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WADC TECHNICAL REPORT 54-75
PART II

PRESTRESSED CERAMIC STRUCTURES

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FOREWORD

This report was prepared by F. R. Shanley, project leader, W. J. Knapp, assistant project leader, in charge of ceramic development, and R. A. Needham, in charge of structural design and testing, of the Department of Engineering, University of California, Los Angeles, California. Staff members of the project, in addition to the authors of this report were: Robert B. Simonson and Peter Kurtz, Jr., who were chiefly concerned with the preparation and development of ceramic materials; and Robert D. Chipman, who participated in the structural design and development of prestressing facilities. Others associated with the project were D. W. Chamberlain, Charles Linsey, John Marion, P. G. Paley, and C. Poland.

This report is the final one and summarizes work done on the contract during the period 1 November 1953 through 31 December 1954.

The work was accomplished under U. S. Air Force Contract No. AF 18(600)-120. It was administered under the direction of the Aeronautical Research Laboratory, Wright Air Development Center, with Mr. M. A. Schwartz as task scientist, and it is identified as Task 70635, "Prestressed Ceramic Structures" under Project 1368, "Construction Techniques and Application of New Materials."

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ABSTRACT

The objectives of the project are reviewed; methods of attaining these objectives are discussed; a summary of the testing program is presented. Details of various phases of the project are covered in appendices.

A primary result of the project was to reveal various technical difficulties in the design and construction of a small prestressed ceramic wing structure. The most serious of these was the cracking of the high-strength ceramic members. Although one of the test wings was able to carry a normal loading, the inherent strength properties of the ceramic material were not fully utilized. The report contains suggestions for further research to determine the causes and ways to eliminate such cracking.

Satisfactory methods of prestressing were developed and applied, including highly efficient end fittings for the high-strength cables. Special ceramic materials were developed and tested; various ways of making the ceramic components were investigated; a study of gasket materials was made; some fatigue tests of ceramic materials were conducted.

Preliminary work on cellulated ceramic materials revealed that considerable gains in efficiency were possible through the use of directional porosity. Various ways of obtaining such porosity were tried out.

The overall results indicate that eventual development of an efficient structure which will withstand high temperatures appears possible through the use of prestressed ceramic structures, but that further research and experimental work must be done before such construction can be incorporated into actual aircraft or missiles. Recommendations for future programs are included.

PUBLICATION REVIEW

The publication of this review does not constitute approval by the Air Force of the findings or the conclusions contained therein. It is published only for the exchange and stimulation of ideas.

FOR THE COMMANDER:

Leslie B Williams

LESLIE B. WILLIAMS
Colonel, USAF
Chief, Aeronautical Research Laboratory
Directorate of Research

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1. INTRODUCTION

The successful use of prestressing techniques in concrete structures has been due to the simple fact that a member which is subjected to an initial compressive stress will resist bending moments, up to a certain point, without developing any tensile stresses in the material. Since concrete cracks at a low tensile stress, but has relatively high compressive properties, prestressing overcomes the deficiency in tensile strength and enables the full properties of the cross-section to be utilized in bending. Another advantage of prestressed concrete construction is the fact that wires of very high tensile strength are used; this reduces the amount of steel required, as compared with conventional reinforced concrete construction.

The possibilities of using prestressed concrete for aircraft and missile structures have been recognized and considerable progress has recently been made in the design and testing of such structures (Ref. 1). It is well known, however, that the compressive strength of concrete is considerably lower than that obtainable from certain kinds of ceramics. The ratio is roughly in the order of one to ten. A compressive strength of 20,000 psi for concrete would be considered very high, while small aluminum oxide bodies have been tested to compressive strength as high as 450,000 psi at room temperature and 70,000 psi at 2200° F (Refs. 2 and 3). A value of 200,000 psi is therefore not unreasonable. Considering the fact that such ceramic materials have only slightly greater specific weights than aluminum alloy, the possibilities of obtaining efficient structures are apparent.

This, however, is not the main reason for investigating ceramics

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for aircraft and missile structures. It is well known that at very high speeds aerodynamic heating will raise the skin temperature beyond that which can be withstood by available alloys of metal. Ceramic materials offer possibilities of withstanding very high temperatures; in fact, about the only other type of material that is capable of resisting still higher temperatures is carbon.

In the form of graphite, carbon is often employed for very high-temperature applications. As shown in Ref. 8 the strength of graphite actually increases with temperature, up to about 4000° F. Little information is available concerning the compressive strength of relatively large bodies, but the tensile strength is in the order of 3,000 to 5,000 psi. The density is about 0.06 lb. per cu. in., which is an attractive feature. (Aluminum alloy and ceramics have densities in the order of 0.10 lb/cu. in.) It can be machined and cut with standard equipment. Graphite should be thoroughly investigated in connection with prestressed construction. At the time the present project was initiated, however, it appeared that ceramics offered greater immediate possibilities.

It should be noted that ceramics may have definite advantages with respect to production and supply of raw material. There are many large producers of ceramic ware and the industry has a long background of experience. These facts must be considered in connection with any structures which would have to be manufactured in large quantities.

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2. BACKGROUND

A brief description of the developments which preceded the initiation of this project will be given. In January 1951, a report was prepared for the Rand Corporation (Ref. 4) in which a design of a hypothetical prestressed ceramic wing was made. This report included methods of analysis of prestressed structures.

The conclusions and recommendations of RM-598 are quoted below:

1. The unit weight of the basic material (ceramic and steel) appears to be in the order of 7 lb./sq.ft. for the wing investigated. This indicates that the prestressed ceramic wing has possibilities which make it worth further investigation and research.
2. One of the most important developments needed is the manufacture of a porous ceramic with a density in order of 0.035 lb.cu.in. (relative density about 0.3) and a compressive strength of about 12,000 psi. Even if these properties cannot be obtained, any reasonable approach to them will offer attractive possibilities.
3. The most efficient methods of prestressing involve placing the wires so that the precompression in the flanges is no greater than that needed to cover both positive and negative bending conditions.
4. Maximum stiffness and ultimate strength will be obtained by using separate sets of wires for the upper and lower flanges.

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5. A single set of wires may be placed at a suitable point below the neutral axis, to produce the same prestress as two sets of wires.

6. The ceramic units may be fabricated in the form of relatively narrow chordwise strips and will require no tension bonding. Means should be provided for transmitting torsion and transverse shearing loads. This might involve keys or serrations on the mating surfaces of the units.

7. Further investigation should be made to determine whether prestressing in a chordwise direction is necessary. The effects of transverse shear stresses should also be investigated.

8. Practical and efficient means for applying the pretension stresses should be devised.

   (Note: In present prestressed concrete construction the cables are tensioned by means of hydraulic jacks, which are removed after the cables are locked in place).

9. To reduce the weight of the steel wires they should be used in the form of straight-lay cables composed of many wires of small diameter (.06 in. diameter or less). See Appendix I for strength of music wire. (Not included in this report.)

10. For wings which must operate at high temperature for an appreciable time it may be necessary to insulate the wires in some manner. The effects of differential temperatures should also be investigated.

11. The biconvex airfoil section (2 circular arcs) appears to be more efficient than the double-wedge section used in this study.

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The above recommendations formed the basis for the present project.

By way of additional background information it should be noted that engineers at the University of California (at Los Angeles) had become interested in the possibilities of using prestressed ceramic construction for civil (non-aircraft) structures. The first specimen was assembled in the spring of 1951. Ordinary building tiles were used, with cardboard gaskets. (The tiles developed about 9,000 psi in direct compression tests.) The prestressing means was a 3/4 inch diameter carbon-steel rod. A transverse end load of 700 pounds caused yielding of this rod before failure of the ceramic occurred. A second specimen (Fig. 1), identical to the first except that it had a prestressing element of 1 1/8 in. diameter, withstood a concentrated transverse load of 1830 lbs. before yielding of the rod took place. The ceramic tiles were not broken in either test. Further details of this and other tests are given in Ref. 5.

Ref. 5 shows a "two-way" prestressed slab in which prestressing cables were run in two directions. This was tested by applying a normal pressure of 180 lbs per sq. ft., without failure (water tank was used to apply load).

Several other tests were conducted (mostly by students) in which favorable indications were obtained. For example, impact tests (falling weight) showed that prestressing greatly improved impact resistance. There were also indications that thermal shock properties were appreciably improved by prestressing.

Before this project was started, the Rand Corporation initiated some studies (at Battelle Memorial Institute) to determine the relation-

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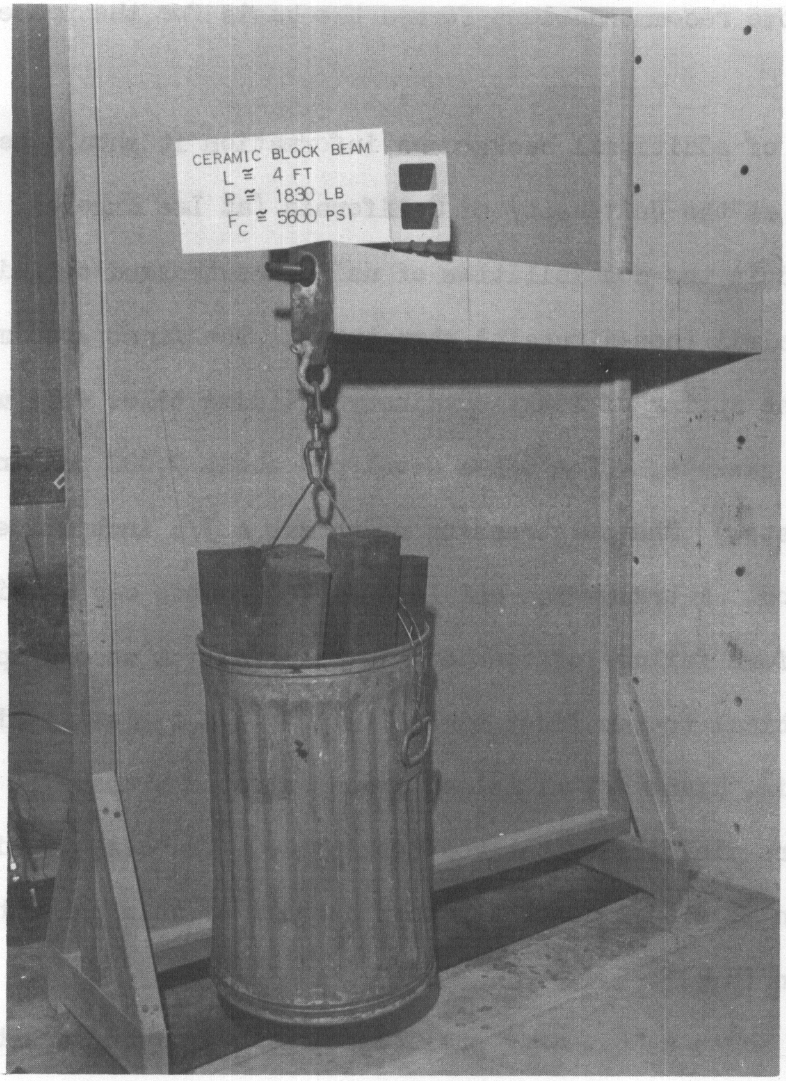

FIG. I - PRESTRESSED CERAMIC BEAM

ship between porosity and compressive strength. The results indicated that ordinary, randomly-distributed (spherical) porosity caused too large a reduction in compressive strength. (This was one of the reasons why the initial specimens were made from uncellulated material.)

All these tests, together with various other experiments, indicated that no serious problems would be encountered in using such construction for aircraft structures. It appeared that the major objectives should be:

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(a) To develop ceramic parts of suitable shape, having higher strengths than the commercially available tile.

(b) To design and test cables made from high-strength wire, having efficient end fittings.

(c) To test an assembled wing under prestressing and normal loads.

(d) To develop porous ceramic bodies having low density and relatively high compressive strength.

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3. DISCUSSION OF BASIC DECISIONS AND DESIGNS

One of the functions of a research report, such as this one, should be to show clearly where mistakes in planning or original design were made and to indicate, if possible, the reasons involved. This type of information should be useful to others who may be engaged in similar programs. The major decisions will therefore be outlined and discussed briefly, on the basis of the results which were finally obtained.

(a) Choice of structural component.

It was decided to start with a wing structure and to investigate fuselage (shell) structures later, if possible. This choice was based in part on the fact that some investigations of wing structures at elevated temperature had already been made and had been used as a basis in the Rand study previously mentioned (Ref. 4).

It now appears that the problem of very high temperatures will be encountered first in ballistic missiles, which have no wings. It would perhaps have been better, therefore, to start with the shell structure and to investigate wings later. On the other hand, there will undoubtedly be a need for wings or control surfaces of some sort, at very high temperatures, so this problem will have to be solved sooner or later.

(b) Size and shape of wing structure.

The chord of the wing was determined primarily by the maximum length of a ceramic section which could be fired in the largest furnace available at the University. A nominal value of 15 inches was chosen.

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The wing thickness was arbitrarily selected as approximately 10 per cent. This was known to be high, for supersonic airfoils, but a smaller value would have severely limited the space available for prestressing. Furthermore, the test results could be extrapolated to lower thickness ratios by assuming a greater chord, at the same depth.

A symmetrical biconvex wing section was chosen (upper and lower surfaces composed of two circular arcs).

A cantilever wing of constant chord was used. In the original configuration the cantilever span was approximately 42 inches (7 sections, each six inches wide). This corresponded to an aspect ratio, for the entire aircraft, of 5.6. Although it was realized that this was too high for supersonic wings, the original idea was to obtain high bending moments with relatively low transverse (shear) loading. There appeared to be a possibility that high shear or normal loadings would cause other types of failure, thus making it difficult to evaluate the structure on the basis of bending moment.

All of the above decisions now appear to have been satisfactory, with the possible exception of the choice of a high aspect ratio. When applying prestressing loads to the assembled wing it was found to be very sensitive to initial eccentricity. As the load was increased the wing would tend to bend, even when the cables were located at the neutral axis. This could have been eliminated by installing close-fitting spacers in each element, to compel the cables to take on the curvature of the wing. Such tendencies are associated with column instability and are therefore very sensitive to the length involved. (See Sec. 6 d for further discussion of this effect.)

In the last test specimen the cantilever chord was reduced to

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22 inches, giving an aspect ratio of about 3 for the entire airplane. This was more nearly in line with the proportions likely to be encountered in design; perhaps even smaller aspect ratios should be used.

The dimensions of the wings tested are shown in Fig. 2.

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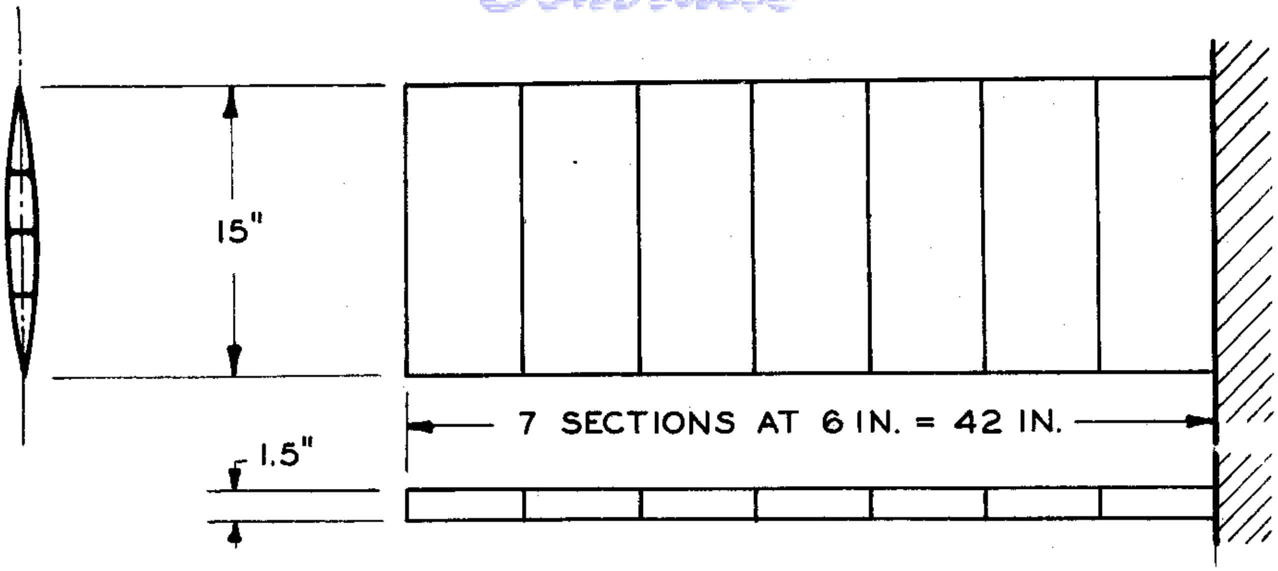
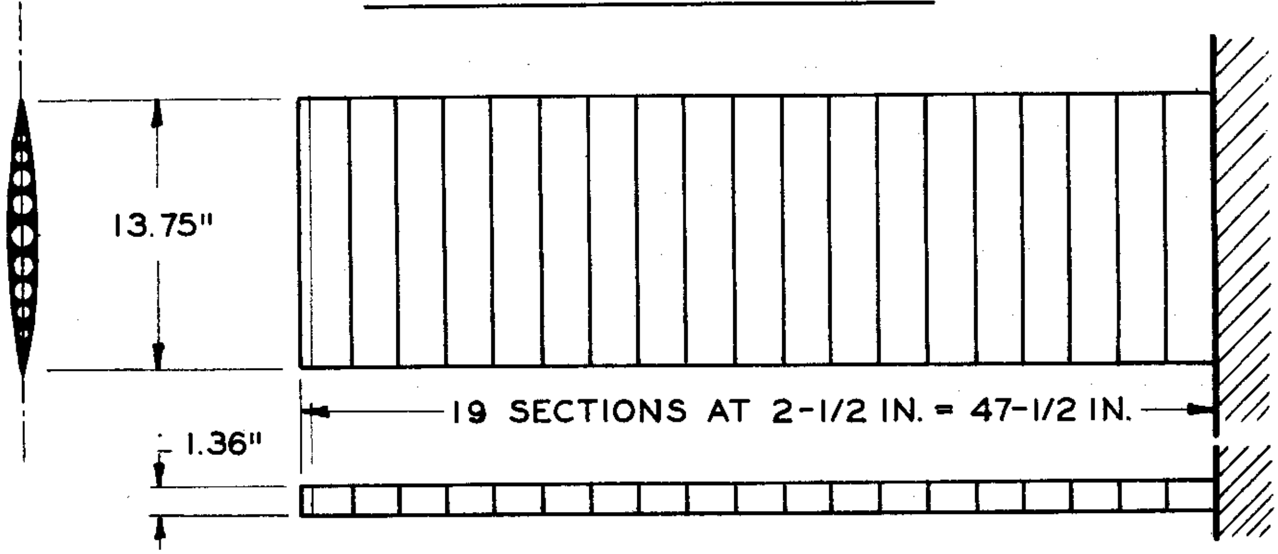
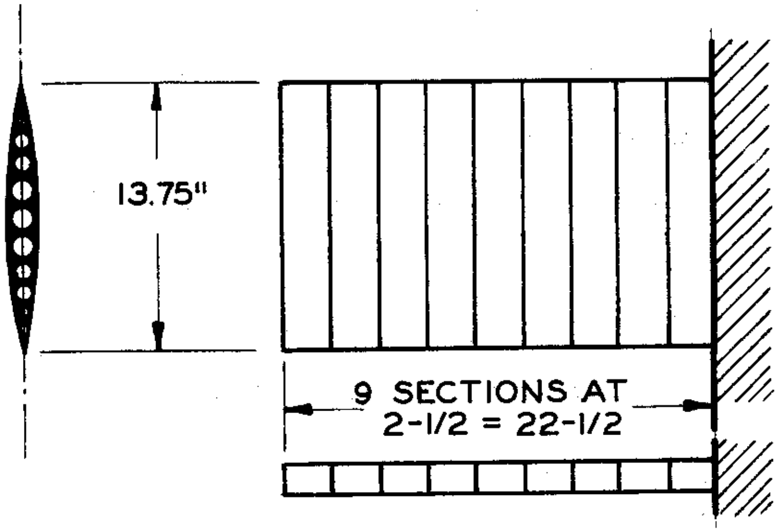


TYPES I AND II TEST WINGS



TYPE III TEST WING



TYPE IV TEST WING

FIG. 2 - DIMENSIONS OF TEST WINGS

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(c) Details of cross-section

Figs. 3 and 4 show the types of cross-sections employed. In previous investigations at Rand it had appeared desirable to use a section lightened by large holes, as shown in Fig. 4. (See also Fig. 14.2, page 209, Ref. 6.) In the ideal case such a section would be made from material of low density, with relatively high strength. It is now believed that this type of section would be successful if it could be made with many small spanwise holes, in addition to the large lightening holes. (This will be discussed later.)

