and R_2 = dial indicator readings as described in 6.081.5

6.081.8 Test Equipment. Curved surfaces of supports and loading foot should have a radius of 0.187 ± 0.003 in., and a length of at least 1.01 in. Distance between supports should be 2.000 ± 0.002 in.

6.081.9 Measuring and Recording Equipment. The top end of the loading rod should be attached to a deflection indicator.

6. TEST METHODS - MECHANICAL PROPERTIES

6.08 Elastic Modulus Tests

6.082 Test T6.082 ASTM

6.082.1 Source. ASTM D638-60T, Tensile Properties of Plastics.

6.082.2 Specimen. See T6.011.

6.082.3 Conditions. Conditioning of test specimens should conform to ASTM D-618 for purposes of obtaining reproducible results. See Section S10.01. No environmental conditions are specified by source.

6.082.4 Procedure - Preliminary. See T6.011.

6.082.5 Procedure - Testing. The speed of testing shall be 0.20 or 0.25 inches per minute except for molded laminated thermosetting materials which are to be tested at 0.05 inches per minute. Modulus values should be obtained using separate specimens from those used to determine tensile strength and elongation when the speeds are not the same.

6.082.6 Observations. At least five specimens should be tested and an additional five if the material is orthotropic. The testing speed and load carrying capacity shall be recorded when a strain of 0.02 in/in. is reached. If failure occurs before this strain, record the data as at failure.

6.082.7 Report. The average value and the standard deviation should be computed.

6.082.8 Test Equipment. See T6.011.

6.082.9 Measuring and Recording Equipment. See T6.011.

6. TEST METHOD - MECHANICAL PROPERTIES

6.08 Elastic Modulus Tests

6.084 Test T6.084 ASTM

6.084.1 Source. ASTM D747-58T, Stiffness in Flexure of Plastics.

6.084.2 Specimen. The specimen may be either molded or cut from a sheet. The size is to be determined by the capacity of the machine and stiffness of the material. They should not be polished or buffed but should be rubbed with talc if the surface is "tacky".

6.084.3 Conditions. Pre-conditioning, and tests should be done in accordance with Method A of ASTM D-618 Specification. See Section S10.01. If the tests are to be conducted at elevated or reduced temperatures, the specimens and the tester should be conditioned for at least two hours prior to test.

6.084.4 Procedure - Preliminary. Place specimen in apparatus and level the machine and adjust the load scale to zero. The specimen should be clamped firmly in the vise and aligned parallel to the face of the dial plate. To test below 32°F the gear and bearing lubricant should be removed and kerosene used as the lubricant.

6.084.5 Procedure - Testing. The rate of loading is controlled by the rate of angular rotation of the specimen which is fixed at a rate of 58 to 66° per minute. Initial rotation of 1° is to be applied by the hand crank device and the angle measuring device then set to zero. A motorized drive may then be engaged and load readings taken every 3° until a total of 20° is measured, thereafter, 10° increments shall be read until failure or 90° is reached. Once the test is started, it is to continue to completion without stopping.

6.084.6 Observations. The load and angle of rotation are to be measured. It is necessary to know the length, width, and depth of specimen, in order to determine the stiffness. Three specimens should be tested and the results avaraged.

6.084.7 Report. The report should include the stiffness which is evaluated in the following way.

$$E = \frac{4S}{wd^3} \times \frac{M \; s \; \text{Load Scale Reading}}{100 \, \phi}$$

where:

S = Span length in inches
w = Width of specimen in inches
d = Thickness of specimen in inches
ϕ = Angular deflection in radians
M = Total moment of the pendulum system, a_1, plus the moment indicated on the calibrated weight, a_2, (a_1, and a_2 refer to Fig. 6.084.8.
E = Stiffness in flexure in pounds per square inch

The data are to be plotted showing load as a function of the angle of rotation. The plot is to be moved parallel to itself until it passes through the origin of the coordinate system, if the initial curve failed to do this.

6.084.8 Test Equipment. See Fig. 6.084.8. The vise of the apparatus rotates clockwise indicating the angle through which it has turned on the deflection scale A. The weight system rotates as the specimen carries load into the bending plate, Q, with magnitude indicated on the load scale by pointer I.

6.084.9 Measuring and Recording Equipment. The angluar deflection scale, read in degrees, is used to determine the difference in rotation between the specimen and the attached weights. The load measuring scale measures the deflect 10X θ, and shall be calibrated to read directly 100 L Sin θ.

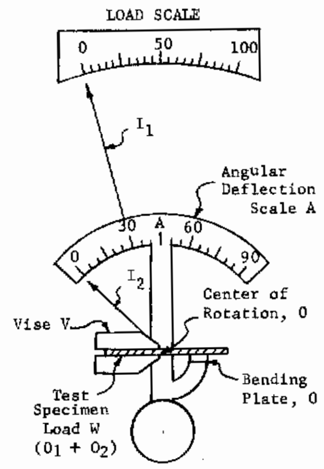


FIG. 6.084.8 MECHANICAL SYSTEM OF STIFFNESS TESTER

6. TEST METHOD - MECHANICAL PROPERTIES

6.08 Elastic Modulus Tests

6.083 Test T6.083 ASTM

6.083.1 Source. ASTM D1530-58T, Tensile Modulus of Elasticity of Thin Plastic Sheets.

6.083.2 Specimen. All specimens are to be less than 0.040 in. thick and at least 2 inches longer than the distance between the grips. The test section should be 10 in. long, with a width greater than 0.19 in., but less than 0.25 in. The dimensions are to be chosen such that non-linear behavior occurs above 2/3 the total load range. Also, a width to thickness ratio greater than 8 should be achieved. All specimens are to be cut so that nicks and tears are not eliminated.

