SESSION 1. DESIGN PROCEDURES AND GENERAL METHODS 1

Session Chairman

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THE ROLE OF DESIGN ANALYSIS SYSTEMS FOR AEROSPACE STRUCTURES, AND FUTURE TRENDS

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This paper attempts to lend some insight into the role of the design analyst during the evolution of an aerospace structural design, and examines the analysis tools available to him for doing his job. Of all the constraints to which he is subjected, the time schedule is likely to be dominant. This and other restrictions currently dictate that simplifying assumptions be made in carrying out his work. These are discussed and it is shown that the entire stream of analyses that must be employed, including those needed for obtaining applied loads, must be closely coordinated and integrated, in order to meet required schedules. Related comments are made also about structural optimization as it is currently being practiced in design, and trends for both it and integrated design analysis systems are indicated.

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INTRODUCTION

We are all painfully aware of how the aerospace industry has fallen upon hard times. Employment is way down, the prices of our products are soaring, and our customers apparently are quite unsympathetic. The result is that our companies are asking their people, with much leaner technical staffs, to turn out better products than ever before, and at lower cost.

There are a number of areas related to the structures part of the business in which we can look for improvements. Apparently, there is a general consensus that the most promising of these areas are in the development and use of new materials, in better manufacturing methods, and in reduction of maintenance costs.[(1)]

But the design analysts can help too. They also play a vital role, specifically in their support of the designers during the evolution of a new vehicle. The key question is: are they able to perform their function properly, which is to provide structural evaluations sufficiently early that the right design decisions can be made? And an equally important, related question - do those of us who are developing methods for the design analysts to use really understand what their requirements are? One sometimes gets the depressing feeling that some of the best talent we have is misguidedly working on projects that are believed to be relevant to the design process, but really are not. Or if relevant, are peripheral rather than central to the main problem.

This is not to say that research and exploratory development work is not required. It most certainly is required. It adds needed depth to our understanding of basic phenomena, and in some cases obviously leads to methods that are useful in design. But the objectives of methods development work on the one hand, and research and exploratory development on the other, should not be confused. They are very different.

In an attempt to clarify this, I am going to try to lend some insight into the role of the design analyst during the evolution of an aerospace structural design. In so doing, naturally, we shall have to examine the tools that our design analyst has available to do his job, and how they might be improved.

In discussing the design process and the nature of the support that the design analyst provides, it is very difficult to generalize. Therefore, while attempting to get my message across, I shall have to refer extensively to examples. Since my experience is with Grumman hardware, this will be a major focal point. However, I believe that our experiences are broadly representative of those of the entire industry, and so should be of general interest.

A key point to bear in mind in reviewing a company's approach to the design process is that there are several external constraints that have a vital influence. One is the time available for the design work, i.e., the period from contract go ahead to first flight; this can vary greatly from one vehicle procurement to the next. Another constraint is the design analysis philosophy of the customer. Our military services, of course, require final analyses of the airframes they buy, but they place greater emphasis upon satisfactory completion of static and fatigue tests of entire vehicles for proof of design adequacy. The airlines and FAA, on the other hand, rely much more heavily upon final detailed analyses for the large commercial transports, and less upon large scale testing. These factors are bound to make a difference in how a given manufacturer goes about his analytical work.

The design of an airframe structure is an exceedingly complex procedure. Early in the design, rather dramatic alternatives in the primary structure configuration, materials and methods of construction must be considered. Later on, the changes to be investigated are more those of detail. The earlier configuration changes, which are obviously of special importance to the analyst, are sometimes made solely for the purpose of increasing structural efficiency. More often, however, the motivation is likely to be a mixture of other things as well - an attempt to improve aerodynamic performance, a rearrangement of equipment and accessory locations for functional reasons, etc.

The applied loads acting upon the structure can also change significantly. In the case of a new vehicle whose external lines and performance represent real departures from anything already in existence, the preliminary applied loads which must be used initially are subject to sizable redistributions, as well as changes in magnitude, as more information (such as wind tunnel pressure distribution test data) becomes available. These changes can have a major impact upon the vehicle design.