At the beginning of the project it was decided to adopt the type of section shown in Fig. 3. This was done primarily because the ceramic elements could be made by the slip-casting process, in which a "slip" made of fine ceramic material and water is allowed to stand in a plaster of Paris mold until the desired wall thickness is obtained. It was found necessary to form the webs separately and place them in the mold before casting, as indicated by the dotted lines in Fig. 3.

As described in the first summary report, these sections cracked during prestressing, near the juncture of the webs and the shell. It was thought that this cracking was associated with the web type of design. Because of this the design was changed as indicated in Fig. 4, for wings III and IV. (See Appendix B.) As shown later, this did not eliminate the cracking tendency. Therefore it is not yet clear whether the type of cross-section used has any large effect on cracking. It is likely that other factors, to be discussed later, have a greater influence.

The production problem must also be considered in choosing the

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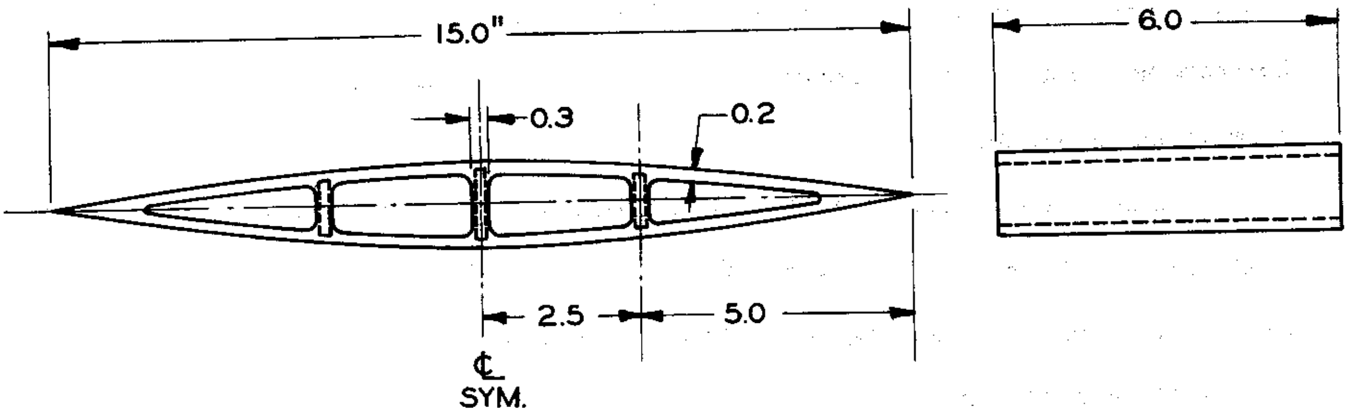

FIG. 3 - SECTIONS FOR WINGS I AND II

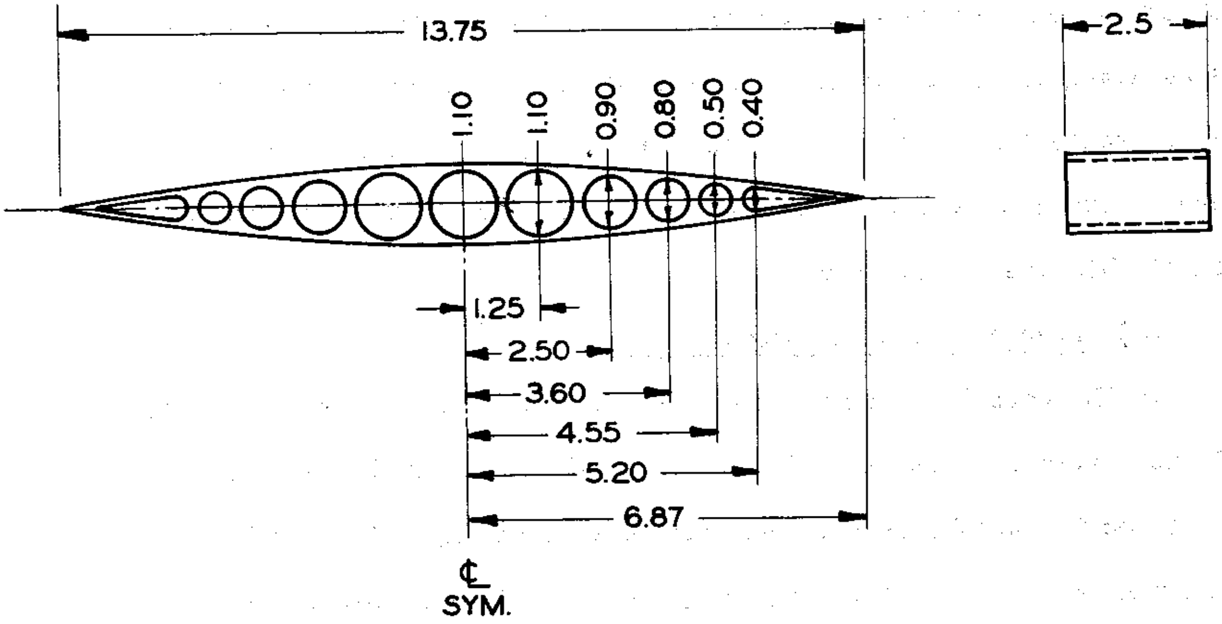

FIG. 4 - SECTIONS FOR WINGS III AND IV

FIGS. 3 & 4 - CROSS-SECTIONS USED IN WING TESTS

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type of cross-section. The slip-casting method, although relatively simple, does not appear to be suitable for high production to close tolerances. Some form of pressing of relatively dry material would seem to be preferable.

The eventual development of a hot-pressing method of production would seem most desirable in view of the need for close sizing. The type of section shown in Fig. 4 appears to be adaptable to this method of fabrication.

The test results indicated that it might have been desirable, or even necessary, to use "brick-like" elements in which the chordwise length of the element would be broken up into shorter sections. These could be staggered so as to provide an integral structure. Such construction would tend to reduce any tendency to build up high local stresses through misalignment of the mating surfaces. Further investigation of this idea is recommended.

(d) Preparation of mating surfaces.

At the outset it was necessary to decide on the manner in which the joints between elements would be made. The decision to use gaskets was based on the knowledge that ceramics are extremely stiff and have virtually no plastic deformation. They are therefore unable to deform locally without developing high stresses. By using a gasket of softer material (such as asbestos) it was believed that small deviations from planeness of the mating surfaces could be tolerated. This would eliminate the need for costly grinding and lapping processes.

The use of grout (as in masonry) was also considered. This did not seem to be as well adapted to production methods as gaskets. Furthermore, it appeared that the strength properties of the grouting material might not be equal to those of the fired ceramic elements. None of the

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tested specimens were assembled with grouting. However, this method should be further investigated, in view of the results obtained.

The complete elimination of either gaskets or grouting was not at first considered to be practical, but in an effort to eliminate longitudinal cracking the fourth wing was assembled in this manner. Joints were very carefully lapped, as described in Appendix B.

It is not yet clear whether the method of preparing the joints is the major factor in causing premature cracking at relatively low compressive stresses, but it is believed to have an important influence on the strength that can be developed. Further investigations along these lines are desirable.

(e) Method of prestressing.

Steel wire of 0.010 in. diameter (No. 1 gage) was selected for the cable material. This wire is available as "music wire" and has an ultimate tensile strength in the order of 400,000 psi. It was recognized that design of the cable fittings would be a major problem, because it is difficult to develop high efficiency in the attachment of wires of such high strength. Furthermore, the fittings had to be small in order to permit stringing the cables through the ceramic sections.

It was decided to construct the cables by wrapping, so as to maintain unbroken wires at each end. Details are given in Appendix E.

In wings I and II the cables were wrapped around circular thimbles. This method was further improved for wings III and IV, by wrapping cable elements around flat end pieces, after which the elements were assembled to the desired cable size.

Excellent efficiencies were developed by the cables, in tension tests to destruction. The cables used in wings III and IV developed

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efficiencies in the order of 85 to 90 per cent at average stresses (for the entire cable) in the order of 330,000 psi.

Several other ways of constructing the cables were investigated, including the use of thin straps, but it appears that the method used for wings III and IV is the best that has yet been developed.

In wing No. I the four cables were located one-eighth inch "below" the neutral axis, in order to provide greater strength in the "up" loading direction. (For actual locations see Fig. 6, WADC TR 54-75 Pt 1.) In the second test wing the cables were located on the neutral axis at the tip, but remained in their original location at the root. This was done partially to avoid overstressing of the outboard sections, which of course are not required to carry much bending moment.

In wings III and IV the cables were symmetrically located at all stations. This was done mainly because of lack of space. Cables were run through each of the holes shown in Fig. 4 and the cross-sectional area of each cable was proportioned to the area of the ceramic material involved.

In the first test it appeared that the end plate at the tip might be deflecting locally. A much stiffer end plate was therefore used in subsequent tests. (See Fig. 10 of WADC TR 54-75 Pt 1.) In wing No. 4 there was some bowing of the temporary root plate (used to shorten the span) and this may have contributed to the early cracking of the sections at the root.

The prestressing loads were applied by means of a hydraulic jack (see Fig. 11 of WADC TR 54-75 Pt 1). After the load had been applied, nuts were tightened in order to maintain a constant condition such as would exist in an actual structure. The method of distributing the

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jack load to the cables was not ideal and could possibly have resulted in some unevenness of load. In the ideal case a multiple leverage system would have to be used to insure constant proportionality of loads in all cables. In the original design this did not appear necessary, in view of the stiffness of the end plates. In other words, uniformity of strain was virtually assured. Furthermore, a complicated equalizing system would probably be unsuitable for actual use in an aircraft.

In view of the fact that the wing, as a whole, was unable to resist high prestressing loads without cracking, it may be possible that some of the trouble came from the prestressing system. Although this does not appear very likely, it would be wise to take special precautions to eliminate any such effects in subsequent tests. In particular, very rigid end plates are recommended.

Another factor which should be considered is the fact that the number and size of cables was determined so as to permit prestressing of the ceramic up to very high stresses. (This decision was made because in the earlier tests the tension bars had yielded before the ceramic material gave way.) As it turned out, only a small fraction of the cable strength was ever utilized. This means that much smaller cables could have been used, in which case the load-deflection curve for the entire cable system would have been much flatter, consequently less sensitive to differences in strain. A more uniform distribution of cable loads would then have been obtained. In future tests it might be advisable to start with a cable system more nearly in line with the strength actually developed in the ceramic.

(f) Instrumentation.

Since the main object of the wing tests was to determine the

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strength and behavior of the entire assembly it did not appear desirable to employ extensive instrumentation. It was expected that the first tests would show whether the basic idea was sound, after which more elaborate tests could be made in which extensive data could be obtained. Accordingly only twelve strain gages were attached to the ceramic structure in the first two tests (three at top and three at bottom, both root and tip. See WADC TR 54-75 Pt 1, p. 19).

For test wing No. III twenty gages were used (five on top, five on bottom, at tip and root sections). In the last test (No. IV) lack of time and funds prevented the use of any strain gages.

Although it would be highly desirable to have accurate data on the local stress distribution over the cross-sections, this is difficult to accomplish with any degree of accuracy by the use of conventional techniques. The reason is that a very small irregularity can cause a large localized stress in a non-yielding material such as a ceramic. Hence it is doubtful if much could have been learned through the use of additional strain gages on the wing.

In the first two test specimens, strain gages were employed on the four tension bars which transmitted the load from the jack to the cables, in order to check the applied load and to insure that the loading was uniform. The pressure gage for the jack was also calibrated so as to provide a measure of the total prestressing load.

(g) Ceramic materials.

A major portion of the program was devoted to the exploration and development of ceramic materials suitable for this project. As previously noted, extremely high compressive strengths can be obtained in small specimens of alumina, but at present such materials cannot be

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satisfactorily formed and fired in the sizes and shapes which were used for the wing design.

Details of the ceramic development program are given in Appendix A and WADC TR 54-75, Pt 1. In general, the body used for the wing specimen (No. 42) developed compressive strengths in the order of 40,000 psi. Later developments provided materials having average compressive strengths in the order of 90,000 psi (minimum value = 70,000), but these were not available in time to be used for the complete wing tests.

Looking back, it now appears that it might have been wise to begin the test program with relatively low-strength commercially available ceramics, such as those used in other tests previously mentioned, to be followed by the use of the higher-strength materials. This might have afforded a clue as to the source of the cracking which occurred in the wing tests. If the low-strength materials were able to develop, in the wing, strength values comparable to those developed in smaller specimens, it would have indicated that the primary difficulty is in the high-strength material itself. It is interesting to note that some of the high-strength elements in the wing cracked at average compressive stresses considerably lower than those developed in bending tests of prestressed tile.

Further comments on the possible causes of cracking will be given later.

Another factor which should have been given more attention in planning the test program is the matter of variability of the strength properties of the ceramic bodies. In the original planning it was felt that this factor, although known to be relatively large for ceramics,

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would not prevent the achievement of adequate load-carrying capacity. In view of the low values actually developed in the wing tests it is now evident that it would have been wise to run a direct compression "proof" test on each element before using it in the wing assembly. The frequency distribution of compressive strengths for various types of elements and materials should be carefully evaluated in future programs.

A considerable effort was made to develop a light-weight ceramic material having good compressive properties. (See Appendices C and D). Promising results were obtained from specimens having directional porosity, but these materials were not available in time to be used for wing sections.

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4. SUMMARY AND DISCUSSION OF RESULTS OF WING TESTS

The results of the tests of wings I and II are given in WADC TR 54-75 Pt 1, but will be summarized briefly here.

(a) Wing No. I (See Figs. 3 to 8, WADC TR 54-75 Pt 1) (web-type; eccentric prestressing load; 42" span) The ceramic elements cracked longitudinally while prestressing loads were being applied. The cracks were located near the juncture of webs and shell. (See Figs. 7 and 8 of WADC TR 54-75 Pt 1, page 11) Strain gauge readings indicated that the maximum compressive stress developed in the ceramic was in the order of 3,000 to 3,500 psi. After cracking, there was no overall failure and strain gage readings did not drop off appreciably. Upon release of the prestressing load the elements fell apart.

(b) Wing No. II (See Figs 10 to 13, WADC TR 54-75 Pt 1) (web-type; prestressing cables eccentric at root, concentric at tip; stiffer end plate at tip; 42" span)

During prestressing, spanwise cracks developed in the "compression" surface (nearest to cables) in the vicinity of the wing root. Loading was continued until complete failure of the wing occurred, at a prestressing load approximately 50 per cent higher than that at which the first cracks developed. From strain gage readings the maximum compressive stresses in the ceramic, at final failure, was estimated to be about 7,000 psi near the root.

(c) Wing No. III (Lightening-hole type, symmetrical prestressing; 42" span) Fig. 4 shows the type of element used in this wing (ceramic body No. 42). See Appendix E for cable details.

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When prestressing loads were applied, considerable bending of the wing was observed. This indicated that the faces of the elements were not absolutely parallel and that the gaskets were contributing a considerable amount of differential strain. The cables were "floating" in this wing, that is, spacers had not been used. (This would have been difficult because of the small clearance and large number of cables.) Because of the long span (relative to the depth) any tendency to bend was magnified by secondary bending effects.

Before any substantial prestressing load had been applied the wing elements cracked longitudinally. From strain gage readings it was estimated that the average prestress was in the order of 1,000 psi, or less, when cracking occurred.

(d) Wing No. IV (Lightening hole type, symmetrical prestressing, 22" span, lapped joints; no gaskets).

Although project funds had been exhausted at this stage, an additional sum was provided by the University for the purpose of assembling a wing of shorter span, with all joints lapped and gaskets eliminated. It was thought that these steps might reduce secondary bending and delay cracking. A special adapter was constructed, to reduce the span to about one-half of that used in previous tests. The ceramic sections were of the same type as for wing No. III. The same cables are used. Fig. 5 shows the test setup.

A prestressing load was applied such that the average compressive stress in the ceramic was about 2,000 psi. At this point it was noted that the heavy steel plate used as a temporary base for the root section had bowed slightly. Since lack of time and funds prevented reworking the jig, it was decided to attempt normal loading by means of 10-pound

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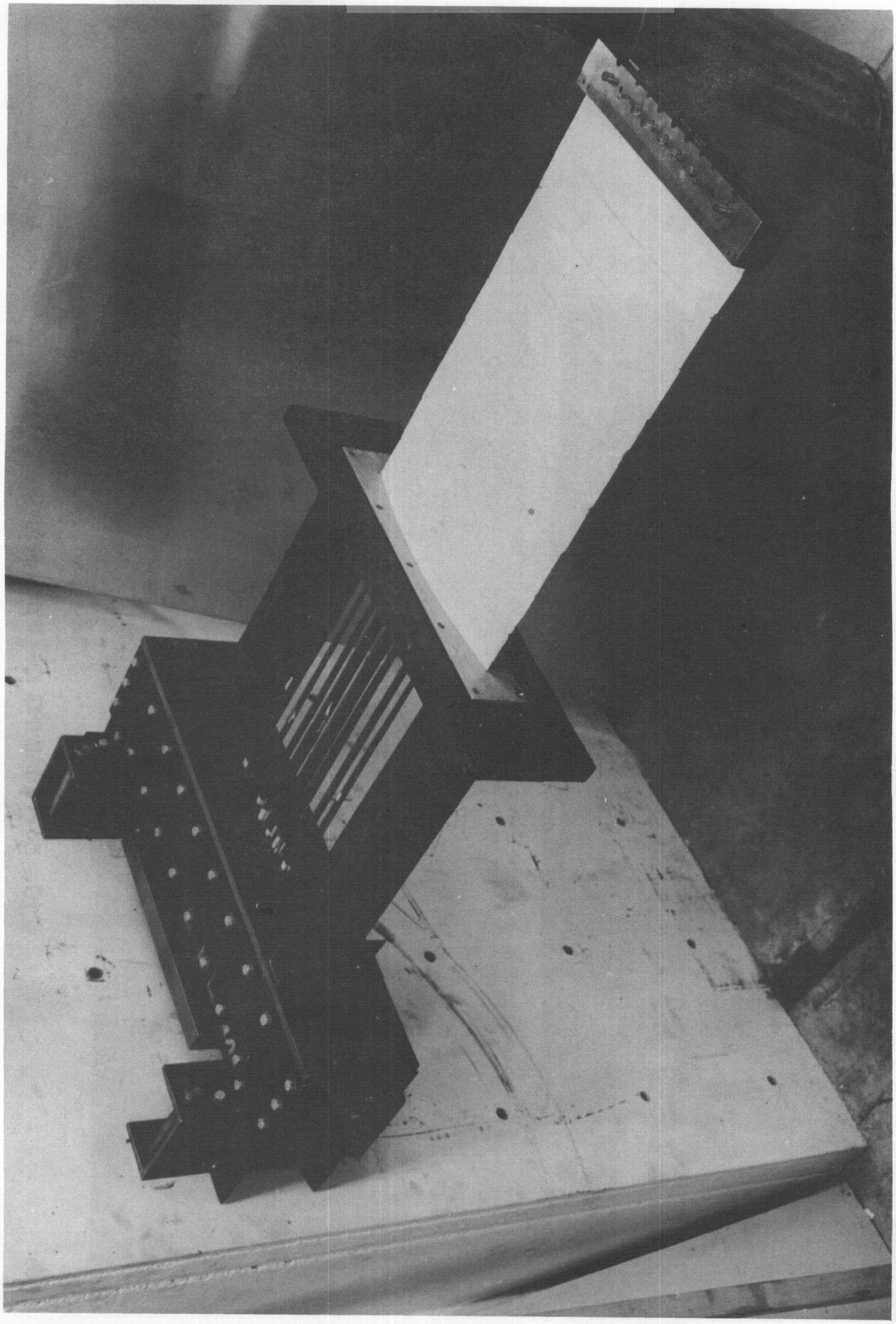