6.083.3 Conditions. Conditioning of test specimens should conform to ASTM D-618 for purposes of obtaining reproducible results. See Section S10.01.

6.083.4 Procedure - Preliminary. Measurement of thickness to 0.000 in. and width to 0.010 in. is to be made before placement of the specimen in apparatus. Care must be used when placing the specimen in the grips so that it is aligned in such a way that no moment can be produced during loading. Set the grips firmly to minimize slippage.

6.083.5 Procedure - Testing. The speed of testing shall produce a strain rate of 10 ± 0.5 percent per minute.

6.083.6 Observations. For isotropic material five specimens should be tested. For orthotropic materials ten specimens should be tested, five normal and five parallel to the principal axis of anisotropy. The test is to be discontinued when the load extension curve deviates from linearity. If an extensometer is used, this should be so indicated.

6.083.7 Report. A load-extension curve should be drawn and this curve used to calculate the modulus of elasticity. A secant modulus at a given strain can be calculated by dividing the tensile stress by the strain. The standard deviation shall be recorded. It is to be arrived at as follows:

$$S = \frac{\Sigma X^2 - n\bar{x}^2}{n-1}$$

where:

S = estimated standard deviation,
X = value of a single observation,
n = number of observations, and
$\bar{X}$ = arithmetic mean of the set of observations.

The following should be included when reporting the data: the type of material, any prior history, orientation of sample, conditioning, dimensions, gripping arrangement and number of specimens tested.

6.083.8 Test Equipment. A constant strain testing machine, accurate to ± 2 percent in travel ratio and load measurement, shall be used. The grips are to give an even stress distribution across the specimen. To achieve this it may be necessary to line the grips with thin rubber or crocus cloth.

6.083.9 Measuring and Recording Equipment. Micrometers accurate to 0.0001 in. are necessary. A set of cutting devices which will produce a specimen with no edge nicks and clean straight parallel edges should be used. If short grip separations are employed an extensometer should be used to determine elongations.

6\. TEST METHODS - MECHANICAL PROPERTIES

6.1 Hardness Tests

6.101 Test T6.101 ASTM

6.101.1 Source. ASTM D785-60T, Rockwell Hardness of Plastics and Electrical Insulating Materials.

6.101.2 Specimen. The minimum size of specimens cut from sheet material shall be 1 in square and at least 1 sq. in. if cut from other shapes. The minimum width shall be 1/2 in. and the thickness should be greater than 1/4 in. If the thickness is less than 1/4 in., care should be taken to insure correlation with thicker specimens and that the indentation cannot be seen from the reverse side of the specimen. In order to achieve the 1/4 in. thickness, several sheets may need to be stacked with care to get complete contact between the surfaces. The diameter of rod specimens should be at least 3 times that of the steel ball indenter.

6.101.3 Conditions. Conditioning of test specimens should conform to ASTM D618, Procedure A, for purposes of obtaining reproducible results. See Section S10.01.

6.101.4 Procedure - Preliminary.

a. PROCEDURE A. The apparatus should be leveled and the dashpot adjusted to complete a cycle in 4 to 5 sec without a specimen. When a specimen is in place it should take 5 to 15 sec to complete a cycle. The calibration block of soft metal or plastic is to be placed on the anvil and the elevation ring turned until the specimen contacts the indenter. Set the dial and note the position. A reading between B 50 and B 70 on the red scale indicates that no adjustment is necessary, between B 45 and B 50, adjustment is advisable and for other readings, adjustment is required. These readings are to be observed as the auxiliary hand on the dial passes beyond the zero dial setting.

b. PROCEDURE B. The calibration constant is to be determined using a soft copper block. The pointer is set to zero as in Procedure A and the load release lever is tripped. Continue to reset to zero and trip the lever until no further indentation is indicated. The value in dial divisions is the correction factor.

6.101.5 Procedure - Testing.

a. PROCEDURE A. The load to be applied shall be

TABLE 6.101.5a

Rockwell Hardness Scale (Red Dial Numbers)	Minor Load, kg	Major Load, kg	Indenter Diameter, in
R	10	60	0.5000 $\pm$ 0.0001
L	10	60	0.2500 $\pm$ 0.0001
M	10	100	0.2500 $\pm$ 0.0001
E	10	100	0.1250 $\pm$ 0.0001

selected from Table 6.01.5a such that small readings on the indicator are obtained. Readings over 100 or below 0 are not acceptable but should be reported up to 115. In the high ranges, the accuracy of the instrument is not good. The first data point should be discarded, as the indenter may not be properly seated. The specimen is to be loaded to within $\pm$ 5 divisions of B 30 and final adjustments made. Specimens should not be loaded less than 1/4 in. from the edge nor on the reverse side. Within 10 seconds of the zero adjustment, the trip lever is released and the hardness read on the red scale. If the indentation exceeds the limit of the machine, the next smaller loading from Table 6.1015a should be used. For very soft plastics, ASTM D1706-59T should be used (See T6.102 ASTM).

b. PROCEDURE B. The specimen is placed beneath the indenter and the apparatus zeroed. The load is applied immediately after zeroing and the number of dial divisions passed during the 15 sec immediately after zeroing are observed (black scale).