During the evolution of such a structure, a fundamental responsibility of the analyst is to provide the designer with evaluations of his designs. Does the configuration currently being considered use the structural material efficiently? Are there undesirable discontinuities in strength or stiffness? Are there severe structural dynamics problems? This information must be available at the right time, so that the right decisions can be made as the design evolves. Since the major decisions that largely determine the success of the vehicle are made early in the design phase, this is where the analyst too must make a major contribution. Of course, he must also be responsible for the integrity of the structure as it is finally built.

It should be noted that in real life, the design analyst usually does more than just this. Ordinarily, he participates actively in the design function as well - resizing structure, making suggestions on changes in configuration, etc. Nevertheless, his basic responsibilites are primarily in performing the analysis tasks.

The aerospace industry is well aware of the nature of these tasks. And it is obviously looking for improvements, as evidenced by the activity in such fields as integrated design and analysis systems, structural optimization and computer graphics.

For its part, Grumman four years ago conducted a major study of the stream of analysis and optimization tools required to support its design activities, with primary attention being given to the time frame for their application. Deficiencies were identified, and a plan for remedial action was formulated. Initially, its implementation required a major effort to bring about certain basic changes in our procedures. Thereafter, our activities have been, and will continue to be, directed toward making evolutionary changes to the existing system, in the order in which improvements will be most cost effective. As might be expected, the Grumman approach is not necessarily identical in its philosophy to that of other members of the aerospace community.

This paper seeks first to describe the highlights of the study just mentioned and of the resulting analysis system as it now exists. Thereafter, it touches upon how the system has been used to contribute to the design of the new Navy fighter, the F-14. Comments are also made concerning its application to Space Shuttle design studies.

From this base we will take a brief look at other automated analysis methods development activities throughout the industry as they apply to design. Finally, I will attempt to identify the more critical needs of the next few years.

STUDY OF ANALYSIS NEEDS

Approximately eighteen months prior to the date that it was believed the Navy would be issuing an RFP for the F-14, Grumman management became convinced that the aerospace industry was headed for some major new challenges in the development of future military aircraft. In particular, for the F-14, these challenges were associated primarily with the drastically shortened schedules that were contemplated for its design, manufacture and flight testing. As a result, studies were made in all these areas to see what could be done to speed things up.

One of the studies concerned the analysis methods we used in determining the internal loads needed for sizing primary structure. This is obviously a crucial design requirement. The time period particularly emphasized was from the vehicles's contract go-ahead to its first flight. At the same time, we realized that methods suitable for this period would also be applicable for preliminary design, if they were streamlined and used properly.

As we examined our ability to quickly perform the required analyses, it immediately became clear that many technical groups and disciplines were involved. To obtain internal loads in primary structure, far more was involved than merely performing an adequate finite element analysis. If anything, the finite element work was the least of our troubles. The real pacing item turned out to be the determination of the applied loads acting upon the structure.

When one includes in the chain of required calculations all of the applied loads critical for design, he must draw upon many technical areas - aerodynamics, weights, dynamic analysis, loads and criteria, structural analysis, contour development, structural design, etc. All of these are needed to determine the loads due to flight maneuvers, gusts, landing, catapulting and taxiing. In addition, there are the closely related flutter analyses. In all cases, structural flexibility effects must be considered to some degree in the final determination of the applied loads for which the structure is designed. The whole process of ultimately determining internal loads is surprisingly complex, and there were actually very few people in the Grumman organization who understood the entire picture, except in a general way.

Personnel in each technical specialty had many analysis procedures, and many of these had been programmed for computer solution. The primary difficulty was that such computer programs had tended to grow in an uncoordinated fashion in each technical area. Some programs were not general enough and were limited to specific classes of airplanes. Some overall tasks within a given technical area had been programmed in pieces that were not properly combined for rapid execution. In general, output data from one technical group was not in a form suitable for use by some other technical group downstream. Instead, all too often, the "answers" from one group required a large amount of hand manipulation before they could truly be used as input data for the work of some other group.