FIG. 5 - SET-UP OF TEST NO. IV

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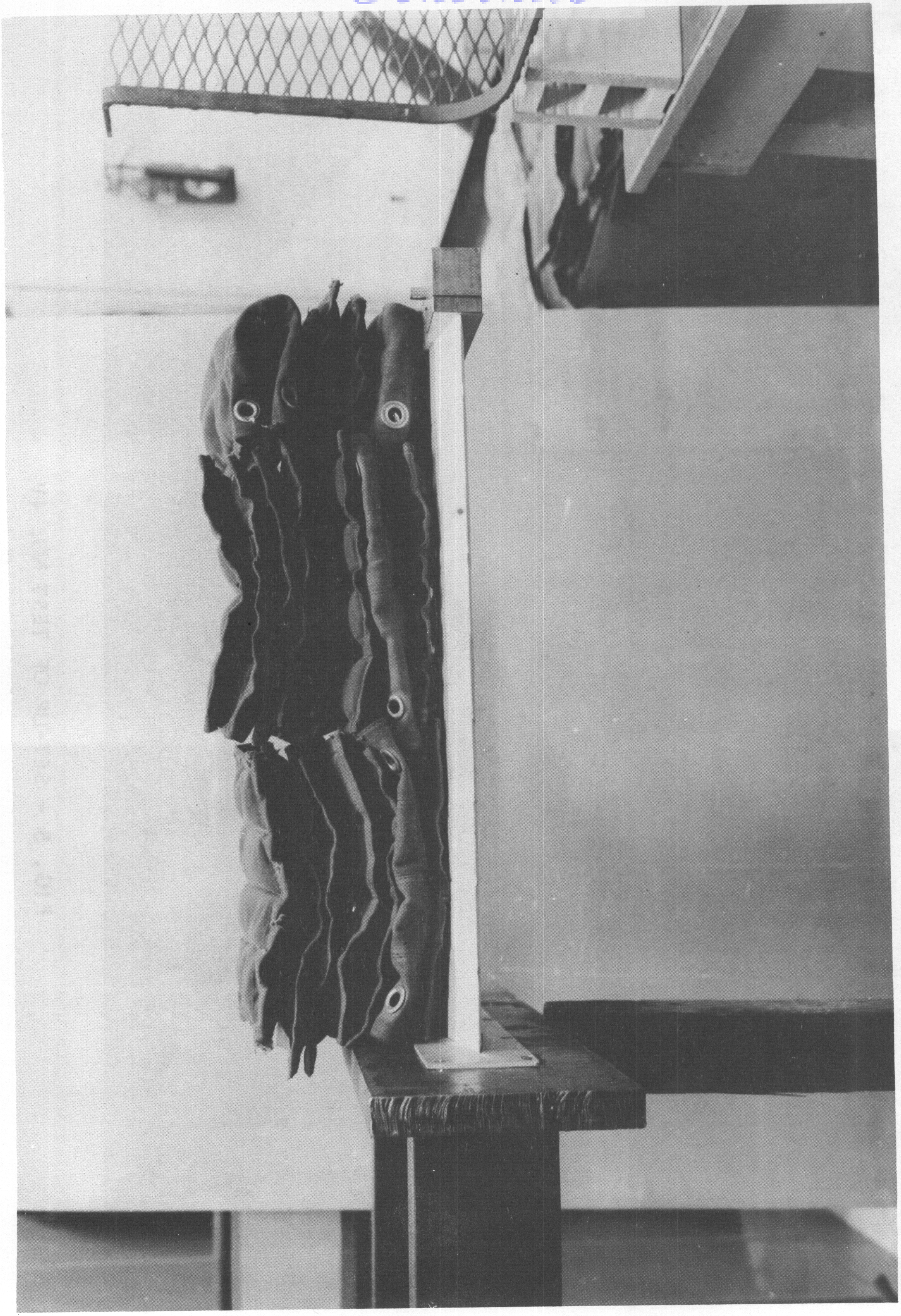

FIG. 6 - LOADING OF WING NO. IV

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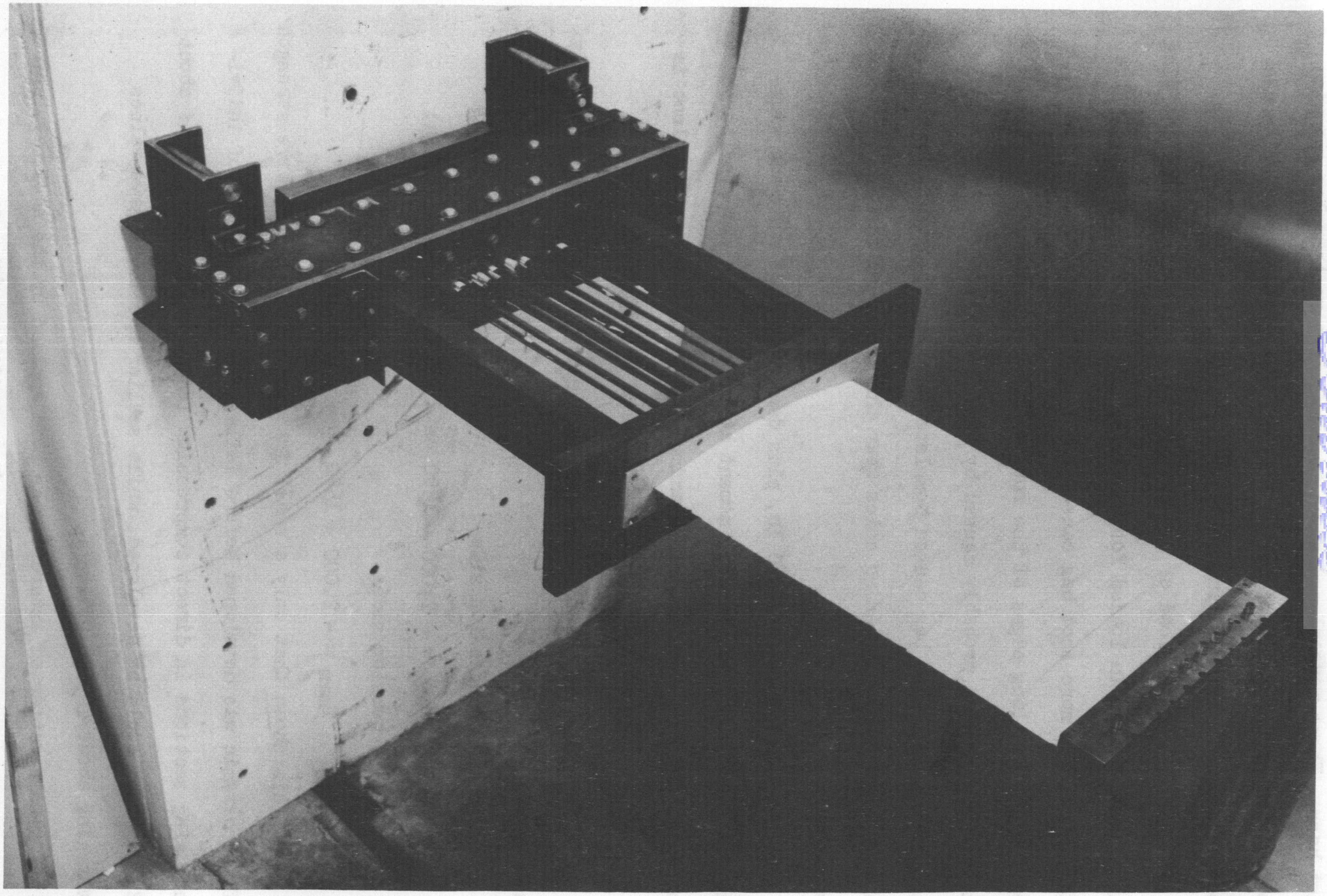

FIG. 7 - FAILURE OF WING NO. IV

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shot bags. These were placed so as to simulate a rectangular spanwise load distribution, as indicated in Fig. 6. The center of pressure was located approximately at mid-chord.

After a total load of 180 lb. had been applied (Fig. 6) the wing was allowed to remain loaded for 24 hours. No changes were noted. The addition of one more shot bag caused small 45-degree cracks in the leading and trailing edges of the root section, adjacent to the base plate. (These were probably caused by bowing of the plate.) The addition of one more shot bag caused complete failure, by spanwise cracking through one of the lightening holes near the center of the cross-section, as shown in Fig. 7.

At a total load of 180 lb, plus dead weight of wing and wing-tip jig (22.3 lb) the bending moment at the root was computed to be approximately 2350 in. lb. The maximum stress due to bending alone is

$$f = \frac{M\,c}{I} = \frac{2350 \times 0.675}{1.0} = 1590 \text{ psi}$$

This must be added to the precompression stress of approximately 2,000 psi.

On the compression side:

$$f_{max} = -\,2{,}000 - 1590 = -\,3590 \text{ psi (compression)}$$

On the tension side:

$$f_{max} = -\,2{,}000 + 1590 = +\,410 \text{ psi}$$

This shows that only a small fraction of the compressive strength of the ceramic was developed before failure occurred. Tests of individual wing sections in direct compression indicated that a value of about 12,000 psi could be developed, while smaller specimens gave values averaging about 40,000 psi.

As a matter of interest, the load applied by the shot bags corresponds to a running load of 8.2 lb./in. or 98.5 lb./ft. The average

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(air) pressure was 0.58 lb/sq.in. or about 84 lb/sq.ft. This would represent, for example, flight at 570 mph indicated airspeed, at a lift coefficient of 0.10.

It is quite apparent that if the potential strength of the ceramic material could be more efficiently utilized a wing of this size would provide much more strength than required, so far as bending moments are concerned.

(e) Estimation of wing weight

The average weight of the ceramic material for Wing No. IV was 6.05 lb. per square foot of wing area. The cables averaged 1.20 lb. per sq. ft., exclusive of end fittings. However only about 28 % of the cable strength was utilized. Hence the average cable weight could have been reduced to about 0.34 lb. per sq. ft. The average weight of ceramic and cables would then have been 6.39 lb per sq. ft.

These figures can be used as a rough guide in obtaining an estimate of possible wing weights for larger structures. The ceramic weight can be reduced by whatever proportion the strength of the ceramic material could be increased. The cable weight can be adjusted accordingly. To extrapolate to larger wing sizes it is only necessary to apply the principles of dimensional similarity. If all dimensions are multiplied by a factor N, the total load carried will be multiplied by N^2; bending moments by N^3; weights by N^3; areas by N^2, etc. However, since the tests did not develop satisfactory strength values, no attempt will be made here to apply the results to wings of other sizes and proportions.

(f) General conclusions from wing tests

The general conclusions to be drawn from these four tests of

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assembled wings are obvious. The potential strength of the ceramic material was not developed in the tests, because of longitudinal cracking. The compressive stresses which were obtained were too low for practical use.

The reasons for this are not clear, because there are a number of factors which could have caused such behavior. The most important appear to be:

(a) Uneven distribution of stress over the cross-sections of the ceramic elements.

(b) Lateral expansion (Poisson) effects in the material itself.

(c) Poisson effects on the transverse (chordwise) stresses, associated with bending.

(d) Effects of gasket material.

(e) Possible low strength of some of the ceramic elements.

In order to determine the relative importance of these factors it would be necessary to conduct a systematic series of tests using different ceramic materials, various kinds of gaskets, etc. It is possible that the use of directionally cellulated material might eliminate all of these difficulties, as well as provide a lighter structure. Different methods of fabricating the elements might also improve the resistance to longitudinal cracking. As previously noted, the use of many small elements might be successful.

The tendency for high-strength ceramic bodies to crack longitudinally when compressed is a well-known phenomenon. Ref. 7 (pages 343 to 346) contains interesting information on this. It is generally believed that a sort of wedging action causes transverse tensile stresses which produce the cracks. However, it is possible that such transverse stresses must exist because of the atomic or molecular structure of the

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material itself. This is discussed in Sec. 6 e. The possibility of such action is particularly interesting in connection with a material having directional porosity.

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5. SUMMARY AND DISCUSSION OF SPECIAL INVESTIGATIONS

In addition to the construction and testing of an assembled wing, various supplementary investigations were carried out. The results will be summarized briefly. (See Appendices for further details.)

(a) Development of ceramic materials.

Throughout the course of the project a continuous investigation of ceramic bodies was carried on. The results have been reported in WADC TR 54-75 Pt 1 and in Appendix A of this report.

The compressive strengths obtained in tests of small specimens are summarized in Table IV of Appendix A, which lists 56 different specimens. The highest value listed is 101,600 psi. Average values for groups of specimens are in the order of 60,000 to 90,000 psi. Bending strengths (modulus of rupture) were also obtained and are listed in Table IV. These were in the order of 9,000 to 14,000 psi. Apparent porosity covered a range between zero and 25 per cent. Bulk densities ranged from about 0.070 to 0.090 lb/cu.in. Figure 1 of Appendix A indicates how the composition affects the compressive and transverse strengths.

Fig. 14 of WADC TR 54-75 Pt 1 shows a typical compressive stress-strain diagram for portions of a ceramic wing segment. Pages 21 to 24 give details of the determination of Poisson's ratio, which was found to be between 0.20 and 0.25.

The results indicated that ceramics possessing compressive strengths of about 100,000 psi may be prepared readily with standard procedures with a clay-feldspar-alumina body; such materials may be fired at tem-

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peratures of 1500° C, or below.

If, in the future, it is desired to develop materials possessing compressive strengths of the order of 300,000 psi to 400,000 psi, it is suggested that a ceramic composed chiefly of alumina (plus 2-5% of feldspar, or other bonding agents) be used. Special preparation procedure will be required, but such procedures have been well developed in the ceramics industry. It probably would be desirable to have high-strength alumina specimens prepared by an industrial firm specializing in high-alumina ceramics.

(b) Development of fabrication methods for ceramic elements.

WADC TR 54-75 Pt 1 covers the methods used in molding, firing and machining the sections for Wings I and II (web-type). Appendix B gives details of methods used for Wings III and IV (lightening-hole type). Although successful methods were worked out, it is believed that better methods of fabrication could be developed. In particular, the technique of dry-pressing should be investigated. This process appears to be more suitable for quantity production of accurate parts; it may also lend to development of better strength properties. The possibility of obtaining directional porosity with this technique should be thoroughly investigated. (See Appendix D for a possible method of doing this.)

(c) Gasket study. (See WADC TR 54-75 Pt 1, pp. 27 to 29.)

The results of this investigation, using small specimens, showed that highest compressive stresses (average = 42,650 psi) were developed with asbestos gaskets. Soft materials, such as neoprene, gave low values. Brass and copper sheet did not do as well as asbestos.

Although apparently satisfactory in tests of small specimens, the use of gaskets for the larger components of the wing may still be ques-

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tionable. It is possible that the gaskets were not able to equalize stress differences which occurred through misalignment and irregularity of surfaces. Another fact revealed in the wing tests was that gaskets of any appreciable thickness have a tendency to amplify the effects of initial curvature or eccentricity of prestressing load, as might be expected. These two effects are conflicting, one indicating the need for thicker gaskets, the other indicating a desirability of thin gaskets. This appears to be a major problem in wing high-strength ceramics for prestressed structures and it should be thoroughly investigated in future work.

(d) Design and fabrication of cables.

Wings I and II employed four cables, each made from 900 strands of 0.010 in. diameter music wire.(See WADC TR 54-75 Pt 1, p. 3, for details. Fig. 1 of that report shows the wrapping jig; Fig. 2 shows the assembled cable.)

For Wings III and IV a new type of cable was developed, in which individual flat elements are formed by wrapping wires around thin plates at each end of the cable, as shown in Fig. 8. These flat elements were then assembled into cables of the desired size. A special jig was designed and constructed for the cable-wrapping operation (see Fig. 9).

This method of fabricating the cables eliminated some of the disadvantages of the original method and also provided the necessary small end fittings. By wrapping smaller elements individually the compressive loads caused by initial tension were reduced.

From destruction tests of the cables it was found that the average tensile stress developed at failure was about 330,000 psi. This represents an overall efficiency in the order of 85 to 90 per cent.

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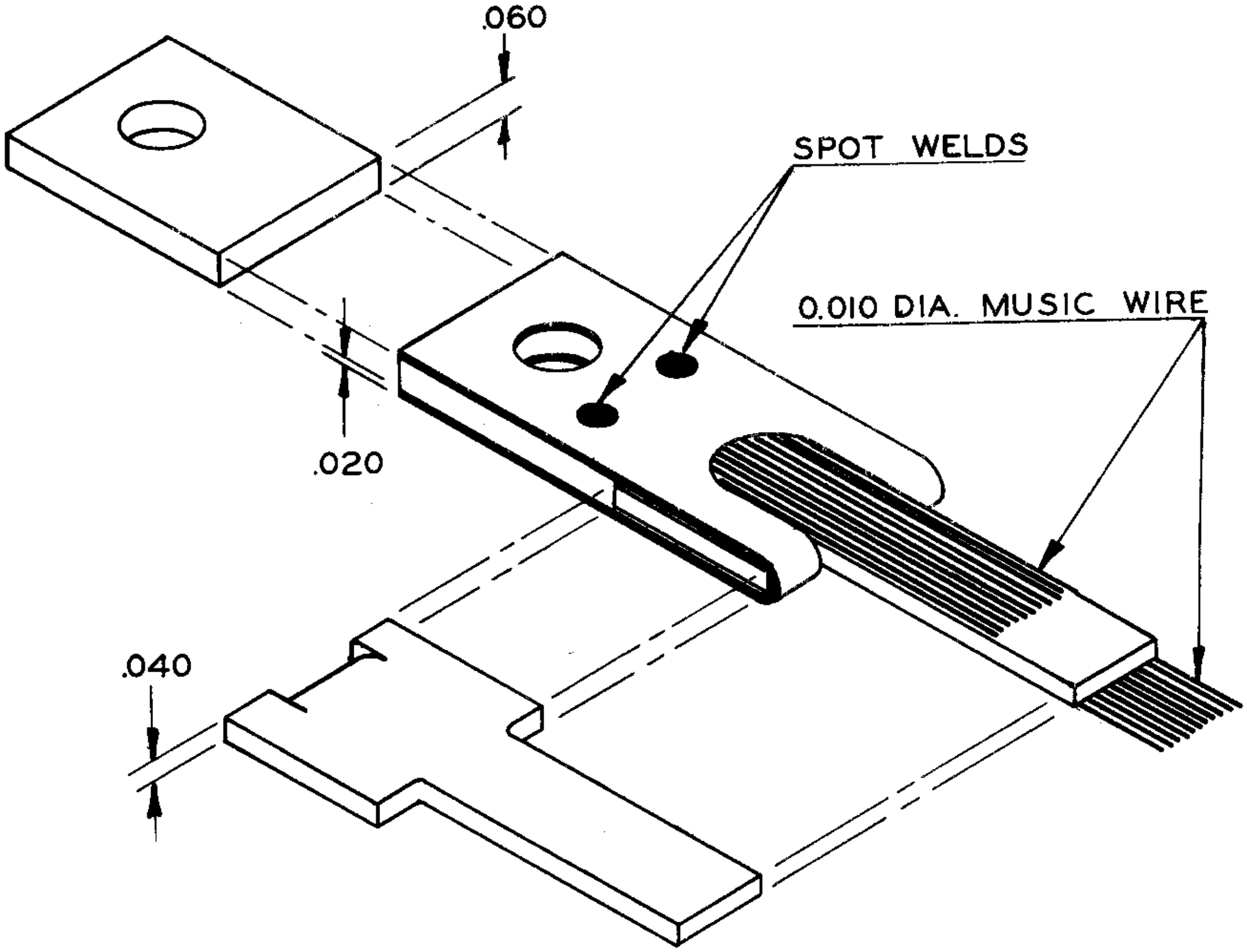

FITTING MAT'L. - HALF-HARD STAINLESS STEEL

FIG. 8 - END FITTING FOR PRESTRESSING CABLE (WINGS III AND IV)