6.101.6 Observations.

a. PROCEDURE A. The number of times that the needle passes zero on the red scale when loaded and when unloaded shall be ovserved. If the two are equal, record the hardness number as the scale reading plus 100. If the unloaded reading is less than the loaded one, record the hardness number as the scale reading minus 100.

b. PROCEDURE B. The total scale divisions indicated by the dial gage represent the hardness plus the spring constant correction. The difference between these two is the indentation.

6.101.7 Report. The Rockwell hardness values by Procedure A are reported directly. By Procedure B, the Rockwell hardness is to be given as R_{α} = 150 minus the indentation. Also to be reported are the material tested, filler used, number & size of specimens, specimen surface condition, procedure, Rockwell scale number and the standard deviation.

6.101.8 Test Equipment. Rockwell hardness tester and standard test block.

6.101.9 Measuring and Recording Equipment. These are a part of the standard test equipment.

6. TEST METHODS - MECHANICAL PROPERTIES

6.1 Hardness Tests

6.102 Test T6.102

6.102.1 Source. ASTM D1706-59T, Indentation Hardness of Plastics by Means of a Durometer.

6.102.2 Specimen. The specimen shall be at least 1/4 in. thick unless it can be shown that identical results can be obtained from specimen 1/8 in. thick. Thinner specimens should be stacked. All specimens must be flat.

6.102.3 Conditions. Conditioning of test specimens should conform to ASTM D-618, Procedure A. See Section S10.01. For other conditions, the specimen and instrument should be placed in the test environment for 1/2 hour for every 1/8 inch of thickness. If used below room temperature, the durometer should be placed in a desiccator until its temperature is above the dew point temperature.

6.102.4 Procedure - Preliminary. To calibrate the durometer it is held against flat plate glass with the reading for this case being 100. Calibration of the spring in the meters shall be as given in the source. The force on the spring is to be measured in grams by pressing the indenter against the pan of a balance.

6.102.5 Procedure - Testing. The test specimen is to be placed on a flat horizontal surface and the durometer pressed into the plastic while held in a vertical position. The presser foot is to be parallel to the specimen. Maximum values occur immediately after the total pressure is applied. In some instances a time interval will be specified at which the reading is to be taken. In this case the maximum indicator type durometer cannot be used. Measurements over 95 and below 5 are not recommended on the Type A durometer. If they are below 5, use the Type D durometer and if over 95, use a Rockwell hardness tester as in ASTM D785-60T (T6.101 ASTM).

6.102.6 Observations. At least 5 tests should be made. The data from these should be rounded off to the nearest whole number.

6.102.7 Report. The report should include the hardness and standard deviation of the data, complete identification of the material tested, description of specimen, test conditions, type of instrument, description of dead weight used and time of application.

6.102.8 Test Equipment. Standard Durometers shall be used. The indenter foot shall be made of hardened carbon steel.

6.102.9 Measuring and Recording Equipment. None specified.

6 TEST METHODS - MECHANICAL PROPERTIES

6.1 Hardness Tests

6.103 T6.103 ASTM

6.103.1 Source. ASTM D 1526-58T, Bierbaum Scratch Hardness of Plastic Materials.

6.103.2 Specimen. The specimen should be 3 in. by 1 in., but may be any other convenient size. Materials greater than 0.020 in. can be used without mounting. For materials less than 0.020 in., laminated systems can be used. If anisotropy is suspected, specimens should be cut from sheets parallel and perpendicular to the suspected principal axis.

6.103.3 Conditions. Conditioning of test specimens should conform to ASTM D618, Procedure A. See Section S10.01.

6.103.4 Procedure - Preliminary. Specimens less than 0.020 in. in thickness should be bonded to microscope slides by gluing at 1/4 in. from each end. The microscope is to be calibrated against standard stage micrometers. Clamp the scratching stand to the microscope and place a 3 gram weight on the spindle above the diamond point.

6.103.5 Procedure - Testing. The 3 gram weight is applied to the specimen through the diamond needle which is held in a level arm. The sample is to be moved at 0.25 to 0.30 mm per second. This corresponds to 2 turns per second of the staging table crank.

6.103.6 Observations.
a. Method A - Transmitted light. The scratch is to be moved into the field of the microscope by adjusting the mirror such that it is perpendicular to the micrometer scale and causes a well shaded image on the mirror. The force is to be adjusted such that the inside edges of bands Y and Z of Fig. 6.103.6a are sharply focused. Measure the distance between the boundaries Y and Z. Repeat this 3 times at each of three points which are separated by at least 1 mm.
b. Method B - Reflected light. The groove is shown as a dark band bisected by a faint line. Measure between respectived edges on the boundary of the groove.
c. Number of specimens. At least 3 specimens should be tested. For anisotropic materials, three specimens are to be taken parallel and three normal to the suspected principal axis.
d. Data. The data taken is the width of the scratch resulting from the diamond tool. This is to be measured within 5 min. after scratching unless recovery of the scratch is to be studied. Reproducibility of the data should be within 10 percent.

6.103.7 Report. Calculation of the Bierbaum hardness is given as the load on the diamond point in Kilograms divided by the square of the width of the scratch in millimeters. The report shall include this value, identification of the test material, thickness of the specimens, method of measuring the scratch width, and the axis selected for anisotropic materials.

6.103.8 Test Equipment. The Bierbaum scratching tool, which is attached to the microscope stage, consists of a diamond point ground on three surfaces to form the corner of a cube. No roundness of this corner is to be present under a 2000X magnification. The load tool should be capable of applying a 3 gram $\pm$ 10 milligram force. The microscope should have a magnification of 100 to 200X and be suitable for viewing by transmitted light or by reflected light.