In brief, the crucial problem was not one of lack of basic capability in any narrow technical area - it was the blending of all these skills into a properly balanced, coordinated systems approach. Frankly, this general situation also appeared to exist throughout the rest of the aerospace industry.

In the preceding discussion, no mention has been made of structural optimization. Instead, we have spoken only of "determining the internal loads needed for sizing primary structure." One might imply from this that structures engineers are unaware of the interaction which exists between changes in the distribution of material throughout the structure and the internal loads. Of course, this isn't true. Actually, as a matter of necessity, we have learned by experience how to make changes in material distribution in order to bring stresses reasonably into line with allowables, while at the same time making allowances for the accompanying changes in the internal loads. Whenever possible, revised analyses are then run as a check, but there is usually a limit to how much of this can be done before the drawings are signed and manufacture begins.

Under the preceding circumstances, it becomes quite clear why stress analysts are so much interested in automated methods for obtaining fully stressed designs. By this we mean idealized structures for which every element is either stressed to its allowable value for at least one design condition, or is at a specified minimum size. Historically, for strength critical structures, fully stressed designs are exactly what we have been striving for all along. They may or may not be truly minimum weight, but the capability for rapidly obtaining fully stressed designs of idealized airframe structures should be recognized as being a really significant step forward. We will have more to say about this later.

We were also aware of the necessity of using graphic display devices, wherever economically feasible, for visually checking input data for the computer, and displaying results. As for the interactive devices that have been emerging over the past few years, their potential was also very attractive, especially for smaller structural analysis applications. However, the benefits to be gained by their use appeared to be less crucial than the alleviation of our more basic problems. Accordingly, less attention has been given to them than some of the other matters to be discussed next.

INTEGRATED DESIGN AND ANALYSIS SYSTEM (IDEAS)

We began to put our house in order. Approximately 50 men from the applicable engineering groups worked as a team for about a year to establish the present analysis system. It was a high priority effort in regard to selection of the best qualified personnel and in regard to computer availability. The result is called IDEAS. The system has been made compatible with Grumman's computing facilities which embody the IBM 360/75 computer.

Basically, IDEAS[2] is an integrated collection of many different kinds of computer program modules and formalized hand calculations. The sequencing and execution of these program modules allow one to plan, schedule, coordinate and control all of the analytical efforts of the several sections that make direct contributions to the determination of internal loads for the sizing of primary structure for an aerospace vehicle. It is the "systems approach" for the problem at hand.

System capability was planned from the start to be sufficiently broad to provide state of the art analysis procedures for both variable-sweep and fixed-wing subsonic and supersonic aircraft. As such, it treats all applicable flight maneuvers, landing and catapulting conditions, taxiing conditions, and gust and flutter analyses. A suitable starting point for application of the system can occur with a definition of the loading condition requirements and knowledge of external vehicle contours, including control surfaces and stores. Also needed are weight estimates of concentrated masses, fuel, and major structural components such as wing, fuselage, etc.; a configuration for the primary structure and landing and arresting gear; and initial estimates for the sizing of primary structure. Early in the design, such information will necessarily be very sketchy. For the later IDEAS cycles, the data will naturally become more definitive and detailed.

The technical groups associated with IDEAS use various mathematical models to perform their calculations. The establishment and standardization of these models in regard to sign conventions and coordinate systems is another key feature of the IDEAS system. With standardized models, it is easy to pass data between the various technical groups by means of suitable transformation matrices.