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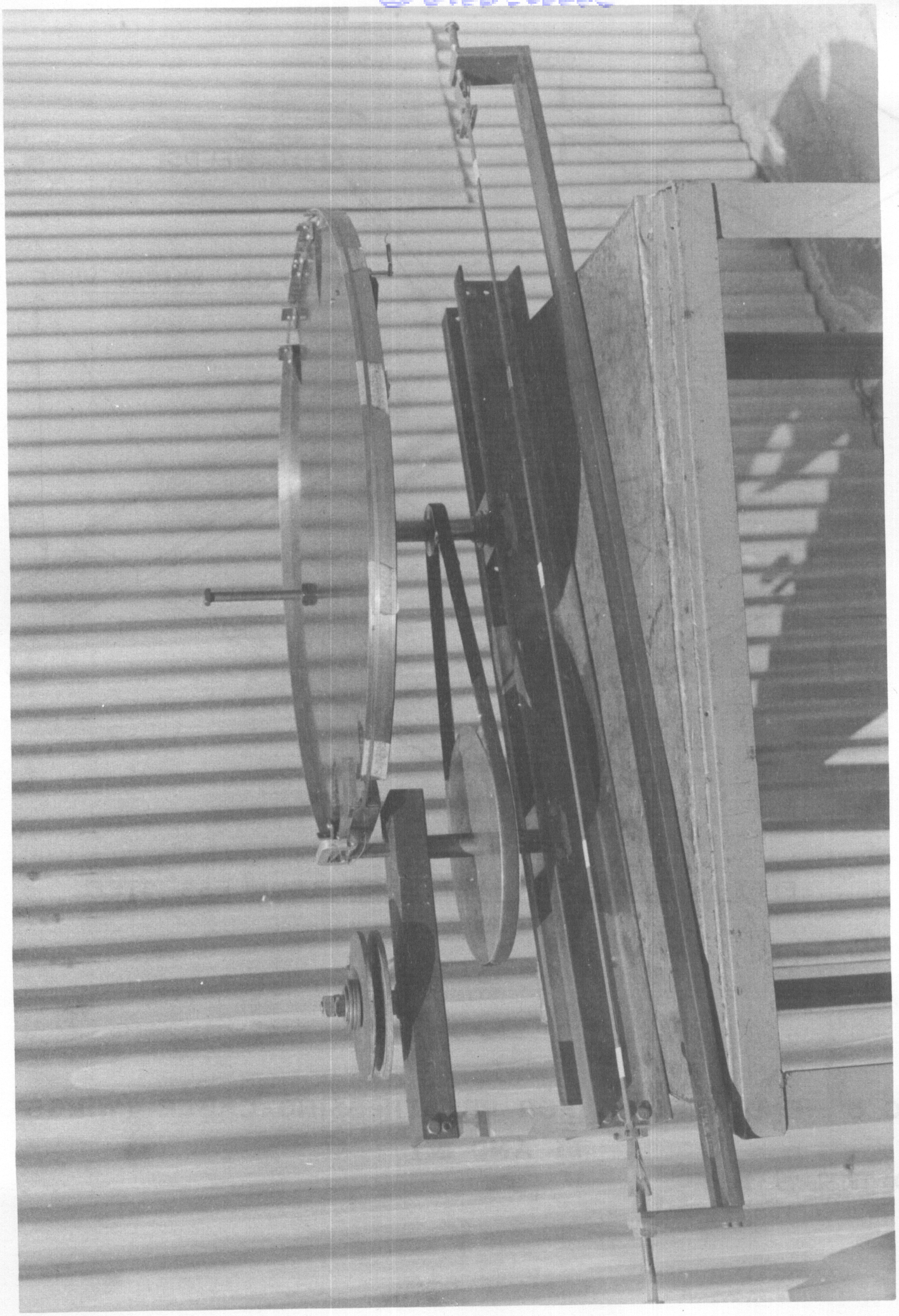

FIG. 9 - CABLE WRAPPING JIG (WING TYPES III AND IV)

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See Appendix E for further details.

(e) Development of cellulated materials.

As previously noted, one of the objects of the investigation was to develop, if possible, ceramic materials having low density, with reasonably good compressive strength. Previous efforts, by others, had indicated that ordinary randomly-distributed (spherical) porosity caused too high a reduction in strength, for low densities. Efforts were therefore concentrated on various ways of obtaining directional porosity.

Details of the tests are reported in Appendix C. The results were not only favorable, but revealed the surprising fact that the total compressive load carried by a cored specimen with 5% of the material removed averaged 24 per cent higher than that obtained from solid specimens. As shown in Fig. 5 of Appendix C the total strength dropped off with increasing porosity, but the net compressive stress (load divided by actual material in cross-section) remained nearly constant. The average value for all cored specimens was 45,300 psi, as compared with 34,750 for the solid specimens.

Fig. 5 also indicates that over 20 per cent of the material can be removed without reducing the total compressive strength below that of the solid specimens.

These results are important because in many structural applications the wall thickness which would be required for high-strength ceramics are too low to be used successfully. By introducing directional porosity the wall-thickness can be increased to a practical value without a corresponding weight penalty; in fact, it appears that there may be a weight reduction.

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The reasons for the unusual behavior of specimens with directional porosity are not clear. It is possible that the presence of the holes has a favorable effect on firing of the specimens. Another possibility is that the presence of longitudinal holes reduces the "Poisson effect", i.e. the tendency to develop lateral tensile stresses which may cause cracking. This is an attractive subject for further research.

The results of the porosity experiments were not obtained in time to permit development of actual wing sections having directional porosity. This appears to be an important step to take, because it would not only lighten the wing, but might also reduce the tendency to crack. The calculations given in Sec. 4 (d) indicate that Wing No. IV would not need to develop the full strength of the ceramic specimens in order to provide adequate strength for actual use on an aircraft.

The method of cellulation described in Appendix D appears to have possibilities for quantity production by means of dry-pressing. Preliminary results indicated that fibers or other combustible materials could be coated with a ceramic compound and then formed into a unit by pressing in a die, after which the fibers would be burned out in the firing process.

(f) Fatigue tests of ceramic specimens

The original plans for these tests are reported in WADC TR 54-75 Pt 1, pages 30 to 40. Under a separate research program, sponsored by the Edward Orton, Jr. Ceramic Foundation, tests were made on the Krouse cantilever bending machine, using the plate type of specimen. (See Figs. 19 and 20 of WADC TR 54-75 Pt 1.) The results indicated that a completely reversed stress of about 2100 psi could be withstood for an indefinite period. The "S-N diagram" appears to be a horizontal straight line, indicating virtually no "time effect".

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These tests were made primarily to verify the assumption that there would be no danger of fatigue in the ceramic elements. Furthermore, most of the ceramic material will be under compression in a prestressed structure and cannot develop high tensile stresses.

It would be desirable to conduct additional tests using a constant-load type of machine instead of a controlled-displacement type. In the latter type it is difficult to obtain a controlled stress, because the ceramic elements are quite "strain-sensitive".

(g) Design of prestressed ceramic shell structures.

As previously noted, it had been planned to include some tests of shell structures made from small ceramic elements. A design for such elements was worked out, but difficulties with the wing tests precluded any possibility of actually building such a structure. The original design was based on the use of full rings, to be assembled by means of longitudinal prestressing wires running through holes in the rings. As a result of the cracking experienced in the wing this design was changed to one in which small brick-like elements were assembled in staggered arrangement.

Possible methods of prestressing such a shell structure were considered and are briefly discussed in Sec. 6.

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6. ANALYSIS AND DESIGN INFORMATION

The methods of stress analysis for prestressed concrete structures have been thoroughly developed and can be applied to ceramic structures with practically no modifications. Many articles, reference books, and bibliographies are readily available. For this reason no attempt will be made here to include a bibliography of all available material. A few of the fundamental principles and formulas will be reviewed and certain interesting features will be pointed out.

For elastic materials the usual formulas for compressive and bending stresses may be used. Since ceramics are elastic over most of their range of stress, even at relatively high temperatures, the conventional formulas will apply even more accurately than for concrete.

(a) Central prestressing.

If the tension cables are located on the neutral axis, or relatively near it, they will not change length appreciably during bending. Their function is simply to apply an initial compressive stress which may be calculated from the equation:

$$f_c = -\frac{P}{A} \qquad (1)$$

where P = total load in cables

A = area of cross-section of ceramic

When a bending moment is applied, the bending stresses are computed by the beam formula

$$f_b = \pm \frac{M\,y}{I} \qquad (2)$$

where M = bending moment

I = moment of inertia of ceramic

y = distance from neutral axis

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The total stress in the ceramic is found by adding the above stresses. On the "compression" side:

$$f = -\frac{P}{A} - \frac{My}{I} \qquad (3)$$

On the "tension" side

$$f = -\frac{P}{A} + \frac{My}{I} \qquad (4)$$

These conditions are graphically illustrated by Fig. 10

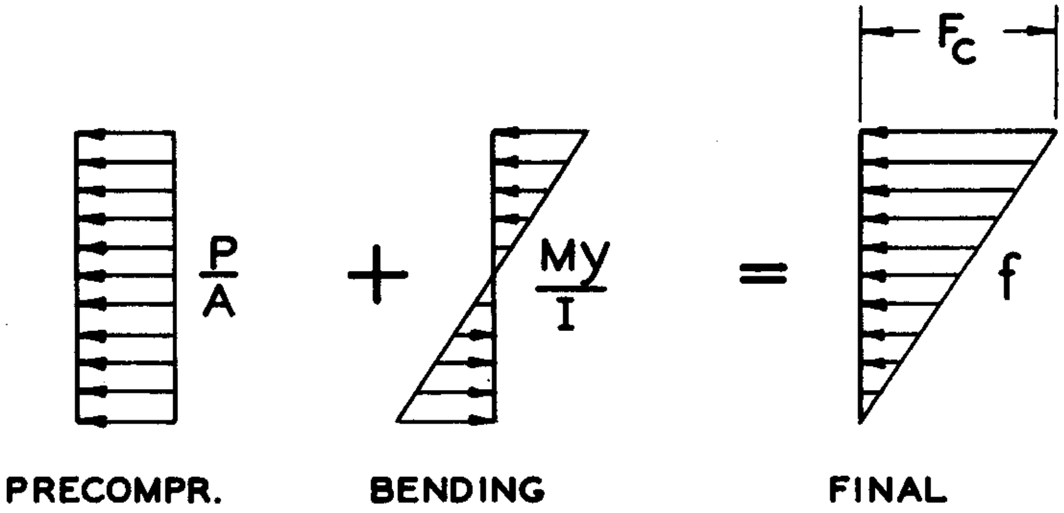

FIG. 10 - STRESSES IN A CENTRALLY PRECOMPRESSED BEAM

For maximum bending stresses the value to be used for y is the distance to the outer fiber, usually denoted by c.

Eq. 4 shows that when the magnitude of Mc/I exceeds that of P/A the apparent stress will be tension. In a prestressed ceramic structure this is impossible, the joints will start to open up when the

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bending stress equals the precompressive stress, P/A.

It is logical to proportion the design so that the maximum allowable compressive stress in the ceramic will be reached when the joints start to open up on the tension side. Under these conditions the stress distribution over the cross-section will be represented by a straight line going from zero on the "tension" side to a value equal to twice the original compressive prestress, on the "compression" side. This is the situation shown in Fig. 10.

The required precompression stress in the ceramic, under such conditions, is equal to one-half the allowable compressive stress for the ceramic material.

The required prestress is then

$$f_c = \frac{F_c}{2} \qquad (5)$$

where F_c = allowable compressive stress for ceramic.

The required prestressing force is

$$P_c = f_c A_c = \frac{F_c A_c}{2} \qquad (6)$$

where A_c = area of ceramic cross-section.

The required cross-sectional area for the steel is then equal to

$$A_{st} = \frac{P_c}{F_{st}} = \frac{1}{2} \frac{F_c}{F_{st}} A_c \qquad (7)$$

Under these special conditions the equivalent allowable bending stress in the ceramic is one-half the allowable compressive stress and the allowable bending moment is given by

$$M = \frac{F_c}{2} Z \qquad (8)$$

where Z = section modulus = I/c.

If the allowable compressive stress of the ceramic is known, or assumed, the required value of the section modulus can be found from Eq. 8.

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Since Wings III and IV were centrally precompressed, the above equations can be used for them. The nominal dimensions for the wing are:

Span = 22 in.

Chord = 14.1 in.

Wing area = 310 in^2 = 2.15 ft^2

A_c = 8.0 sq. in.

I = 1.0 in.^{4}

c = 0.675 in.

Z = 1.48 in.^{3}

For example, the allowable bending moment will be computed for an assumed allowable compressive stress of 50,000 psi.

From Eq. 8

$$M = \frac{50,000}{2} \times 1.48 = 37,000 \text{ in. lb.}$$

This corresponds to a net normal loading (rectangular) of

$$P = \frac{37,000}{11} = 3,360 \text{ lb.}$$

This would represent an ultimate wing loading of

$$\frac{P}{S} = \frac{3,360}{2.15} = 1,560 \text{ lb/sq. ft.}$$

This would provide, for example, an ultimate load factor of about 15 for a wing of about 100 lb./sq. ft. wing loading.

(Note: the actual wing carried only 180 lb. of normal loading, because of cracking of the ceramic at an abnormally low stress.)

The area required for the steel is found from Eq. (7), assuming that a net tensile stress of 320,000 psi can be developed in the cables,

$$A_{st} = \frac{1}{2} \frac{50,000}{320,000} A_c$$

$$A_{st} = 0.078 A_c = 0.078 \times 8 = 0.623 \text{ sq. in.}$$

(Note: In wing No. IV the actual cross-sectional area of the

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steel cables was 0.189 sq. in.)

To obtain an estimate of the unit wing weight (per sq. ft.) the following calculations can be made for the hypothetical wing:

TOTAL VOL. OF CERAMIC = A_c x span

$$Vol._c = 8 \times 22 = 176 \text{ cu. in.}$$

Total weight of ceramic = Vol. x density

$$W_c = 176 \times 0.12 = 21.1 \text{ lb.}$$

Total vol. of steel = A_s x span

$$Vol._s = 0.623 \times 22 = 13.7 \text{ cu. in.}$$

Assuming a density of 0.29 lb./cu.in.:

$$W_{st} = 13.7 \times 0.29 = 4.0 \text{ lb.}$$

TOTAL WING WT. (less fittings)

$$W = W_c + W_{st} = 21.1 + 4.0 = 25.1 \text{ lb.}$$

Unit weight:

$$\frac{W}{S} + \frac{25.1}{2.15} = 11.7 \text{ lb./sq. ft.}$$

The above calculations were made primarily to illustrate the type of calculations that can be carried out for a centrally-prestressed structure. It is obvious that the only quantities that need to be known, so far as the ceramic is concerned, are the allowable compressive stress and the density. For this type of beam, the allowable bending moment is the same in either direction.

For the centrally-prestressed beam the bending deflections are calculated in the usual manner, from the basic equation:

$$\frac{1}{R} = \frac{d^2y}{dx^2} = \frac{M}{E\ I} \qquad (9)$$

Only the values of the ceramic material are used for E I, since it can be assumed that the prestressing cables, at the neutral axis, contribute nothing to the bending stiffness.

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(b) Other arrangements of prestressing cables.

Various other arrangements of prestressing cables are possible and, in some cases, advantageous. For example, if a greater allowable bending moment is desired in one direction (as for a wing) some weight can be saved by locating the cables eccentrically, i.e., they should be displaced toward the "tension" side. The distribution of the initial precompression stress will then be non-uniform, varying linearly over the cross-section. The ideal location is determined by the ratios of the bending moments required in each direction. If there is no reversal of bending moment direction, the ideal location of the cables will be at the "core radius", defined by

$$r_c = \frac{Z}{A}$$

When such a beam is prestressed, there will be zero stress on one side and twice the average compressive stress on the other, as shown in Fig. 11. Consequently the entire allowable compressive stress of the ceramic can (theoretically) be used in calculating the allowable bending moment.

(Note: Wings I and II were made with eccentric prestressing cables, but since no normal load was carried, no calculations will be included.)

A third basic type of prestressing can sometimes be used in which the cables are located at the centroid of flange areas. For example, in a thin-walled shell, such as a fuselage, small cables could be threaded through the ceramic elements forming the shell. For a symmetrical arrangement the prestresses are computed as for central loading, but now the wires will contribute directly to the bending strength and stiffness of the cross-section. The analysis can be performed by transforming the

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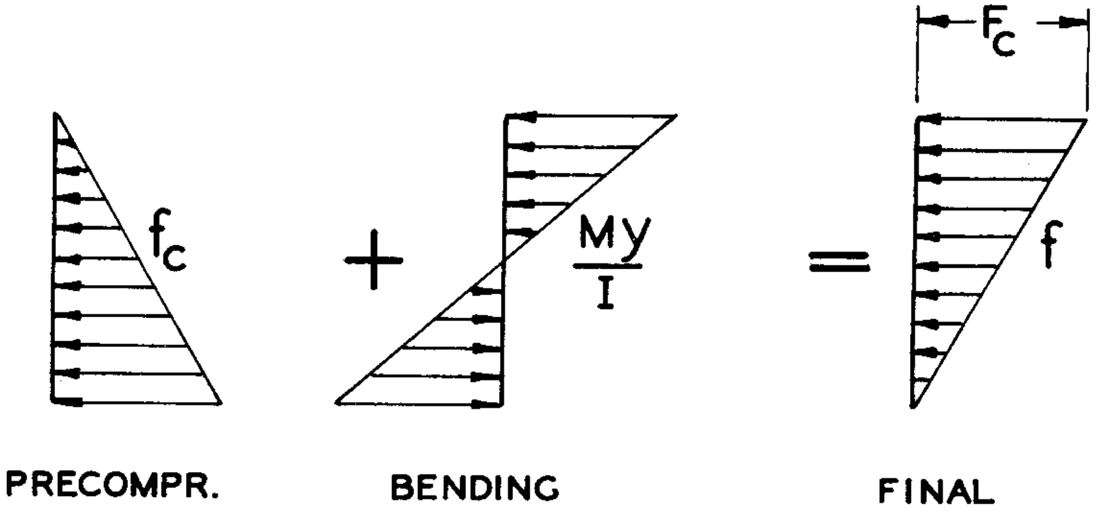

FIG. 11 - PRESTRESSING AT CORE RADIUS

cross-section into an equivalent "all-ceramic" section, using the ratios of E as a weighting factor. In such construction the wires need not be prestressed to their maximum allowable load; in fact it would not be possible to do this. (See also Appendix F.)

(c) Transmission of shear forces

It does not appear likely that any special provision need be made for transmitting the transverse shear forces in a prestressed-ceramic wing, provided that high allowable compressive stresses can be developed. The shear stresses tending to cause slippage of the elements will be very low in proportion to the axial stresses due to bending or precom-

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pression. Consequently the coefficient of friction that would be present in any type of joint should provide more than enough strength.

If the prestressing cables are installed on a slant (as in Wing No. II) they will apply a "preshear" to the beam, because of the transverse component of the prestressing load. This will have to be overcome by the applied shearing forces before any tendency to slip in the direction of shear loading is produced.

This feature is used to advantage in prestressed concrete beams which must resist steady "dead-load" shears of considerable magnitude. However, it does not appear to be needed in wings.

In shell structures it may be found desirable to install cables in a spiral manner, with half the cables spiralling in opposite directions. This construction will enable the cables to resist shear and torsion loads directly. If double-curvature is present, the spiral arrangement will also cause precompression forces to act in a radial direction, thereby inducing circumferential ("hoop") compressive stresses in the elements.

(d) Effects of "floating" cables.

A very important feature in prestressed construction is the effect of "floating" cables, which are permitted to move freely inside the ceramic elements. This is shown diagrammatically in Fig. 12.