6.103.9 Measuring and Recording Equipment. None specified.

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.11 Impact Tests

6.111 Test T6.111 ASTM

6.111.1 Source. ASTM D256-56, Impact Resistance of Plastics and Electrical Insulating Materials.

6.111.2 Specimen.

a. Method A - Izod. Specimen shall be as shown in Fig. 6.111.2a. Specimens taken from sheet material shall be oriented parallel and perpendicular to the length and sheet thickness shall be reduced to not more than 1/2 in. For sheets less than 1/2 in thick, specimens shall be laminated to 1/2 in. However, they may be tested individually if buckling and twisting do not occur under impact loading. Molded specimens shall be notched in the side parallel to the direction of applied molding pressure. Notching is to be accomplished on a milling machine or lathe, and all nicks and burrs shall be removed.

b. Method B - Charpy. Specimen shall be as shown in Fig. 6.111.2a except 1/8 in radius rounded edges shall be provided to fit supports.

c. Method C - Cantilever (0.5 ft lb per inch of notch). Specimen shall be the same as for Method A (See 6.111.2a).

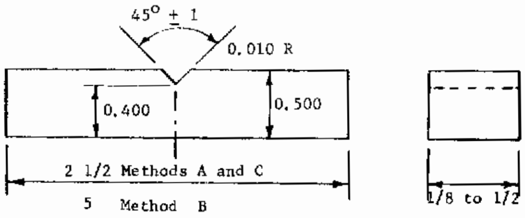


FIG. 6.111.2a IMPACT SPECIMEN

6.111.3 Conditions. Conditioning of test specimens should conform to ASTM D-618 for purposes of obtaining reproducible results. See Section S10.01. No environmental conditions are specified by source.

6.111.4 Procedure - Preliminary.

a. Method A. The specimen should be rigidly clamped in a vertical cantilever position in the impact machine. The notch centerline shall be level with the top of the clamping surface and the notch positioned on the side away from the direction of impact. A jig is suggested to align composite specimens and a torque wrench should be used to tighten clamps to avoid crushing all specimens.

b. Method B. The specimen should be supported on two rigid blocks in a horizontal simple beam position in the impact machine. The center of gravity of the specimen shall be on a line tangent to the arc of the specimen striking surface. The notch shall be positioned on the side away from the direction of impact.

c. Method C. Same as for Method A (See 6.111.4a).

6.111.5 Procedure - Testing. The striking velocity of the pendulum should be approximately 11 ft per sec. For Method C, the "Toss Energy" must be determined. This is measured by repositioning the broken section of the specimen on the clamped end, which remains in the apparatus, and noting the energy required to toss the broken portion of the specimen clear of the apparatus.

6.111.6 Observations. The number of specimens necessary to substantiate a finding is five. For anisotropic materials, five specimens shall be taken parallel and five perpendicular to the principal axis.

6.111.7 Report. The following are to be recorded: number, size, shape and position (in parent material) of the specimens; preconditioning; test conditions; and fracture energy per inch of notch. For Method C, the toss energy shall be recorded.

6.111.8 Test Equipment. A standard pendulum type rigidly constructed impact machine shall be used. It shall be corrected for windage and friction and shall be accurate to ± 0.01 ft lb for energy values of less than 1 ft lb. The center of percussion is to be at the point of striking and the horizontal striking edge shall have a radius of 1/32 in. The striking edge is to hang 0.866 in above the top surface of the vise.

6.111.9 Measuring and Recording Equipment. The impact apparatus shall be equiped with a means of measuring the impact energy absorbed by the specimen. This may be accomplished by a direct reading protractor type scale.

6 TEST METHOD - MECHANICAL PROPERTIES

6.11 Impact Tests

6.112 Test T6.112 ASTM

6.112.1 Source. ASTM D1822-61T, Tensile Impact Energy to Break Plastics and Electrical Insulating Materials.

6.112.2 Specimen. Specimens should be sanded, machined or cut to the dimensions shown in Fig. 6.112.2. It is suggested that they be machined to 1/8 in. in thickness, but this dimension can vary from 1/6 to 1/4 in. The short specimen, Type S, is used when a brittle fracture is expected, while the longer specimen, Type L, is used when a ductile failure may be expected. Both types should be tested to study the effect of elongation.

6.112.3 Conditions. These are to be as given in ASTM-D618 unless otherwise specified. See Section S10.01.

6.112.4 Procedure - Preliminary. The specimen should be positioned to give pure tension when the load is applied, and such that no stress is present until the impact loading takes place. The specimen is to be clamped into the cross head while the cross head is out of the machine. Alignment difficulties may necessitate the use of a jig. The specimen is then to be clamped at the other end to the pendulum.

6.112.5 Procedure - Testing. The pendulum velocity at striking should be 11.3 ft/sec.

6.112.6 Observations. At least 5 specimens should be tested for isotropic materials. In the case of anisotropic materials, 5 specimens should be prepared parallel and 5 normal to the direction of the principal axis. The energy to failure shall be observed.

6.112.7 Report. Corrected impact energy is to be given as follows:

where*: $X = E - Y + e$
X = corrected impact energy to break,
E = scale reading of energy to break,
Y = windage and friction corrections, and
e = bounce correction factor as given in Source.

The report should also include the type of material, specimen shape and preparation, number of specimens, average energy classification as to brittle or ductile failure, and standard deviation of the impact energy.