A main feature of the IDEAS effort is the establishment of a "Data Bank" which provides a central storage facility for all calculated data. This manually controlled Data Bank consists of stored magnetic tapes, cataloged listings, CALCOMP plots, Orthomat drawings, CDC-DD80 microfilm, punched cards and engineering drawings of mathematical models. Any given program draws its input data from the Data Bank and returns its output to it. There are approximately 50 major computer programs currently stored on the accompanying "IDEAS disc." Included among them are the Grumman developed programs for fully stressed design, of which "ASOP" (Automated Structural Optimization Program) is the most recent addition.[3]

Another feature of IDEAS is that it is open-ended and lends itself well to the incorporation of new analysis methods. For example, recently, because of the Space Shuttle and its thermal stress problems, a new structural temperature analysis capability has been formulated, and is being integrated into the system. It provides for coordination of all of the necessary calculations, beginning with trajectories and the accompanying aerodynamic heat transfer coefficients, and ending with transient temperature distributions in appropriate structural models. In combination with the proper coefficients of thermal expansion, these temperatures yield initial strains that are treated thereafter as load cases, along with the mechanically applied loads.

Interactive computer graphics is not yet a part of IDEAS. As has already been indicated, this is the result of deliberate management decision - an attempt to put first things first. We are now investigating ways to incorporate these tools into the system in a cost effective manner.

APPLICATION OF IDEAS TO F-14

As I have indicated, the first project to which we have applied the IDEAS system is the F-14. I shall try to give some of the highlights of the effort. In scope, it should be fairly representative of the analytical work required in support of any advanced airframe design.

As shown in Figures 1 and 2, the F-14 is a supersonic, carrier-based fighter with variable sweep wings, all movable stabilizer and twin vertical tails. It flew for the first time in December 1970, and is now engaged in its flight test program. Its most significant structural innovations are the wing center box, made of titanium, and the stabilizer, with its skins of boron/epoxy composite. The fuselage is also quite complex, being very broad and rather shallow. The way in which it carries overall bending is quite complicated, the bending structure being concentrated in the centerbody in the forward region, and in the widely spread engine nacelles aft, with a transition region in between.

Mathematical Models

The key to developing a feel for the scope of work covered is to look at the various mathematical models that have been employed. There are essentially four different types.

Air Loads
Weights
Dynamics
Structures

Actually, the dynamics and structures models have been changed a number of times during the course of the design. For simplicity, in all cases I shall concentrate primarily upon the models we used for release of structural drawings.

Let's start out by examining the air loads model for the fuselage, Figure 3. This shows the resultant air load distribution for a typical supersonic symmetrical pullout. For the final design iteration, the source of such distributions is wind tunnel tests performed on models with many pressure taps. Earlier in the design, loads are approximated by traditional estimating procedures. Shown is the form in which the results are summarized for application to the structure. Essentially, we have here three types of running loads, one applied down the centerline of the fuselage, one applied along the centerline of each engine inlet, and the third along a curved line, representing the loading on the fairing between the fuselage and the wing. Bear in mind that these running loads must ultimately be applied to a finite element model of the fuselage.

The wing air loads distribution model is shown in Figure 4. The unswept case is illustrated. There are four other models for various sweep positions. Notice that the model goes all the way into the airplane centerline. For the early design iterations, we treat the wing as an isolated surface, and calcu-