Sketch (a) shows an element with some curvature (greatly exaggerated) in which the cable is floating. The tension force applies a compressive force at the ends of the element. Since this force is lined up with the straight cable, the situation is that of an eccentric column. The apparent stiffness in bending will be greatly reduced if the member is long and slim (as in a wing). It is well known that the bending de-

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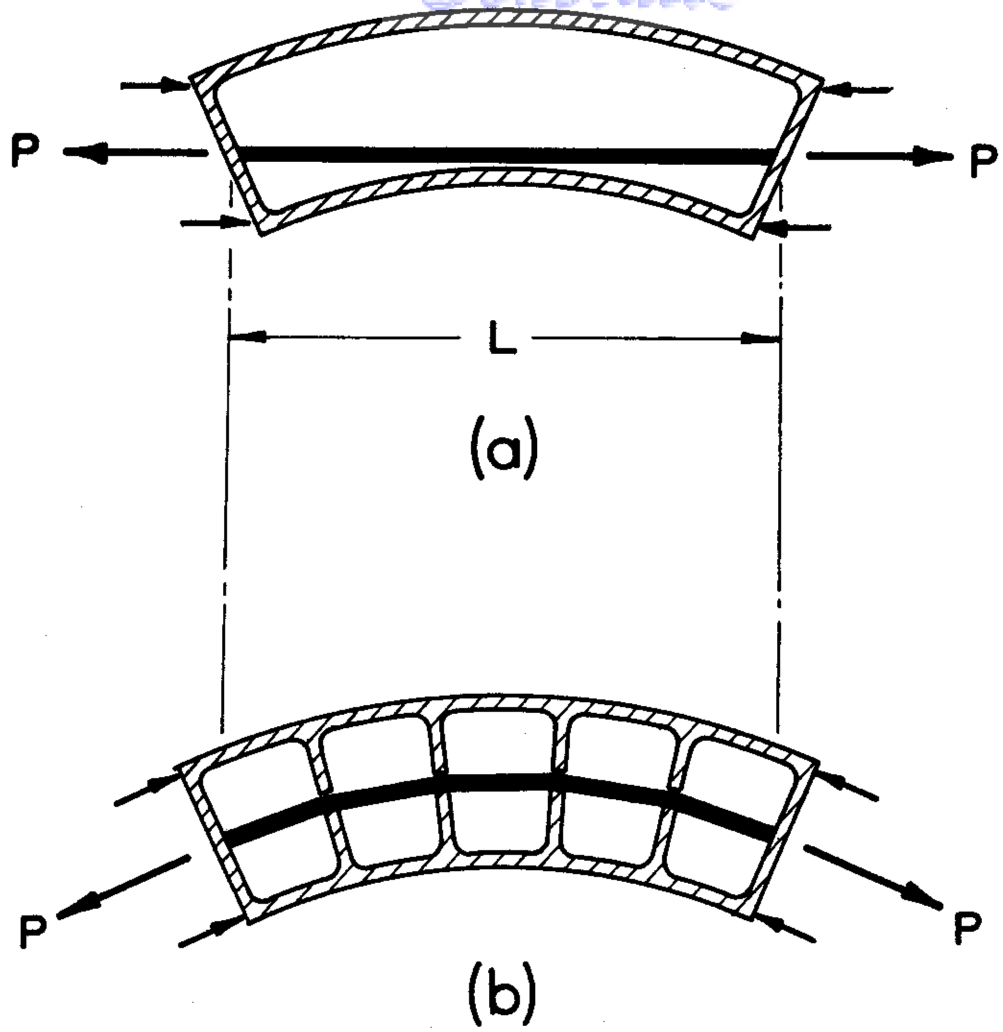

FIG. 12 - EFFECTS OF "FLOATING" CABLE

flections in such cases must be multiplied by a factor which is given quite accurately by

$$k = \frac{1}{1 - P/P_E}$$

where P = end load

P_E = Euler column load = $\frac{\pi^2 E\ I}{L^2}$

As the end load, P, approaches the Euler load, the value of k approaches infinity. Conversely, the decrease in apparent E I is given by the reciprocal, which is $1 - P/P_E$.

Fig. 12 (b) shows the effect of installing closely-spaced bulk-

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heads which require the cable to curve with the entire structure. No overall column action can occur now, and the beam does not suffer any loss in apparent stiffness.

Highly-curved beams can be prestressed, provided that bulkheads (or an equivalent method of supporting the cables) are used.

The effect of floating cables is magnified by any other effects which decrease the apparent stiffness (EI). In prestressing Wing No. III, for example, it was noted that the wing began to bend at low cable loads, even though it was presumably initially straight and concentrically loaded. As previously noted, spacers or bulkheads had not been provided in this wing and this, together with the effects of gasket deflection, caused it to be very sensitive to lateral deflection.

One simple method of providing support for the cables is to fill the interior with some sort of "grout" which hardens after pouring. (This is often done in concrete construction). This should be investigated in future designs, possibly using a light plastic compound such as "Lockfoam" (Ref. 9).

(e) Poisson effects.

The effects of lateral expansion during compression appear to be specially important in brittle materials, in two possible ways:

(a) Development of undesirable transverse stresses in thin beams (anticlastic curvature effects).

(b) Possible cause of cracking of material itself.

The fact that cracking was more prevalent in the relatively thin wing than in the individual specimens led to a hypothesis that the Poisson effect might be causing transverse (chordwise) stresses of considerable magnitude. Since there was no chordwise precompression this could have

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caused cracking. Although other factors now seem to be more likely to have caused the cracking, the tendency of the wing to bend in a chordwise direction when deflecting under spanwise loading should be considered in any thin wing design.

Of greater fundamental interest is the possibility that transverse tension stresses must actually exist in a compression specimen. The tendency for compression specimens to crack longitudinally is sometimes attributed to a "wedging effect" at the ends of the specimen. (See Ref. 7 p. 345.)

In a non-ductile material, however, this explanation does not seem to apply. One hypothesis which has been suggested (1) is that a transverse stress will actually exist in a cylindrical member subjected only to axial loading. This is based on the concept that in a polycrystalline or amorphous material the surface will not consist of atoms or molecules which are in line with the axial load. On the contrary, most of these force-transmitting elements will constitute an irregular path. At the "peaks" of such a path, an internal lateral force is required for equilibrium. In axial compression, this lateral force would have to be tension. The basic idea is illustrated in Fig. 13.

Since all atoms or molecules in the interior of the specimen must be in equilibrium with respect to lateral forces, the above phenomenon, if it exists, would constitute a "skin effect". This would also tend to produce circumferential tension stresses of a "hoop-tension" nature. Such stresses, together with the stress-concentration effects always present in the surface, could initiate longitudinal cracking.

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(1) In unpublished lecture notes by F. R. Shanley, 1953.

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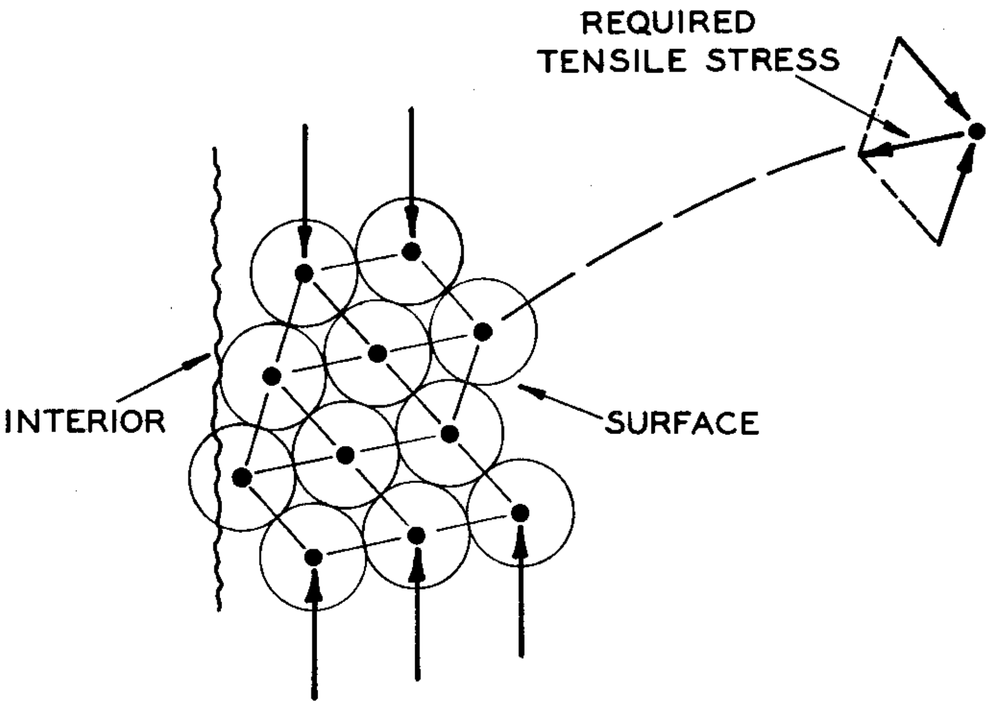

FIG. 13 - SCHEMATIC MECHANISM OF TRANSVERSE STRESS THEORY

Another way of stating this hypothesis is to say that the "wedging action" (usually believed to be associated with the contact plates at the ends of the specimen) is actually present throughout the material and is a necessary result of an irregular alignment of atoms or molecules at the surface.

This theory seems to be in accord with some observed facts. For example, in Sec. 20-5 of Ref. 7 it is shown that a porcelain specimen will develop much higher strength if it is shaped so as to produce circumferential compressive stresses under axial compressive loading.

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In view of the very high potential strength of ceramics in compression it would be desirable to encourage fundamental research toward a better understanding of the causes of longitudinal cracking of brittle materials.

(f) Possible changes in cable tension.

There are two possible causes of change in the prestressing load, once it has been applied and locked by some positive means. These are creep and temperature effects. In prestressed concrete structures it is known that the concrete will creep (shorten) to some extent under the action of the compressive stress. This causes the tension load in the cables to decrease. In design and analysis this is provided for by assuming that the final load in the cables will be a certain fraction of the initial load. (This is based on the fact that the creep of concrete appears to decrease to a negligible value after a certain time.)

With ceramics there is no measurable creep at room temperature and probably very little at much higher temperatures. High-strength steel wires will not creep appreciably at room temperature, but can be expected to creep considerably at high temperatures. Gaskets, if used, may also contribute to the creep effect. These factors can all be included in the analysis, if creep data are available. For relatively low temperatures, or for short times of exposure to high temperatures, creep does not appear to be a significant factor.

Differential expansion of steel and ceramic due to temperature changes does not appear to be a serious problem, because the use of high strength wires permits very large initial tensile strains in the cables. Any change of load in the wires will be governed by the ratio

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between the effective change of strain and the initial strain. With large initial strains this ratio is reduced to insignificant proportions.

This is a very important reason for using high-strength cables, aside from the weight-saving involved. For example, if low-carbon steel were to be used for prestressed concrete the initial strain would have to be low, because of the low yield point. Consequently any subsequent creep of the concrete would cause a large decrease in the prestressing load.

The use of fine wires permits high tensile stresses to be used and this in turn minimizes all effects of creep and thermal expansion. In this connection it appears desirable to investigate the possibilities of using fine ceramic fibers for the prestressing cables.

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7. CONCLUSIONS AND RECOMMENDATIONS

1. The most serious problem encountered in the design and testing of a prestressed ceramic wing was the premature cracking of the ceramic elements in a spanwise direction. It is recommended that further efforts be made to overcome this difficulty, including the use of different materials, methods of fabrication, gasketing methods, etc.
2. Ceramic materials were developed which, in the form of small specimens, had strength/weight ratios that were adequate for efficient designs. Further development of ceramic materials is recommended, with a view to their use in dry-pressing methods of fabrication.
3. Although two different types of ceramic elements were produced by slip-casting techniques, it is recommended that other forms of fabrication be investigated, with a view toward quantity production, close control of tolerances, and elimination of cracking tendencies. Hot-pressing methods appear attractive in this connection.
4. High-strength cables with small and efficient end fittings were successfully developed and tested. It would be desirable to replace metal cables by ceramic cables, for high-temperature operations. Therefore development of high-strength ceramic fibers and cables is recommended.
5. Preliminary tests indicated that directional porosity had very favorable effects on strength/weight ratio. In some cases the failing load (in compression) was increased considerably by the

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removal of material. Investigation of the causes of this phenomenon is recommended.

6. It appears desirable to develop a method of obtaining directional porosity in parts formed by pressing. One possible method of doing this is to use coated fibers as the base material.

7. Fundamental research on the causes of longitudinal cracking of ceramics, under compressive load, is recommended. A possible theory for transverse stresses is suggested. (Page 46.)

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Appendix A

Development of Ceramic Materials

1. Introduction:

One of the first needs encountered in this study was to develop a ceramic material possessing good strength properties and satisfactory forming characteristics. The material compositions evaluated to date have been those which may be fired to maturity at or below 1500°C. It was decided that materials of the clay-feldspar-alumina type would be developed.

This study was initiated during the first contract year of research (see WADC TR 54-75 Pt 1), and this report pertains to work completed during the current contract period (1953-1954).

2. Composition of Ceramic Materials:

The ceramic body mixture used for the preparation of test specimens was body no. 42, which was developed during the first contract year of research (1952-1953). For comparison, the composition of body no. 42 is given at the bottom of Table I.

The compositions of currently evaluated ceramic bodies are shown in Table I and Figure 1.

Typical chemical analyses of body ingredients are given in Table II.

3. Experimental Procedure:

The following is a summary of testing procedures:

Body preparation - The body materials were weighed and mixed with about 35% by weight of distilled water and 0.3% sodium silicate to form a

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slip. The slip is agitated with power stirring for about one hour, and is screened through a 60 mesh sieve prior to use.

<u>Forming</u> - Slip-casting in plaster of Paris molds was used to form 1" x 1" x 10" bars. Behavior in forming was noted.

<u>Firing</u> - Dry bars were fired in an electrically-heated kiln (Harper HS-242029K furnace with "Globar" elements) to several trial temperatures. The furnace heating program was controlled with a controller-recorder. Standard cone plaques also were used.

<u>Transverse strength</u> - Fired bars were broken in flexure on a six inch span. Center-point loading was used (See Fig. 2). Modulus of rupture values were calculated.

<u>Compressive strength</u> - The compression specimens were cut approximately three inches long, using a 10-inch diamond-edge cutting wheel, and measured for parallelism. The variation was measured with a dial indicator and plane table. The specimen was placed on the plane table and the dial indicator adjusted to zero at the center of the specimen. Readings to the nearest .001 inch were taken at each corner of the specimen.

The crushing load was applied with a 400,000 pound Baldwin Hydraulic press at the rate of 20,000 lbs. per minute.

Brass shim stock .005 inch thick was used as gasket material between the specimen and the bearing plates of the press.

The ultimate compressive strength was calculated from the breaking load and the average area of the specimen. The average area was obtained by dividing the volume of the specimen by the length. Only materials whose transverse strength values were 10,000 psi, or greater, were tested in compression.

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Apparent Porosity - Apparent porosity values were calculated by noting the volume of water absorbed by a specimen after complete saturation, and by determining the bulk volume of the same specimen. (For further details of test method, see A. I. Andrews, Ceramic Calculations, John Wiley and Sons, 1928, p. 31.)

Firing Treatment - Table III gives the firing treatment for each material composition.

4. Results and Discussion:

The experimental results for transverse strength, compressive strength, apparent porosity and water absorption are given in Table IV. The deviation from parallelism for specimens also is noted in Table IV. Transverse strengths and compressive strengths also are shown in Figure 1, with the modulus of rupture value plotted above each composition point, and with the compressive strength listed below the same composition point.

In evaluating these results, it may be desirable to list for comparison the following properties of body 42: (From WADC TR 54-75 Pt 1)

Transverse strength (Modulus of Rupture) - 5200 psi

Compressive strength - 40,000 psi

Apparent porosity - 20%

Bulk density - 0.075 lbs. in.$^{-3}$

Modulus of elasticity - 13 x 10^{6} psi

Compositions A, K, Q, R and L (see Table I and Figure 1) were undervitrified when fired to 1500°C; therefore, the strength results are for underfired specimens. In order to check the effect of underfiring, compressive strength tests as well as porosity and absorption

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measurements were made on Compositions L and R (see Table IV). Table IV shows that compositions L and R have low compressive strengths and high porosity and absorption. Table IV includes the average ultimate compressive strength for each composition; these figures also appear in Figure 1. In computing averages, values for bars that showed unusually low strength and great deviation from parallelism of the bearing faces were not included.

In looking over Table IV it is noted that the reason for an unusually low value of compressive strength is obvious in all but two cases. This was considered an indication that the great range of values frequently encountered may in some cases be due to differences in porosities of the specimens and parallelism of the bearing faces.

In review, however, it is seen that compositions C, M, S, T, X, Y and Z show load-bearing capacities in compression, for the test used, of over 70,000 psi, and that about half of the compositions gave values approaching 90,000 psi.

5. Conclusions:

Work with clay-feldspar-alumina ceramic materials indicated that recently-developed bodies (C, M, S, T, X, Y and Z) are about twice as strong in compression as presently-used body 42, as the load-bearing capacity approaches 90,000 psi for several of the materials under existing experimental conditions. The above-mentioned recently-developed materials should be considered for future use in preparing wing or fuselage sections for prestressed test members.

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TABLE I

Compositions of Experimental Ceramics						
% Composition by Weight						
Body No.	"Champion Challenger" Ball Clay (1)	"Bandy Black" Ball Clay (1)	North Carolina Kaolin (1)	Georgia Kaolin (5)	"Kingman" Feldspar (3)	-325 mesh Tabular Alumina (4)
42	16	17		20	17	30
A	15	10	25			50
B	15	10	25		10	40
C	15	10	25		20	30
D	15	10	25		30	20
E	15	10	25		40	10
F	20	10	30			40
G	20	10	30		10	30
H	20	10	30		20	20
I	20	10	30		30	10
K	10	15	15			60
L	10	15	15		10	50
M	10	15	15		20	40
N	10	15	15		30	30
O	10	15	15		40	20
P	10	15	15		50	10
Q	10	5	15			70
R	10	5	15		10	60
S	10	5	15		20	50
T	10	5	15		30	40
U	10	5	15		40	30
V	10	5	15		50	20
W	10	5	15		60	10
X	10	5	5		40	40
Y	10	5	5		50	30
Z	10	5	5		30	50

(1) Spinks Clay Co., Paris, Tenn. (Air-Floated)

(2) Harris-Lunday Clay Co., Dinsboro, N. C.

(3) Consolidated Feldspar Corp., Kona, N. C.

(4) Aluminum Co. of America (Grade T-61)

(5) United Clay Mines, Trenton, N. J. ("Kingsley")

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TABLE II Typical Compositions of Body Ingredients

RAW MATERIAL	Oxides Present Wt. (%)											
	Silicon Dioxide (SiO_2)	Aluminum Oxide (Al_2O_3)	Iron Oxide (Fe_2O_3)	Manganese Oxide (MnO)	Titanium Oxide (TiO_2)	Calcium Oxide (CaO)	Magnesium Oxide (MgO)	Sodium Oxide (Na_2O)	Potassium Oxide (K_2O)	Sulphur Trioxide (SO_3)	Phosphorous Pentoxide (P_2O_5)	Loss On Ignition
"C and C" Ball Clay	53.96	29.34	0.98	0.02	1.64	0.37	0.30	0.12	0.28	0.03	0.15	12.82
"Bandy Black" Ball Clay	61.00	24.54	0.90	0.01	1.29	0.09	0.12	0.36	1.69	0.11	0.07	9.74
Kingman Feldspar	66.9	18.2	0.09			0.1	trace	2.4	11.9			0.6
Georgia Kaolin (U.C.M.)	46.09	37.89	0.528		1.09	0.10	0.16	0.46	0.15			13.66
North Carolina Kaolin	45.8	36.5	1.4		0.0	0.3	0.2	0.3				13.4

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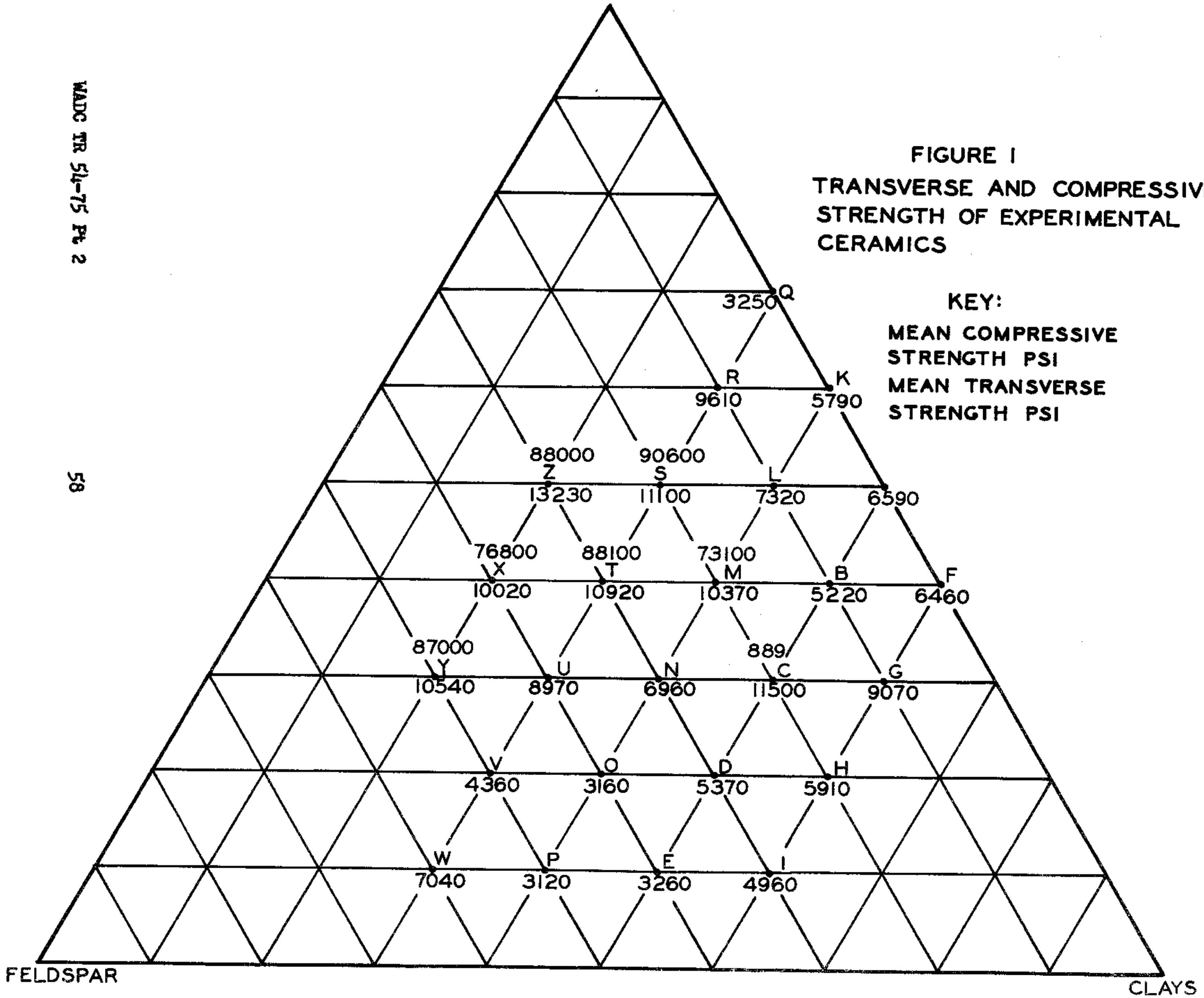

FIGURE I
TRANSVERSE AND COMPRESSIVE STRENGTH OF EXPERIMENTAL CERAMICS

KEY:
MEAN COMPRESSIVE STRENGTH PSI
MEAN TRANSVERSE STRENGTH PSI

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TABLE III

Firing Treatment of Experimental Ceramics

Firing	Composition	Heat Treatment
1	A, B, C, D, F, G, H, I, K, L, M, N, Q, R, S	Fired to 1500° C at 80° C/hr., and held 6 hrs.
2	E and T	Fired to 1400° C at 80° C/hrs., and held 6 hrs.
3	O	Fired to 1450° C at 80° C/hr.
4	P, U, V, X, Z	Fired to 1350° C at 80° C/hr.
5	Y, W	Fired to 1250° C at 80° C/hr.