6.112.8 Test Equipment. The apparatus is to be of the pendulum type with the center of percussion within $\pm$ 0.100 in. of the point of contact of the striker. The machine is to be of rigid construction.

6.112.9 Measuring and Recording Equipment. A measuring device is to be attached to the machine to indicate the energy absorbed by the specimen. This is also to be used to determine the windage and friction loss. Measurements of specimens are to be determined with a ball-type micrometer.

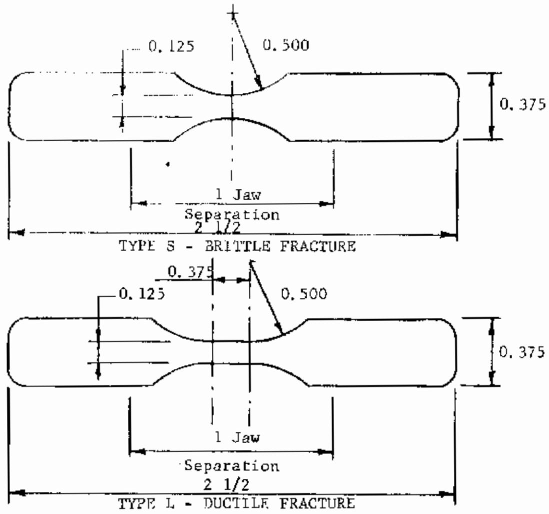


FIG. 6.112.2 TENSILE IMPACT SPECIMENS

6 TEST METHOD - MECHANICAL PROPERTIES

6.11 Impact Tests

6.113 Test T6.113 LP

6.113.1 Source: LP-406b Federal Specification for Plastics, Organic: General Specifications, Test Methods; method 1071: Izod Impact strength. (Note: Although not identical, this method conforms in general to ASTM D256-56, Method A; See T6.111 ASTM.)

6.113.2 Specimen. Specimens should conform to Fig. 6.113.2. The notch should be milled. For molded material, the specimen should be parallel to the direction of molding.

6.113.3 Conditions. None given.

6.113.4 Procedure - Preliminary. The top surface of the vise should be on the center line of the specimen notch. Laminated specimens must be aligned and held close together.

6.113.5 Procedure - Testing. The velocity on impact should be approximately 11 ft/sec.

6.113.6 Observations. The energy to fracture a specimen is to be measured. This is to be corrected for windage and friction losses within the apparatus.

6.113.7 Report. A description of the material should be given as well as the energy in foot pounds per inch of notch.

6.113.8 Test Equipment. An impact tester ot the pendulum type for cantilever beam specimens is to be used. It should be rigid and capable of recording to 0.01 ft-lb for energies less than 1 ft-lb and to one percent throughout the range of the instrument. The center of percussion of the pendulum should be at its point of striking. The striking edge of the pendulum should have a 1/32 in. radius with its axis horizontal.

6.113.9 Measuring and Recording Equipment. A means should be provided to determine the impact value of the specimen. This value is to be indicated on a graduated protractor.

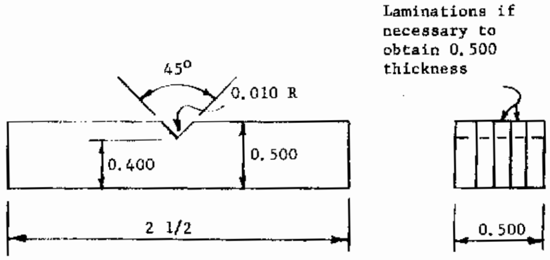


FIG. 6.113.2 IMPACT SPECIMEN

6.0 TEST METHOD - MECHANICAL PROPERTIES

6.11 Impact Tests

6.114 Test T6.114 LP

6.114.1 Source. LP-406b Federal Specification for Plastics, Organic: General Specifications, Test Methods: Method 1074, Falling Ball Impact Test.

6.114.2 Specimen. The specimen shall be 12 in by 12 in by the thickness of the material.

6.114.3 Conditionds. None specified.

6.114.4 Procedure - Preliminary. Specimen is to be freely placed in a horizontally in the mounting frame (Fig. 6.114.8) such that the falling ball will strike it approximately in the center.

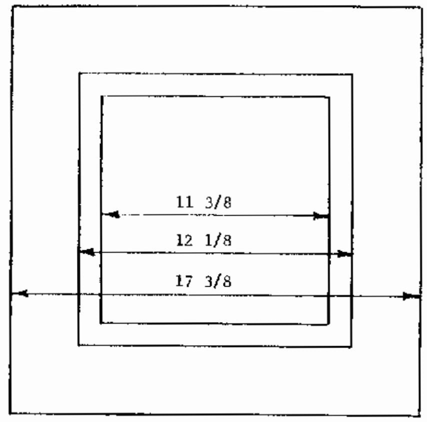
6.114.5 Procedure - Testing. The ball is to be dropped from sucessively increased heights to a maximum of 20 ft in 1 ft intervals.

6.114.6 Observations. The height of fall necessary to shatter the specimen and a description of the failure, are to be observed.

6.114.7 Report. None specified.

6.114.8 Test Equipment. The specimen is to be freely placed in the mounting frame shown in Fig. 6.114.8. The weight of the steel ball shall be 1/2 lb.