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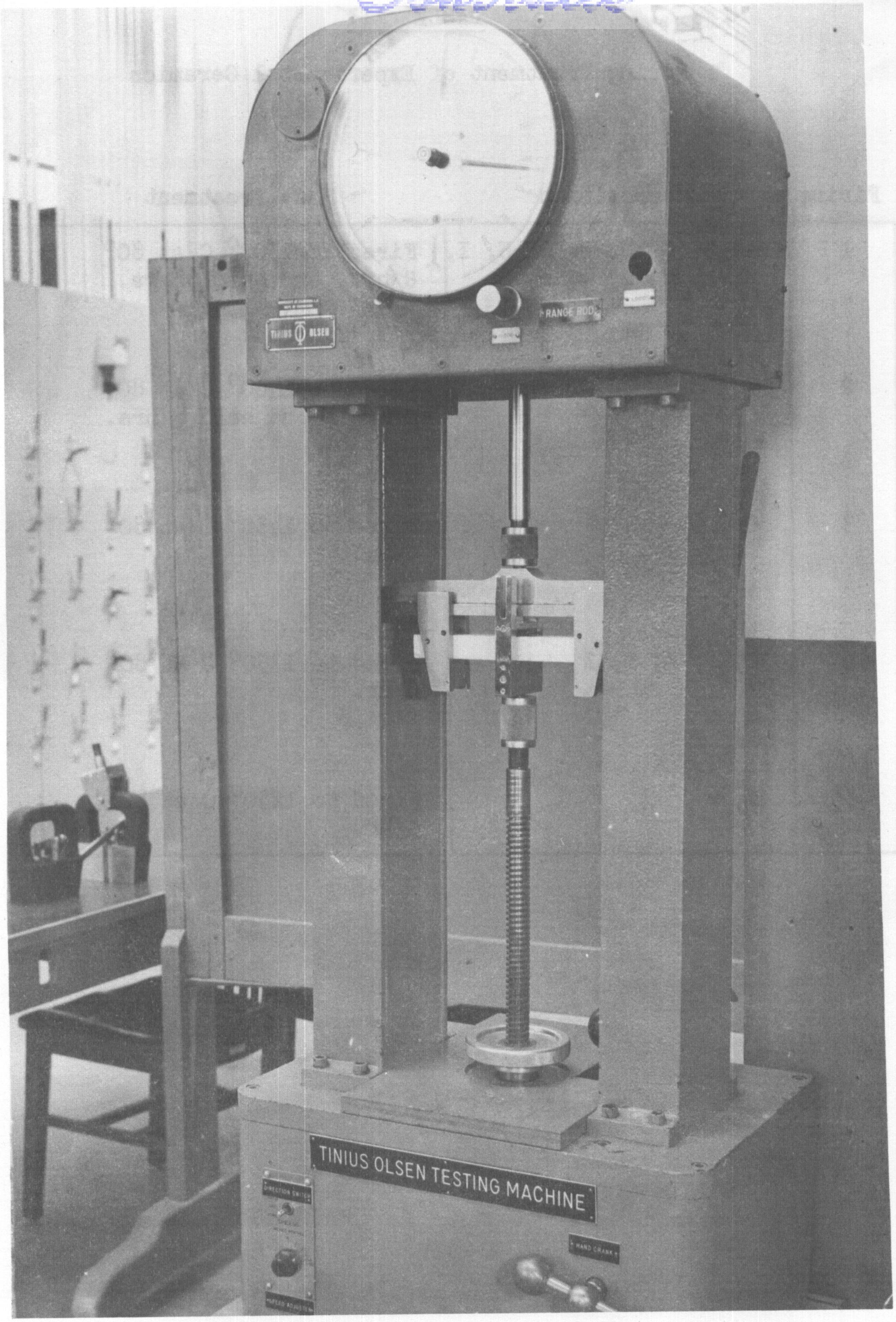

FIG. 2 - BENDING TEST EQUIPMENT

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TABLE IV (page 1)

Composition	Bar (specimen)	Modulus of Rupture (Psi)	Ultimate Compressive Strength(Psi)	Av. Ultimate Compressive Strength(Psi)	Deviation from Parallelism # 1/1000"	Apparent Porosity (%)	Absorption (%)
C	3_1	13,300	20,500* (1)	88,400	14	.89	.36
	3_2		89,200		3	.46	.22
	4_1	10,350	98,300		2	1.00	.39
	4_2		93,000		11	2.94	1.14
	5_1	12,210	20,100* (2)		1	.61	.25
	5_2		73,100		3	.38	.15
G	1_1	9,800	22,000**		3	1.61	.66
	1_2		15,700**		16	1.84	.76
L	3_1	9,280	36,800**		3	18.91	7.04
	3_2		34,200**		4	19.28	7.16
M	1_1	11,650	67,000	73,100	2	.42	.17
	1_2		58,400		1	.94	.38
	3_1	11,240	92,800		1	.34	.14
	3_2		82,100		0	.57	.23
	6_1	8,680	60,600		2	.21	.84
	6_2		77,500		2	.42	.17
N	1_1	11,520	60,800**		7	.67	.25
	2_1	2,510	51,200**		4	10.33	4.22
R	5_1	10,050	73,900**	68,900	1	27.22	9.52
	5_2		69,600**		2	27.29	9.47
	6_1	9,480	27,000**		12	25.25	8.97
	6_2		63,200**		2	25.58	9.05

For compressive specimens. * and ** See end of table.

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TABLE IV (page 2)

Compo-sition	Bar (spec-imen)	Modulus of Rupture (Psi)	Ultimate Compressive Strength(Psi)	Av. Ultimate Compressive Strength(Psi)	Deviation from Parallelism # 1/1000"	Apparent Porosity (%)	Absorption (%)
S	1_1	12,180	97,000	90,600	0	3.93	1.45
	1_2		101,600		4	11.25	3.96
	3_1	10,220	80,200		2	4.64	1.72
	3_2		71,500* (1)		5	1.60	.60
	4_1	13,710	80,400		2	1.85	.70
	4_2		83,900		4	4.80	1.79
	6_1	11,550	99,900		2	11.19	3.95
	6_2		99,500		1	3.71	1.37
T	1_1	10,590	91,500	88,100	4	.23	.85
	1_2		79,700		2	.56	.22
	2_1	11,320	90,700		4	1.44	.45
	2_2		93,400		4	4.34	1.56
	4_1	11,690	36,300* (1)		9	.56	.22
	4_2		85,000		5	2.57	.93
U	1_1	9,150	44,200**		6	.74	.30
	1_2		74,000**		4	.31	.12
X	3_1	9,175	71,570	76,800	4	.61	.24
	3_2		77,500		4	.72	.29
	5_1	12,380	55,400* (3)		6	.61	.24
	5_2		81,500		6	1.03	.42

For compressive specimens. * and ** See end of table.

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TABLE IV (page 3)

Compo-sition	Bar (spec-imen)	Modulus of Rupture (Psi)	Ultimate Compressive Strength(Psi)	Av. Ultimate Compressive Strength(Psi)	Deviation from Parallelism # 1/1000"	Apparent Porosity (%)	Absorption (%)
Y	1_1	10,910	65,700* (1)	87,000	8	.36	.14
	1_2		79,900		1	.35	.13
	2_1	9,950	82,100		2	.87	.33
	2_2		90,600		4	.0	.0
	3_1	9,780	95,600		2	.43	.16
	3_2		66,400* (3)		2	.65	.25
Z	1_1	14,500	95,600	88,000	4	12.50	4.16
	1_2	1	55,000* (4)		2	1.45	.53
	2_1	12,200	73,400		2	6.49	2.26
	2_2		92,800		0	.62	.23
	3_1	13,400	96,100		1	.94	.34
	3_2		82,000		2	6.27	2.18
	4_1	14,700	52,200* (4)		2	.77	.34
	4_2		62,100* (4)		2	10.73	3.59

For compressive specimens.

* Not included in averaging: (1) Deviation from parallelism; (2) Used a spherical head, specimen was not centered; (3) Low for unknown reason; (4) Used asbestos gasket material.

**Not reported in Figure 1. These specimens were tested to spot check the assumption that a low transverse strength meant a low compressive strength.

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Appendix B

Preparation of Ceramic Wing Sections

1. Introduction:

During the first contract-year of work, considerable difficulty was encountered in attempting to assemble type-1 and type-2 ceramic wing sections (See WADC TR 54-75 Pt 1), in that the ceramic wings failed prematurely during the application of prestressing loads. It was felt that the causes of premature failure may have been (a) stresses produced by Poisson's ratio effects (transverse expansion of upper wing surface and corresponding contraction transversely of the lower surface brought about by bending of the wing), and (b) lack of complete flatness and parallelism of mating wing section surfaces.

Therefore, the preparation of ceramic wing sections during the current contract year (1953-1954) was planned so as to minimize the causes (a) and (b) of failure mentioned above. Steps undertaken to accomplish this were the design of a new (type-3) wing section shape (to reduce stress concentrations due to (a) Poisson's ratio effects), and the development of improved methods of preparation of wing section mating surfaces (to obtain better flatness and parallelism).

2. Design of a Cellular Wing Section (Type-3):

It was felt that a wing section cellulated with holes of circular cross-section would reduce the development of stress concentrations mentioned above (1).

When the decision was made to use cellular wing sections, new design considerations were necessary. With this type of configuration

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there are considerable variations in incremental wing areas over the cross section (See Figure 3, area graph). A theory was developed for determining the areas which would be influenced by prestressing elements located in the cells. It was noted that over most of the cross section variations of cell areas paralleled variations of incremental ceramic areas. However, near the leading and trailing edges the area of ceramic material increased sharply while cell areas continued to decrease (See Figure 3, Type-2).

In order to be consistent with principles of optimum design (also to avoid excessive strains in some prestressing elements) it was thought that tension elements over the cross section should be stressed equally (or proportionately, with relation to ultimate strength) at any given time. This would necessitate varying the area of these elements proportionately with the ceramic areas they would influence. The design of Figure 3, Type-3, represents an effort to achieve reasonably uniform stress distribution.

In view of the above design considerations, it was decided to use the type-3 design for wing section preparation, wherein the cellulation is mainly circular in cross-section, excepting for the slots near the leading and trailing edges.

3. Preparation of Type-3 Ceramic Wing Sections:

The cellulation characteristics and shape of the type-3 wing section are shown in Figure 3. As indicated earlier, this design is aimed at a reduction of stress concentrations during prestressing in the wing assembly.

The following procedure was used for preparation of type-3

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wing sections:

Material - Ceramic body no. 42 (see Table I, Appendix A of this report).

Forming - Solid-cast wing sections are formed by slip casting in plaster of Paris molds. The casting is allowed to dry partially, until the material is in a firm, but relatively tough ("leather-hard") condition, and the cellulations (corings) are drilled in the casting with standard steel drills. A jig and template has been constructed to allow quick spotting of the drill holes. After drilling, the wing sections are air-dried and finally oven dried at about 150°F.

Firing - The wing sections were fired in an electrically-heated furnace (Harper HS-242029K) to the equivalent of a heat treatment of Cone 18, using a heating time of about 24 hours. The furnace heating program was controlled with a controller-recorder, and standard pyrometric cones also were used.

Cutting - The fired wing sections were cut, to provide finished mating ends, using a 10-inch diamond-edge cutting wheel mounted on a surface grinder. A more detailed description of the cutting procedure is given in Section V of the WADC TR 54-75 Pt 1 report.

Lapping - A portion of the wing sections were hand-lapped on the mating surfaces, after cutting, to develop good flatness and parallelism. Lapping was done on a plate-glass surface, using several grades of fine silicon carbide and water.

As is indicated in another part of this report, one wing test member was assembled with sections which had been cut, but not lapped, whereas another test member was assembled with lapped wing sections.

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4. Results:

Approximately 40 wing sections (type-3) were prepared by the procedures described in (3). A photograph of a typical type-3 wing section is shown in Figure 4.

It was felt that the method of preparation of wing sections used offered several disadvantages, including the difficulty of meeting size tolerances with the slip-casting forming method, and considering the losses incurred during drilling of the partially dried sections.

The use of a dry-pressing forming method for preparing wing sections in future work should be given much consideration in view of the above-mentioned difficulties, although the method used proved entirely adequate for the purposes, and was convenient in that only plaster of Paris molds were required as additional facilities to accomplish the forming.

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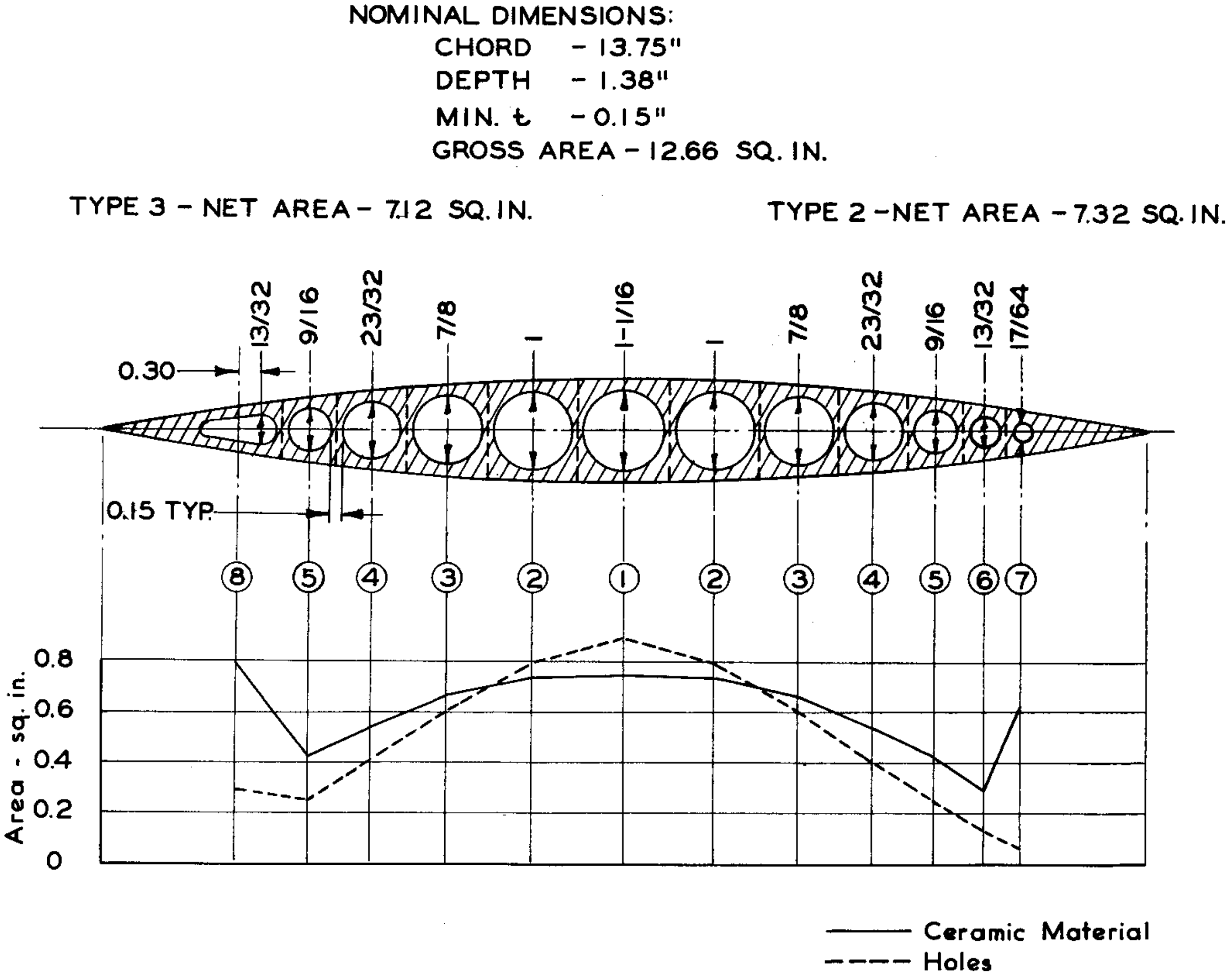

FIG.3 -AREA GRAPH

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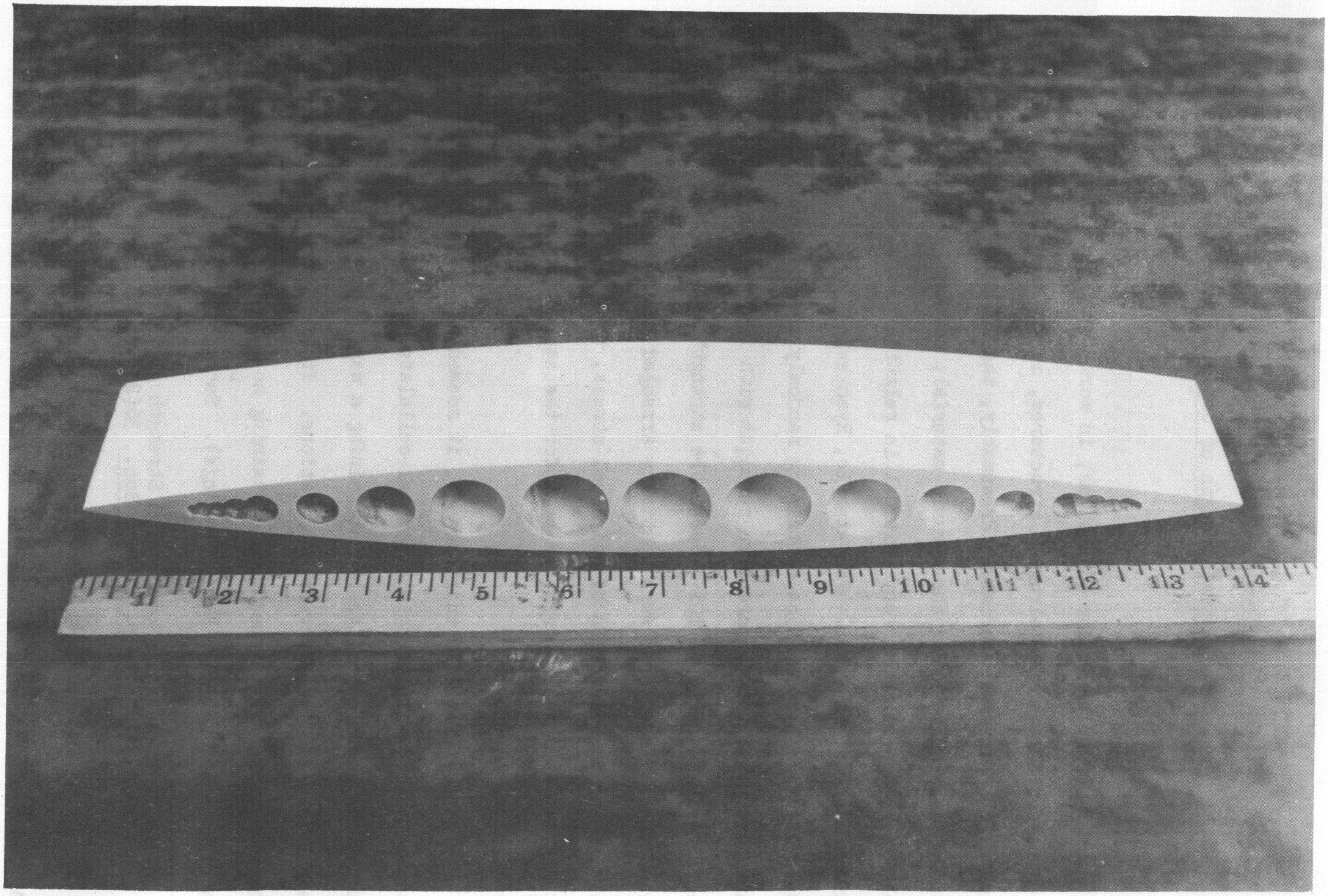

FIG. 4 - PHOTO OF FINISHED WING SECTION

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Appendix C

Effects of Coring (Unidirectional Cellulation) on the Compressive Strength of Ceramic Specimens.