6.114.9 Measuring and Recording Equipment. None specified.



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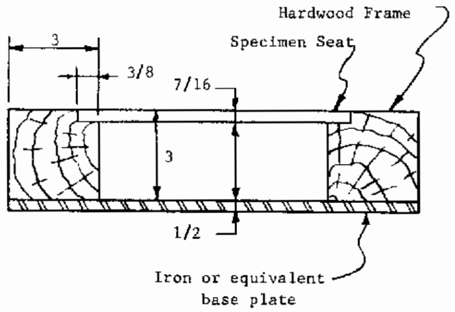


SECTION

FIG. 6.114.8 MOUNTING FRAME

6.0 TEST METHODS - MECHANICAL PROPERTIES

6.11 Impact Tests

6.115 Test T6.115

6.115.1 Source. S.P.I. 14th ANTEC, "Tensile-Impact Measurements on Reinforced Plastics", Section 12-C, pp 1-8, 1956.

6.115.2 Specimen
a. Specimen machined from sheet material is shown in Fig. 6.115.2a.
b. Specimens produced by injection-molding or compression-molding are shown in Fig. 6.115.2b.

6.115.3 Conditions. None specified by source.

6.115.4 Procedure - Preliminary. The specimen is placed with one end in the fixed anvil of a pendulum type testing machine. A cross-head is attached to the other end of the specimen such that the swinging pendulum strikes it causing tensile impact loading. Care must be taken to assure correct alignment of the specimen in the machine.

6.115.5 Procedure - Testing. Two pendulums and two striking velocities were used as indicated in Table 6.115.5.

TABLE 6.115.5

Pendulum	Striking Velocity Ft per Sec	Maximum Impact Energy Delivered, Ft-lb
A	11	25
	17	60
B	11	100
	17	240

6.115.6 Observations. Data to be recorded includes the energy necessary to fail a specimen, velocity of the striker at time of impact, and volume of the specimen. Windage and friction losses for the machine and a loss factor for different specimens should be determined.

6.115.7 Report. The size and shape of the specimen and complete data on manufacturing and curing should be reported.

6.115.8 Test Equipment. A modified B-L-H Impact Machine was used with the specimen mounted to receive pure tensile impact loading.

6.115.9 Measuring and Recording Equipment. The energy imparted to the specimen is to be measured on a direct reading protractor scale.

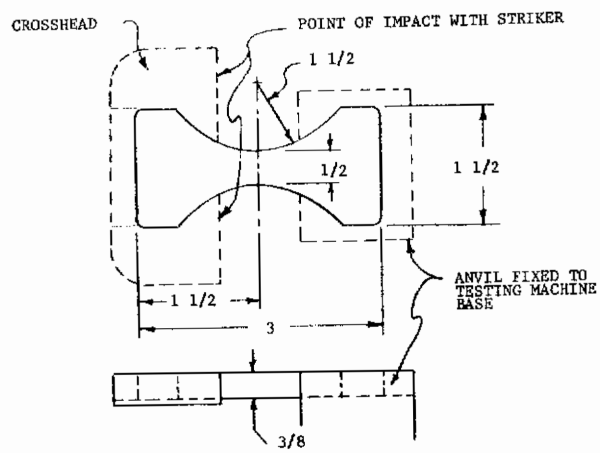
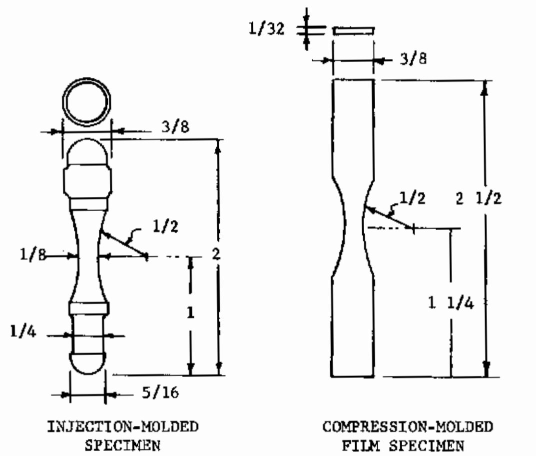


FIG. 6.115.2a SHEET SPECIMEN



Note: Thinner films are stacked to give 1/32 thickness.

FIG. 6.115.2b MOLDED SPECIMENS

6.0 TEST METHOD - MECHANICAL PROPERTIES

6.14 Burst Strength Tests

6.141 Test T6.141 ASTM

6.141.1 Source. ASTM D1180-57, Bursting Strength of Round Rigid Plastic Tubing.

6.141.2 Specimen. Tube specimen size and depth of insertion of plugs shall conform to Table 6.141.2. Specimen ends shall be parallel.

TABLE 6.141.2

Nominal Inside Diameter in	Specimen Length in	Plug Length in	Depth of Plug Insertion in
1/8 to $\leq$ 1	2	1	1/2 $\pm$ 1/8
> 1 to $\leq$ 4	4	2	1 $\pm$ 1/4
> 4 to $\leq$ 6	6	3	2 $\pm$ 1/2

6.141.3 Conditions. Conditioning of test specimens should conform to ASTM D618 for purposes of retaining reproducible results. See Section S10.01.

6.141.4 Procedure - Preliminary. The specimen is to be filled with very high viscosity hydraulic fluid (for example, General Electric's organosilicon). The plugs are to be inserted and seated firmly by hand prior to placing the specimen in the apparatus.

6.141.5 Procedure - Testing. Crosshead speed is to be approximately 0.10 in/min to rupture.

6.141.6 Observations. Five specimens should be tested, and the load to failure recorded.

6.141.7 Report. The report should include the type of material, inside and outside diameter, ultimate load, burst strength, test conditions and any flaws which may be present in the specimens.