1. Introduction:

One of the major objectives, in work leading to the use of prestressed ceramics as aircraft structures, is the development of lightweight ceramic materials. Presumably, the best way to reduce weight is by cellulating the ceramic material; however, the manner of cellulation seems to be very critical in relation to the mechanical strength of the material. For example, Ryshkewitch* reported that alumina and zirconia ceramics containing randomly arranged pores showed marked reductions in compressive strength with increasing porosity; an increase in porosity of 10% reduced the strength by 50%. However, he found that if the pores were spatially arranged in lines of direction parallel to the direction of principal stress, the compressive strength of the material was better than that for the same material with randomly-arranged pores.

Therefore, in this project, it seemed desirable to study the strength properties of unidirectional-cellulated ceramics, keeping in mind the general objective of determining a way of preparing lightweight ceramics for aircraft applications. It was decided to initiate the work with ceramic specimens containing no closed pores, but with continuous and parallel holes (corings). Such holes (or corings) could

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* Eugene Ryshkewitch, "Compression Strength of Porous Sintered Alumina and Zirconia", J. Amer. Ceramic Soc., 36(2), 65-68, (Feb. 1953).

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be introduced in ceramic specimens of simple shape by drilling operations.

2. Object:

To study the effect of unidirectional cellulation on the compressive strength of ceramic specimens. Cellulation, or coring, was accomplished by removing material with a different number and size of holes drilled parallel to the axis of loading.

3. Experimental Procedure:

Using body no. 42 (see Table I, Appendix A, this report), 12" x 1" x 1" bars were formed by casting. The bars were cut into sections approximately 2" long. While in the leather-hard state, holes were drilled in them, using a drill press and ordinary metal bits. By drilling, material was removed in amounts of 5%, 10%, 15%, 20% and 25% by volume. For each porosity type, the porosity was produced by drilling from 1 to 5 holes, inclusively, of various sizes after air-drying. The bars were fired to 1450°C. After firing the bars were cut approximately 2" long with a diamond-edge cut off saw. The lengths were measured with a micrometer and recorded. They were found to be parallel within 1-3 thousandths of an inch. Each sample was weighed in air and in water and from this the volume was calculated. Using the volume and measured length the area was calculated. The bars were loaded to failure in compression with a 60,000 lb. Baldwin Hydraulic press. The rate of loading was 10,000 lbs/min. Garlock gasketing material was used. Before loading, each sample was scrutinized for defects such as cracks due to drilling and chips off the corners and edges. The observable defects were recorded.

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4. Results and Discussion:

Table V is a tabulation of the average breaking load for like samples, the average ultimate compressive stress, and the spread of each. The spread is the difference between the greatest and least value in each case. Figure 5 is a plot of breaking load versus fraction of material removed (by volume). This graph shows an approximately linear relationship between amount of material and breaking load except in the case of the solid samples. This approximately linear relationship indicates that the compressive strength values agree well for the variously cellulated specimens. This constancy of compressive strength for the cored specimens is shown in Table VI where the average ultimate stress is given for an entire percentage group (columns H and I), Figure 6 is a plot of load-bearing capacity against volume-fraction of solid material, and indicates that unidirectional coring produces light ceramics with good strength. Column K, Table VII, gives the average ultimate compressive stress for all bars having the same number of holes. These figures indicate that the compressive strength is quite constant for the bars having 1, 4 or 5 holes but significantly less for the bars having 2 or 3 holes. This seems to indicate that the symmetry of the holes with respect to the shape of the bar is a factor.

In the procedure it was mentioned that the observable defects in each bar were noted. No correlation was found between observable defects and breaking load. Even the worst appearing defects such as cracks between the drilled holes did not appear to affect the breaking load.

The most outstanding characteristic was the higher net compressive stresses of cored (cellulated) specimens (average = 45,300 psi)

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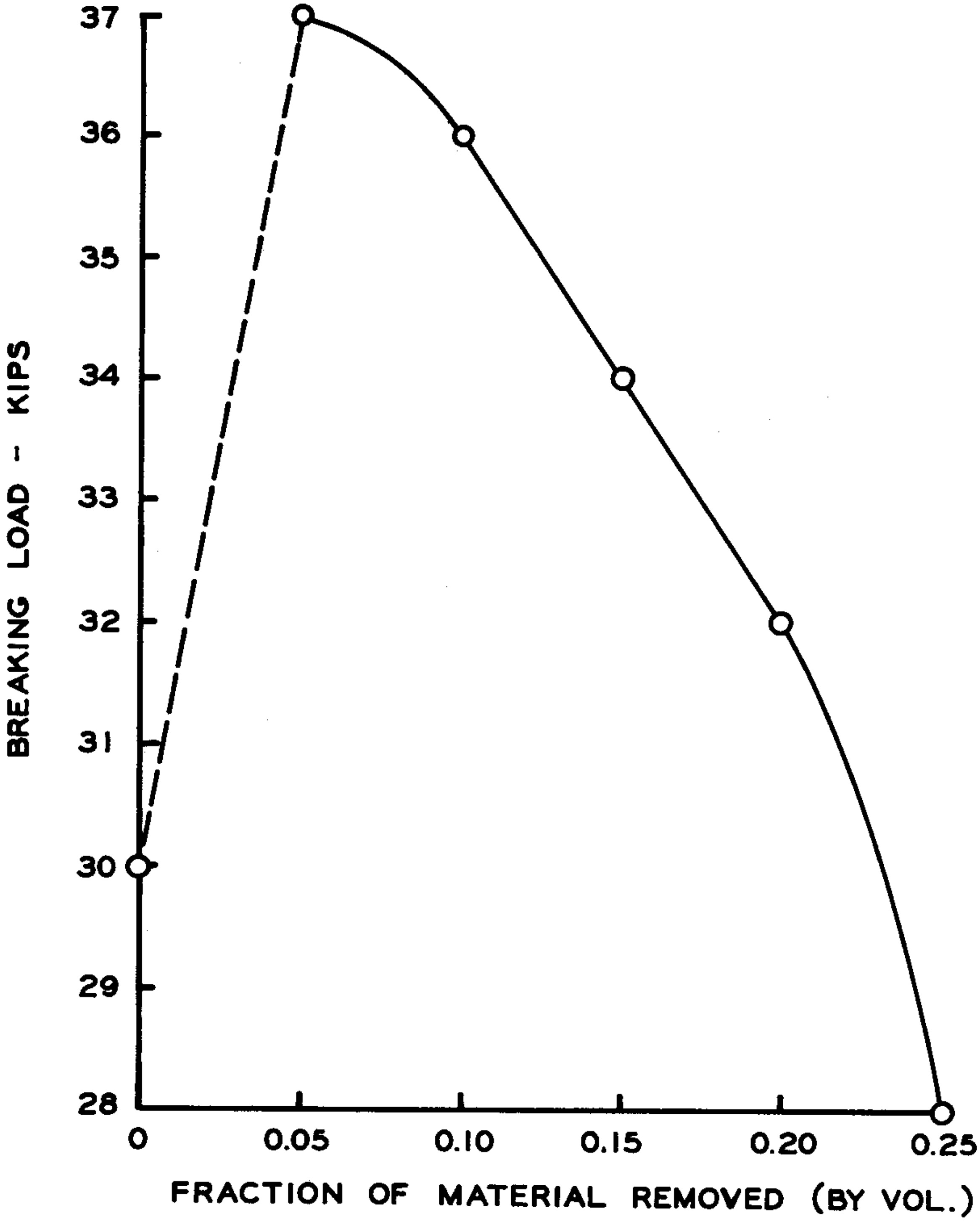

FIG. 5 - BREAKING LOAD VERSUS FRACTION OF MATERIAL REMOVED

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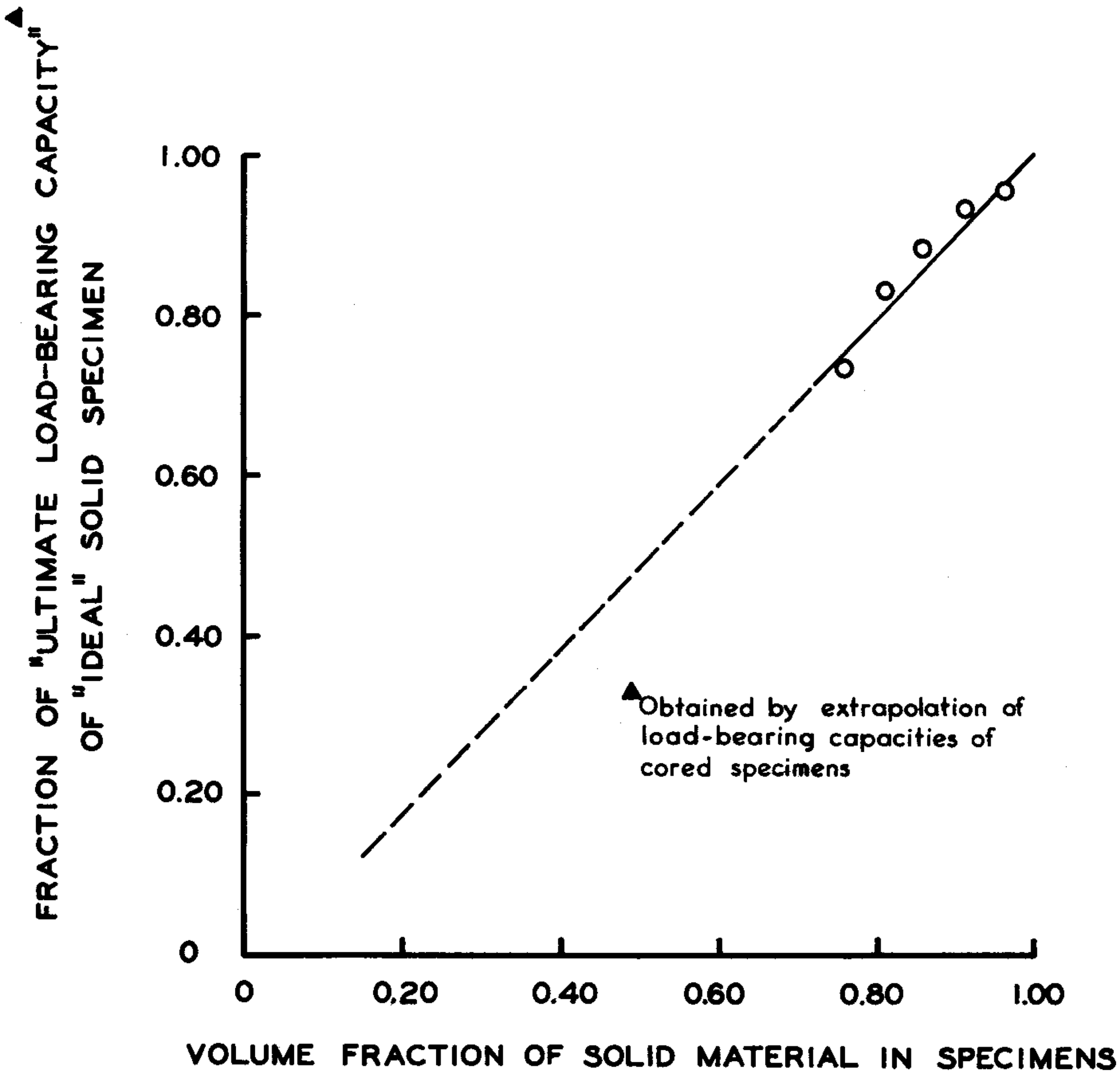

FIG. 6

Load-Bearing Capacity Versus
Volume-Fraction of Solid Material.

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as compared to solid specimens (average = 34,750 psi). Further consideration should be given to this behavior. Additional tests are planned in order to determine whether Poisson effects or temperature distribution (in firing) are causing this result.

5. Conclusions:

A. There is an approximately linear relation between the amount of material and the breaking load for specimens with holes drilled in them parallel to the axis of loading.

B. The results obtained in this work show considerably lower compressive strengths for the solid specimens when compared with those in which holes have been drilled. This very interesting indication suggests that unidirectional cellulation not only produces no adverse effect on load-bearing capacity, but, in fact, may possibly improve it.

C. There seems to be some evidence that the symmetry of the hole placement, with respect to the specimen section, is a factor influencing the compressive strength.

D. No correlation could be made between observable surface defects in specimens and their compressive strength results.

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TABLE V. Compressive Loading Values for Cored Specimens

A	B	C	D	E	F	G
% Material Removed (Volume)	No. of Holes	No. of Samples	Ave. Ultimate Compressive Load(lbs)	Load Spread (lbs)	*Ave. Compressive Strength (Psi)	Psi Spread
0	0	5	29,850	8,570	34,750	9,890
5%	1	5	39,630	7,750	47,420	12,660
	2	5	36,920	8,150	45,540	10,040
	3	5	32,510	10,150	40,600	12,640
	4	5	35,240	10,700	43,340	15,900
	5	3	38,420	9,700	47,710	11,350
			Ave. 37,000			
10%	1	5	37,330	2,250	49,340	2,800
	2	5	32,400	5,400	41,440	8,740
	3	3	29,830	5,850	39,460	7,400
	4	4	35,580	8,150	46,070	11,760
	5	5	33,270	20,950	41,910	28,940
			Ave. 36,000			
15%	1	5	35,500	8,250	49,580	7,840
	2	5	34,370	6,050	47,400	8,080
	3	5	33,550	9,100	46,280	12,710
	4	5	34,180	6,450	46,680	12,350
	5	3	32,400	11,100	43,900	14,230
			Ave. 34,000			
20%	1	5	32,080	8,450	46,760	16,790
	2	5	28,620	9,600	43,880	14,220
	3	5	30,420	3,700	43,790	5,060
	4	4	27,820	15,750	39,900	25,700
	5	4	35,820	10,350	51,440	17,120
			Ave. 32,000			
25%	1	5	26,140	6,800	39,140	11,210
	2	5	29,510	5,000	46,500	8,570
	3	3	28,920	8,550	43,820	14,040
	4	5	25,550	13,800	54,330	29,470

*Average compressive strength of all cored specimens = 45,300 psi.

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TABLE VI. Compressive Strength vs. Material Removed

H % Material Removed (by volume)	I Ultimate Compressive Strength (Psi)
0	34,750
5	44,920
10	43,640
15	46,770
20	45,150
25	45,950

TABLE VII. Compressive Strength vs. Number of Holes

J No. of Holes	K Ultimate Compressive Strength (Psi)
0	34,750
1	46,450
2	44,950
3	42,790
4	46,060
5	46,260

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Appendix D

Development of Methods for Cellulating Ceramics

1. Introduction:

As pointed out in Appendix C of this Report, it appears desirable to cellulate ceramic materials, used in aircraft structures, as a means of weight reduction. However, the type of cellulation seems to have a critical effect on the mechanical strength of the ceramic, and, as also indicated in Appendix C, unidirectional cellulation appears to be the most promising means of producing light-weight ceramic members. The purpose of work described in this Appendix, therefore, is the development of methods for producing unidirectional cellulation in ceramics.

Two techniques of producing unidirectional cellulation were investigated:

(a) Use of ceramic-coated organic fibers.

(b) Forming by core slip-casting.

2. Experimental Procedure:

(a) Ceramic-coated organic fibers - In this method*, organic fibers were incorporated in a raw ceramic body; the fibers were oriented unidirectionally, and upon firing of the ceramic, would burn out, leaving cellulations in the final ceramic.

Materials - Body no. 42 (see Appendix A of this report) was used as the basic ceramic; additions of a wax-in-water emulsion ("Foamrex S", Socony-Vacuum Oil Company, Inc.) and distilled water were mixed with body no. 42 as shown in Table VIII.

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* Suggested by F. R. Shanley, Department of Engineering, University of California, Los Angeles

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TABLE VIII

Mix No.	Composition - Parts By Weight		
	Body No. 42	Wax Emulsion	Distilled Water
C-1	50	50	58
C-2	67	33	67

Mixing - The ceramic materials, wax emulsion, and water were mixed for about 30 minutes in a bakery-type mixer (Hobart Model A-200).

Coating of fibers and cords - To explore the possibilities of coating several types of organic fibers, several sizes of fine nylon strand and cotton cords were dipped in the slips (Mixes C-1 and C-2) to produce a single coating. The dipped fibers and cords were hung by one end in air, and were allowed to dry.

Forming of specimens - Coated fibers and cords, after drying, were cut into short lengths of the proper size for charging into a steel pressing mold. Rectangular-shape specimens were formed by pressing a charge of coated fibers or cords in a steel mold, using a hand-powered hydraulic press (Carver laboratory press). A forming pressure of 1000 psi was used.

Firing - The specimens were fired in an electrically-heated muffle furnace; the temperature was increased at the rate of about 100°C. per hour to 500°C. (slow heating was used in the initial period in an attempt to burn out the organic fibers or cords without producing cracking or other structural failure in the ceramic), and the temperature was then increased at a rate of 400°C. per hour (or more) to the maturing temperature for body no. 42.

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(b) Forming by core slip-casting - The object of this work was the evaluation of core casting as a means of producing type-3 wing sections. The method used previously for cellulating type-3 wing sections, as described in Appendix B of this Report, was drilling-out holes in the partially-dried, solid-cast sections. However, drilling of partially-dried ceramic material is difficult because of the fragile condition of the material, and the drilling operation is rather time-consuming. Therefore, it seemed desirable to evaluate a core-casting procedure, in which the ceramic slip is cast in a plaster of Paris mold containing appropriately-located metal rods. After casting, and when the cast had become reasonably firm, the metal rods are removed, thereby producing suitable cellulation.

Mold and core rods - A plaster of Paris mold, of the same type used for solid-casting type-3 wing sections, was utilized. A series of polished brass rods, each rod of an appropriate size for a cellulation (or core), is held in place by a positioning jig in the plaster of Paris mold. Figure 7 is a photograph of the rods, jig and mold. The rod sizes and positioning were selected to produce a type-3 wing section (see Figure 3, Appendix B) after casting.

Forming by core-casting - A casting slip was prepared with body no. 42 (for composition see Table I, Appendix A), about 35% distilled water and 0.30% deflocculant ($Na_2SiO_3 + Na_2CO_3$). The slip was cast in the mold and core rods assembly, requiring a time period of about 8 hours. At the end of the casting period, the brass rods were withdrawn carefully, and the casting was then removed from the mold.