6.141.8 Test equipment. A constant load testing machine meeting the requirements of ASTM 695, should be used The diameter of the insert plugs is to be 0.001 to 0.003 in less than the inside diameter of the specimen. The plugs shall have parallel ends.

6.141.9 Measuring and Recording Equipment. Not specified by source.

10.0 SUMMARY OF STANDARD TEST PROCEDURES

10.01 Standard S10.01 ASTM

10.011 Source. ASTM D618-58, Standard Methods of Conditioning Plastics and Electrical Insulating Materials for Testing.

10.012 Standard Conditions

10.012.1 Standard Laboratory Atmosphere shall be an atmosphere having a relative humidity of 50 ± 2 per cent at a temperature of 23 ± 1 C (73.4 ± 1.8 F).

10.012.2 Standard Laboratory Temperature shall be a temperature of 23 ± 1 C (73.4 ± 1.8 F).

10.012.3 Standard Room Temperature shall be a temperature in the range of 20 to 30 C (68 to 86 F), in an atmosphere of unspecified relative humidity.

10.012.4 Standard Test Temperatures Other Than Standard Laboratory Temperature. When data are to be obtained for comparison purposes at a specific temperature either above or below the standard laboratory temperature, the temperature should be selected from Table 10.012.4.

TABLE 10.012.4

Source	ASTM D 618-58		
Test Temperature		Tolerance ±	
C	F	C	F
-70	-94	2.0	3.6
-55	-67	2.0	3.6
-40	-40	2.0	3.6
-25	-13	2.0	3.6
0	32	2.0	3.6
35	95	1.0	1.8
50	122	2.0	3.6
70	158	2.0	3.6
90	194	2.0	3.6
105	221	2.0	3.6
120	248	2.0	3.6
130	266	2.0	3.6
155	311	2.0	3.6
180	356	2.0	3.6
200	392	3.0	5.4
250	482	3.0	5.4
300	572	3.0	5.4

10.013 Conditioning Prior to Test

10.013.1 PROCEDURE A. Test specimens 0.25 in. or under in thickness shall be conditioned in the Standard Laboratory Atmosphere for a minimum of 40 hr. immediately prior to testing. Test specimens over 0.25 in. in thickness shall be treated as above, except that the minimum time shall be 88 hr. Adequate air circulation shall be provided on all sides of test specimens by placing them in suitable racks, hanging them from metal clips or laying them on wide-mesh, wire screen frames with at least 1 in. between the screen and the surface of the bench.

NOTE 1:
Procedure A is generally satisfactory and is recommended unless other methods are specified. Note that Procedure A of Methods D 618 differs from Condition A of ASTM Methods D 709 and of the Armed Forces Specifications MIL-P designation in that Condition A means "as received, no special conditioning".

NOTE 2:
If for any particular material or test, a specific longer time of conditioning is required, the time shall be agreed upon by the interested parties. Shorter conditioning times may be used for thin specimens provided equilibrium is substantially obtained.

10.013.2 PROCEDURE B. Test specimens shall be conditioned for a period of 48 hr. in a circulating air oven at a temperature of 50 ± 2 C (122 ± 3.6 F). The specimens shall be removed from the oven and cooled to the Room Temperature in a desiccator over anhydrous calcium chloride for a period of at least 5 hr. for specimens 0.25 in. or under in thickness, and at least 15 hr. for specimens over 0.25 in. in thickness, immediately prior to testing.

NOTE 3:
Procedure B is commonly used for the purpose of obtaining reproducible test results on the thermosetting materials by means of a short-time conditioning period, or where the specific effects of moderate drying are to be determined. Other enclosures, desiccants, or desiccating techniques may be used which produce and maintain an atmosphere equivalent to that over anhydrous calcium chloride. Note that Procedure B of methods D 618 is the same as Condition E 48/50 of ASTM Specifications D 709 and of the Armed Forces Specifications MIL-P designation.

10.013.3 PROCEDURE C. Test specimens shall be conditioned for a period of 96 hr. in an atmosphere of 90 per cent relative humidity at a temperature of 35 C (95 F). The tolerances for this procedure shall be as follows: time ± 2 hr., temperature ± 1 C (1.8 F), and humidity ± 2 per cent.

NOTE 4:
Procedure C is recommended wherever the specific effects of exposure to severe atmospheric moisture are to be determined.

NOTE 5:
It has been found that, for certain tests and materials, more reliable data are obtained in enclosures with circulating air rather than still air. In such cases enclosures with circulating air should be used.

10.013.4 PROCEDURE D. The specimens shall be conditioned by immersion in distilled water for 24 ± 1/2 hr. at 23 ± 1 C (73.4 ± 1.8 F).

10.013.5 PROCEDURE E. The specimens shall be conditioned by immersion in distilled water for 48 ± 1/2 hr. at 50 ± 1 C (122 ± 1.8 F), and cooled by immersion in a sufficient quantity of distilled water to reduce the temperature to 23 C (73.4 F) within 1 hr.

NOTE 6:
Procedures D and E have been found useful in ASTM electrical and mechanical tests, and are used extensively in Armed Forces Specifications MIL-P designation.

10.013.6 PROCEDURE F. The specimen shall be conditioned in an atmosphere of 96 ± 1 per cent relative humidity at a temperature of 23 ± 1 C (73.4 ± 1.8 F) for a period of time as specified in the applicable materials specification.

NOTE 7:
Constant relative humidity can be obtained only by careful temperature control. Procedures for maintaining close tolerances are outlined in Section 8(b) of the Tentative Recommended Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions (ASTM Designation: E 104).

NOTE 8:
A considerable number of other procedures which might be considered as functional are outlined in the Standard Methods of Test for Resistance of Plastics to Accelerated Service Conditions (ASTM Designation: D 756).

NOTE 9:
It has been found that, for certain tests and materials, more reliable data are obtained in enclosures with circulating air rather than still air. In such cases enclosures with circulating air should be used.

10.014 Tests at Normal Temperatures.

10.014.1 Unless otherwise specified, materials conditioned in the Standard Laboratory Atmosphere shall be tested in the same atmosphere.

10.014.2 Unless otherwise specified, materials conditioned according to Procedure B shall be tested at Room Temperature conditions. The test shall be started as soon as possible, but not more than 1/2 hr. shall elapse between removal of the specimens from the desiccator and the start of the tests.

10.014.3 Unless otherwise specified, materials conditioned according to Procedures C and F shall be tested in the same atmosphere.

10.014.4 Unless otherwise specified, materials conditioned according to Procedures D and E shall be wiped immediately with a damp cloth, then with a dry cloth, and tested at Room Temperature. Specimens should only be removed from the water as the tests are ready to be conducted. The tests shall be started immediately and completed as soon as possible.

10.015 Tests at Other Standard Test Temperatures. When tests are desired at Standard Test Temperatures prescribed in Section 3(10.012.4), materials shall be transferred to the test conditions within 1/2 hr., preferably immediately, after completion of the preconditioning (according to Procedure A or B). The specimens shall be held at the test temperature for no more than 5 hr. prior to test, and in no case for less than the time required to insure thermal equilibrium.

10.016 Selection of Conditioning Procedure.

10.016.1 In the case of materials covered by ASTM specifications, reference should be made thereto to determine the conditioning procedures to be used.

10.016.2 In the case of all other materials, the choice between procedures should preferably be based on the one that gives the most reproducible test results.

10.017 Report. The report shall state the conditioning procedure used and also the relative humidity and temperature of the atmosphere in which the tests were made.

10.0 SUMMARY OF STANDARD TEST PROCEDURES

10.02 Standard S10.02 LP

10.021 Source. LP-406b Federal Specification for Plastics, Organic: General Specifications, Test Methods; General Requirements (1951).

10.022 Standard Conditions

10.022.1 Standard Laboratory Atmosphere shall be 23 ± 1 C (73.5 ± 2 F) and 50 ± 4 per cent relative humidity.

10.022.2 Standard Test Temperature Other Than Standard Laboratory Temperature. When data are to be obtained for comparison purposes at a specific temperature either above or below the standard laboratory temperature, the temperature should be selected from Table 10.022.2.

TABLE 10.022.2

Source	LP-406b 1951
Test Temperature	
C	F
-55	-67
-40	-40
-25	-13
0	32
50	122
70	158
77	170

10.023 Conditioning Prior to Test

10.023.1 For Standard Laboratory Atmosphere, (Section 10.022.1), the conditioning period prior to test shall be 48 hours for specimens 1/8 inch or less in thickness and 96 hours for specimens over 1/8 inch thick.

10.023.2 For Standard Test Temperatures Other Than Standard Laboratory Temperature (Section 10.022.2), the conditioning period at the testing temperature and humidity shall be at least 24 hours immediately prior to test, unless otherwise specified.

10.024 Specimen, Selection and Number.

10.024.1 Specimens shall be obtained if possible from the products to be tested, taken at random, and in such case shall be taken in accordance with the requirements of the specification covering the particular material. In case it is not practical to obtain suitable test specimens from the finished article, the manufacturer shall furnish (a) molded test specimens, or (b) sample sheets as required by the specifications or the procuring agency. The number of samples to be selected from each lot shall be as specified in the material specification.

10.024.2 The number of specimens to be tested in each type of test shall be as specified in the material specification; if not so specified, at least five specimens shall be tested.

10.024.3 In stating requirements under a material specification, and in preparing specimens, consideration should be given to the testing of specimens which are representative of both the thickest and the thinnest section of the article, and where mechanical tests are involved, the testing of specimens which have been cut, if possible, lengthwise, crosswise and at 45° to the length, and also normal to the surface of the material, and the loading of specimens both flatwise, and edgewise wherever possible.

10.025 Test Results

10.025.1 Unless otherwise specified, the average of the results for the specimens tested shall be used to determine conformance of materials tested under this specification.

10.025.2 Unless otherwise specified, results for specimens that break at some obvious flaw or that do not break between the predetermined gage marks shall be discarded.

10.025.3 Unless otherwise specified, results that deviate from the mean value of all tests shall be rejected if the deviation of the doubtful value is more than five times the average deviation from the mean obtained by excluding the doubtful value.

10.025.4 Additional specimens shall be tested in place of any for which the results are discarded in accordance with these provisions.

10.026 Report

10.026.1 The report on each test shall include the following information:

a. The name of the Government agency requesting the test.
b. The name of the contractor, and the number and date of the contract covering the material and/or parts.
c. The title, number, and date of the applicable material specification.
d. Description of the material, including thickness, type, source, manufacturer's code numbers, etc.
e. Type and dimensions of specimens.
f. Location and direction of specimens in the original sample.
g. Temperature, humidity, and length of conditioning period.
h. Such additional data which are stated herein under the individual test methods.
i. Such additional data as may be required under the material specification.
j. Any further information which may be considered pertinent, particularly with reference to unexpected behavior.
k. A brief description of the testing apparatus, sufficient to identify it.