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Firing, cutting and lapping - These operations are the same as those described in Appendix B, page 66.

3. Results:

(a) Ceramic-coated organic fibers - The coating and forming operations were quite satisfactory. After firing, however, cracks were found in the specimens normal to the direction of pressing. These cracks may have been produced during the pressing operation because of the compressibility of the cotton cords, or the cracks may have developed during the firing operation when the organic matter was being burned. However, the problem of compressibility of fibers might be avoided with the use of hard, single-strand organic fibers (probably plastic fibers).

The results appeared to be reasonably successful, considering the preliminary nature of the experiments. The dry coated-cords were successfully pressed together, due to the plasticity contributed by the wax ingredient of the coating. A considerable amount of new experimentation on various wax contents of the coating, and using various types of organic fibers, is needed. The effect of fiber size and coating thickness should be evaluated. The use of ceramic-coated fibers for developing cellulation appears promising enough to warrant considerable additional study.

(b) Core slip-casting - The core casting of type-3 wing sections seemed to be quite successful. The most critical step in the forming operation was the withdrawing of the metal rods from the casting; however, the preliminary results indicate that if the withdrawing of rods is carried out at the time that the cast has become firm, but

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before much shrinkage has occurred, that the operation can be carried out with no difficulty. Careful timing for the withdrawing of rods is essential, therefore. No taper is needed in the rods for the ceramic materials used in this project.

It appears that core slip-casting would be a better method for forming type-3 wing sections than the one used heretofore (drilling method). However, it appears likely that the development of a dry-pressing forming method may prove more desirable than either of the previously described slip-casting techniques (see Appendix B).

4. Conclusions:

(a) Preliminary experimentation indicates that organic fibers coated with a (ceramic + wax) mixture may be successfully formed into ceramic articles by pressing. Upon firing, unidirectional, and fine, cellulation is produced in the ceramic. The specimens prepared in this project developed cracks, but it is believed that successful preparation of cellulated ceramics may be accomplished with additional experimentation.

(b) The use of core slip-casting as a forming method for preparing type-3 wing sections has been successful. The core slip-casting method eliminates the drilling operation required previously to produce the cellulations of the type-3 section.

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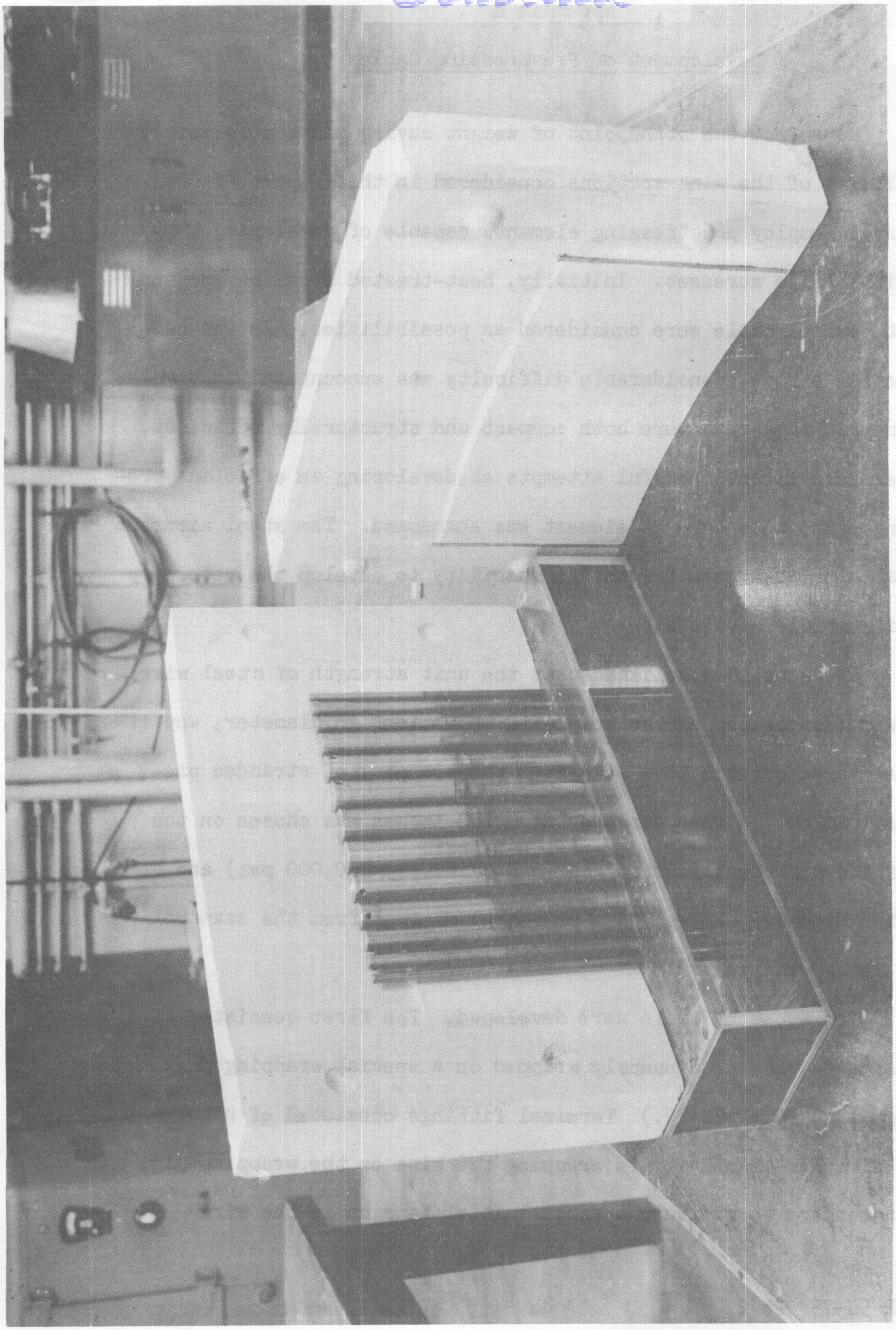

FIG. 7 - ROD-MOLD ASSEMBLY FOR SLIP CASTING

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Appendix E

Development of Prestressing Cables

Both from the standpoint of weight saving and the relatively high solidity of the wing sections considered in this report, it was necessary to employ prestressing elements capable of developing very high unit tensile stresses. Initially, heat-treated steel straps and aircraft control cable were considered as possibilities. In the case of the steel straps, considerable difficulty was encountered in developing end fittings that were both compact and structurally efficient, and after several unsuccessful attempts at developing an efficient prestressing unit, this type of element was abandoned. The steel aircraft cable was also abandoned due to its inability to develop the necessary high unit tensile stresses.

It is well established that the unit strength of steel wire (music wire) increases appreciably with reductions in diameter, and it was this characteristic that suggested the wrapping of stranded prestressing cables. A wire diameter of 0.010 inches was chosen on the basis of its high tensile strength (approximately 400,000 psi) and because this diameter represents a practical minimum from the standpoint of hand cable wrapping.

Two types of cable were developed. The first consisted of 900 strands of wire continuously wrapped on a special wrapping jig. (See Fig. 1, WADC TR 54-22.) Terminal fittings consisted of heat-treated circular thimbles. In wrapping the wire on the wrapping jig, it was necessary to maintain a small initial tension in the wire

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(approximately five pounds) in order to assure uniform laying of the strands. Unfortunately, this initial tension introduced an axial compression load in the swinging arms of the jig with the result that the first strands of wires became slack as wrapping progressed. This effect, of course, can be minimized by use of swinging arms having high axial stiffness. This cable was tested to failure in tension and developed an average unit stress of 212,000 psi. Failure occurred by progressive breaking of individual strands of wire due to uneven lengths as pointed out above.

Four of these cables were employed in each of the wings of Types I and II.

The change-over in configuration of the wing cross-section (wing types III and IV) required a revision of the prestressing cable design. It was also felt that a more efficient cable could be developed by increasing the number of cables and reducing the number of strands of wire in each cable. The basic design of the second cable has been discussed briefly in the main body of this report, and is shown in Fig. 8. To facilitate installation in the wing, three configurations having respectively 100, 74, and 50 wire strands were wrapped.

The wrapping jig is shown in Fig. 9 and consisted of a circular table fabricated from pressed wood (Masonite) one inch thick. A steel rim was attached to the periphery of the table to serve as a base for wrapping. The circular shape was adopted in order to eliminate the cable shortening effect encountered in the swinging arm jig previously discussed. A belt driven pulley system converted the rotary

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motion of the table to an axial motion of a spindle. This reduction system moved the spindle vertically one wire diameter with each revolution of the table. The wrapped cable was then clamped at opposite diameters, removed from the table, and installed in a simple stretching jig, also shown in Fig. 9. At this point, the end fittings were installed (Fig. 8) and the wires were taped at various intervals throughout the cable length to simplify handling of the finished sheath. Upon removal from the stretching jig, each cable was proof tested to a stress of 250,000 psi in a Baldwin Southwark testing machine.

Static tests of several flat cables resulted in average ultimate tensile stresses of the order of 330,000 psi. Failure occurred either by sudden snapping of several wire strands or by tearing loose of the cable terminals. Extensive tests indicate this configuration to consistently develop a 300,000 psi ultimate tensile stress.

This type of cable has two apparent advantages over the heavy cable developed for wings I and II. These advantages are: a) the higher stresses developed permit the use of less wires, and b) the cables can be stacked in sheaths to form prestressing elements of any desired size. The principal disadvantage of this configuration is the number of terminal fittings required. This disadvantage reduces in importance as the length of the cable increases.

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A comparison of the efficiencies of the two cable designs is made below:

	Round Cable (Wings I and II)	Flat Cable (Wings III and IV)
Number of strands of 0.010 wire	900	100
Weight, lb.	1.12	0.24
Length, in.	45	47
Wt./in./100 strands, lb.	0.00227	0.00511
Av. Tensile Ult., psi	212,000	330,000
$\frac{\text{Ultimate Tensile Stress}}{\text{Wt./in./100 strands}}$	76.5×10^6	64.7×10^6

For the particular cables used in this study, the cable having the larger number of strands shows a slight advantage in structural efficiency, due, of course, to the smaller unit weight of terminal fittings.

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Appendix F

Notes on the Deflection of Prestressed Ceramic Structures

(From notes by F. R. Shanley, Oct. 1952)

In view of the possibilities of designing successful prestressed ceramic structures it is of interest to determine whether this type of structure is likely to have any adverse deflection characteristics. This may be specially applicable in the case of long span beams.

The feature most likely to cause trouble would appear to be the use of high-strength steel wires. For example, if an ultimate tensile strength of 300,000 psi were used as a basis for design of the wires, and if an ultimate strength of 60,000 psi is taken as a rough basis for structural steel, the cross-sectional area of the wires would be about one-fifth of that required for the tension flange in structural steel or reinforced concrete construction. (This is based on the type of design in which the prestressing wires are placed near the tension side of the beam). This large reduction in steel, which is one of the advantages of prestressed construction, might appear to result in correspondingly large increases in deflection.

An analysis of the sources of beam deflection will reveal that this is not true. Consider the idealized case of Fig. 10 (see page 89), in which the beam is represented by two ceramic flange elements, one of which is precompressed by wires. This type of beam would be used, for example, in a long narrow structure loaded in one direction only (as in a bridge having simple end supports). The deflection contributed by the upper flange will first be examined. Assume that the ceramic can

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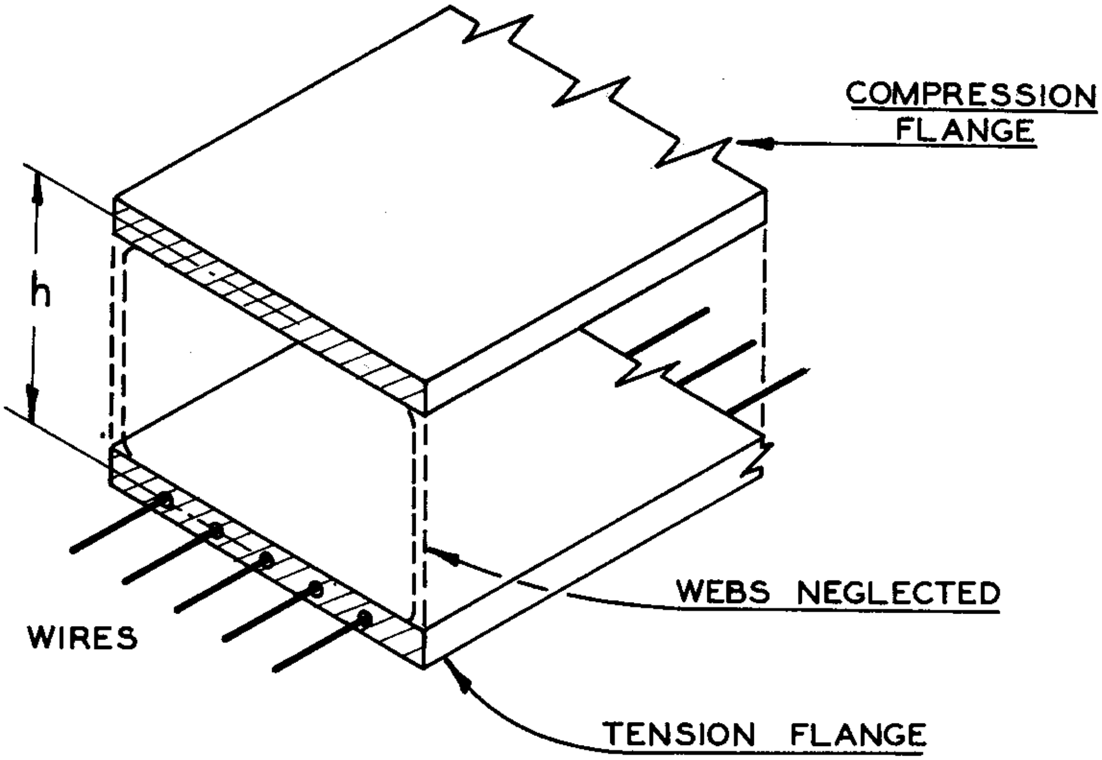

FIG. 10 - IDEALIZED BEAM

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develop 100,000 psi ultimate stress in compression. Assuming no reduction of this by any extra factors of safety, the top flange would be designed so as to have a cross-sectional area which would, under the ultimate bending moment, just develop 100,000 psi in compression. The compressive strain would then be found by dividing this stress by the compressive modulus of elasticity for the ceramic used. This may vary between 5,000,000 psi for ordinary tile to more than 30,000,000 psi (possibly as high as 50,000,000 psi) for materials such as alumina (aluminum oxide). It can be seen that the compressive strain in the top flange will be greater than that for a comparable steel beam. The multiplying factor would be:

$$k = \frac{f_{cr}}{f_{st}} \quad \frac{E_{st}}{E_{cr}} \qquad (1)$$

Thus, if E_{cr} is taken as 10,000,000 psi the factor for the previous case would be

$$k = \frac{100,000}{60,000} \times \frac{30,000,000}{10,000,000} = 5$$

If a ceramic having E = 30,000,000 psi were used, at an allowable stress of 100,000 psi, the factor would be 10/6 = 1.67.

It is obvious that the way to reduce the deflection is to use a greater cross-sectional area, which amounts to using a reduced allowable compressive stress. In order to have deflections comparable to a structural steel beam of the same depth, the factor f/E for the ceramic should be the same as that for structural steel. On an ultimate strength

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basis this value (elastic strain at ultimate stress) would be in the neighborhood of 60,000/30,000,000 = 0.002. Thus a "poor" ceramic having E = 5,000,000 would require that the allowable ultimate stress not exceed 10,000 psi, if the deflection characteristics were to remain about the same as for structural steel. For a "strong" ceramic having E = 30,000,000 the allowable stress would be about 60,000 psi, on this basis.

It should be noted that the density of ceramic materials is much less than that for steel, being in the neighborhood of that for aluminum alloys. Assuming, for rough calculations, a ratio of 1/3, the two extreme cases noted above would represent weight ratios (ceramic to steel) as follows:

$$\text{"poor" ceramic} \quad \frac{60{,}000}{10{,}000} \times \frac{1}{3} = 2$$

$$\text{"strong" ceramic} \quad \frac{60{,}000}{60{,}000} \times \frac{1}{3} = 1/3$$

The second case obviously represents a ceramic material for which the (allowable) properties are about the same as for structural steel.

On the basis of such reasoning, it may be predicted that a good ceramic material would permit a design in which the weight of the ceramic would be somewhat less than that for steel, without any reduction in bending stiffness.

The foregoing reasoning has been applied only to the compression (upper) flange, which was assumed to act as it would in a non-prestressed beam. When bending moment is applied to the prestressed beam, the lower flange tends to elongate. Assume that the lower flange has

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the same net cross-sectional area as the upper flange. When a bending moment is applied the lower flange will be relieved of some of its compressive stress. The pretension load in the wires can be adjusted so that the stress in the ceramic will just be reduced to zero when the ultimate bending moment is applied. The equivalent strain (which contributes to the bending deflection) will then be equal to the strain originally caused by the load from the wires. If the original pretension load had caused a stress equal to the ultimate compressive stress, and if all of this stress were removed at ultimate bending moment, the contribution of the lower flange would be exactly the same as that of the upper flange and the previous reasoning could be extended to the entire beam.

This would actually be unfair to the ceramic beam, however, because it would amount to assuming that the load in the wires would remain constant while the bending moment was applied. Actually, in order to reduce the pre-compressive stress in the ceramic flange its elements would have to become longer and the wire itself would have to lengthen, which would cause an increase in wire load.

In a beam of the type shown in Fig. 10, the effective stiffness of the lower flange is actually equal to the <u>sum</u> of the stiffnesses of the ceramic and the wires, up to the point of zero stress in the ceramic, at which time the flange units would start to separate. The load required to produce a unit strain, below this point, would be

$$P_1 = E_{cr}A_{cr} + E_{st}A_{st} \qquad (2)$$

The effective value of E, reduced to the basis of the ceramic area,

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would be equal to

$$\bar{E}_{cr} = \frac{P_1}{A_{cr}} = E_{cr} + E_{st}\frac{A_{st}}{A_{cr}} \qquad (3)$$

Since the deflections of interest to the designer always occur at loads considerably below the ultimate, eq. 3 represents the actual behavior of a beam in which the prestressing wires are located at the centroid of the tension-flange area. This type of design is not only the most efficient for one-way loading, but also results in a considerable reduction in deflection, as shown above.

It can now be seen that the use of high-strength wires of small cross-sectional area does not have any adverse effect on deflection. On the contrary the full additional effect of the wires, in reducing deflection, is obtained by placing them at the centroid of the tension flange area. Both flanges of ceramic material are also fully effective.

For a beam in which the wires are placed at the neutral axis (reversible loading) the stiffness of the wires has no helpful effects. For such a design the bending stiffness is obtained in the usual manner, by considering only the ceramic material. If the beam is capable of being loaded beyond the point where the stress in the tension flange becomes zero (separation of units) a large reduction of bending stiffness will apply to any further increase in bending moment (Slope of moment-deflection curve suddenly decreases). It should also be remembered that the beam with wires at the neutral axis must have a greater amount of ceramic material, (approximately twice) which tends to

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compensate for the loss of effectiveness of the wires.

The general conclusions to be drawn from this preliminary analysis are:

1. The use of high-strength wires, with low cross-sectional areas, has no adverse effects on the deflection characteristics of prestressed ceramic beams.

2. If the beam is designed for one-way loading, with prestressing wires located at the centroid of the tension (lower) flange, the stiffness (EA) of the wires can be added to the stiffness of the ceramic material, up to the point where the tension flange units start to separate.

3. Considering the strength properties and densities likely to be realized for ceramic materials, it appears that the deflection characteristics of prestressed ceramic beams are likely to be equal to or superior to those of structural steel beams of the same depth, when designed to develop the same ultimate strength. The overall weight of the ceramic beam may be greater or less than a steel beam of equivalent strength, depending on the properties developed by the ceramic material.

4. The prestressed ceramic beam is likely to be superior to an aluminum alloy beam, so far as bending deflections are concerned, but will probably be somewhat heavier unless high properties are developed in both the ceramic and the steel wires.

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Additional Note

The total curvature of the beam, at a point, is given by the equation:

$$\frac{1}{R} = \frac{e_u + e_L}{h} \qquad (4)$$

where e_u = strain in upper flange

e_L = strain in lower flange
(i.e. change of strain)

h = distance between flanges.

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