Figure 1

Figure 2

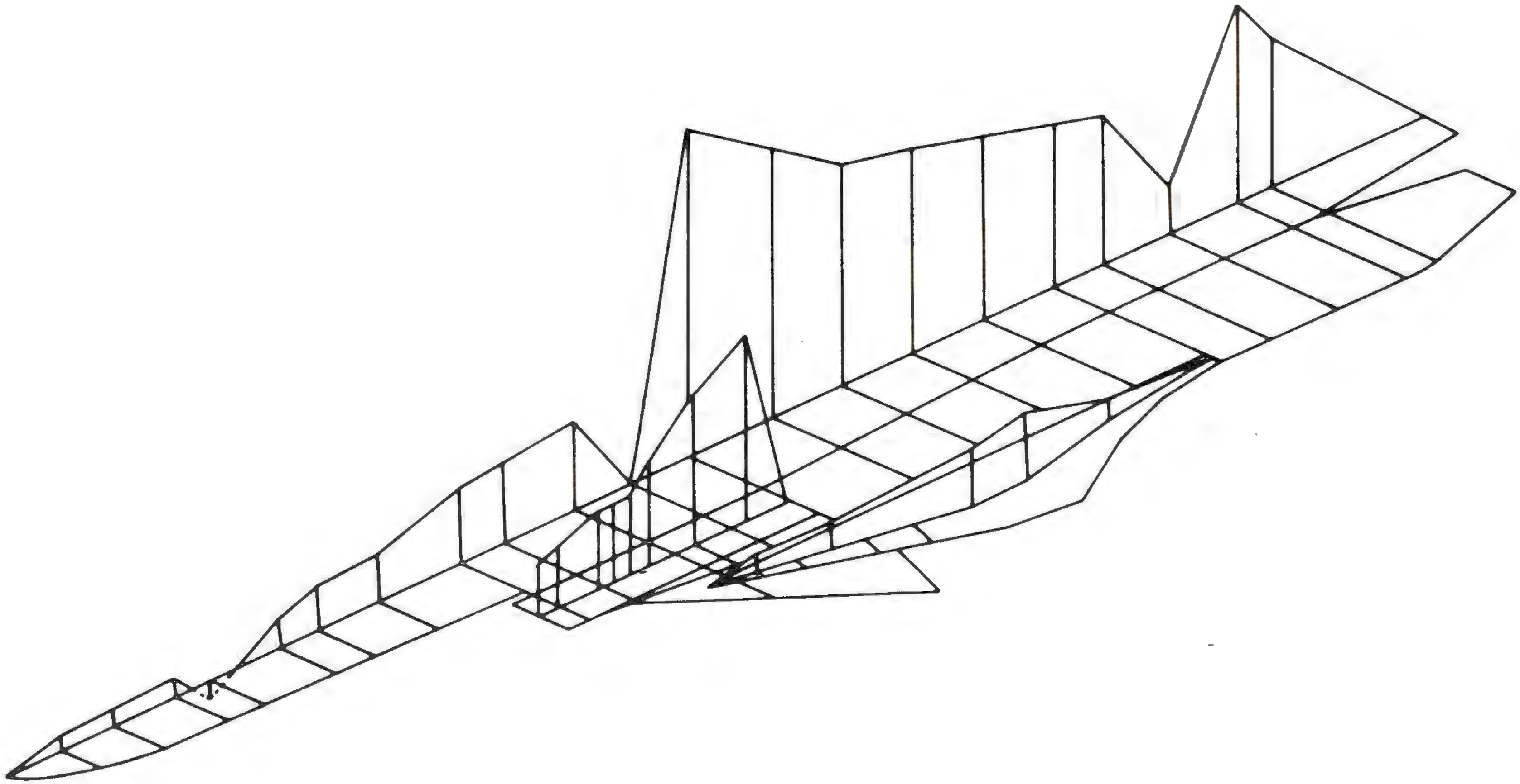


Figure 3 Fuselage Air Loads Model

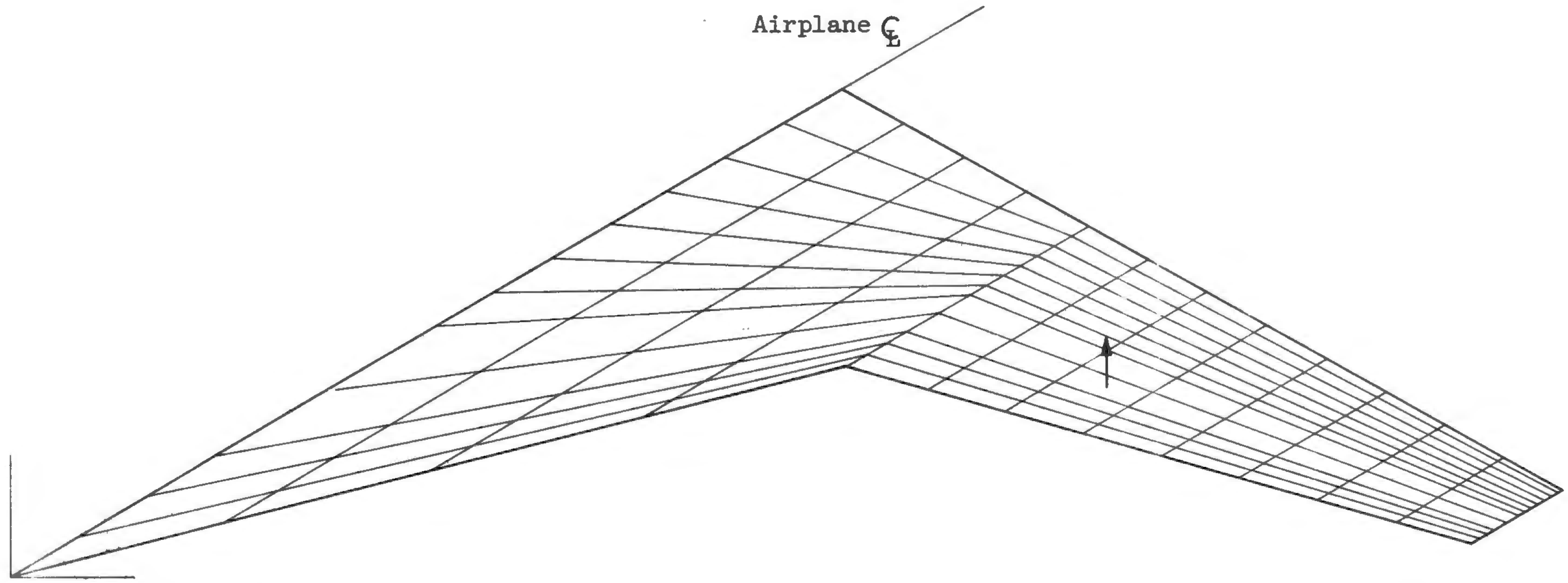


Figure 4 Wing Air Loads Model

late distributions of loads acting on all of the 144 quadrilateral areas shown. We then correct for the effects of the fuselage aerodynamics on a semi-empirical basis using overall experimental aerodynamic derivatives wherever possible. For the final iteration, wind tunnel pressure distribution data is used to obtain forces acting upon the portion of the quadrilaterals that represents exposed wing. Air load models for the stabilizer and the combined fin and rudder are similar in nature to the wing.

As for the weights models, the fuselage is shown in Figure 5, again in a configuration suitable for a flight maneuver. Note that two types of masses and moments of inertia are considered, one representative of distributed, fixed structure and fuel, and the other representative of large, concentrated items such as engines and external stores. Some of these items will of course vary from one design condition to the next. As in the case of the fuselage air loads, the inertia loads that go with these masses must be redistributed to the finite element model of the fuselage.

In the case of the wing and empennage structures, the weights people have used the same grids as employed for the air loads.

The third class of models is dynamics. Figure 6 shows the flutter model. The dots indicate lumped masses, and the arrows show the degrees of freedom considered. In the case of the curved arrows, for rotational degrees of freedom, moments of inertia and mass first moments are included as well. (Existence of the mass first moments means that, for the wing and for the fin and rudder, the mass cg's actually do not fall on straight lines, as seems to be indicated in the figure.) Some degrees of freedom are not shown; they include those to represent various combinations of external stores. When all of the stores are included, the number of degrees of freedom for the half airplane is 222 symmetric, and 253 antisymmetric. There is also a dynamics model for use in calculating landing and catapulting loads. This model is similar to that for flutter, except that certain simplifications have been made, as for instance, in the wing and empennage structures. On the other hand, the fuselage portion of the airframe is now modelled in more detail, and there are roughly twice as many degrees of freedom for this region as in the flutter model.

Of course, structural flexibilities are also required. These are essentially provided by the structures models to be described next.

As for the structures models, the most complex is that for the fuselage. Figure 7 shows one half of the principal fuselage structural model, including a wing center section which has been detailed sufficiently to account for its interaction with the fuselage. The model as shown employs about 3000 structural elements, including bars, beams, warped (non-planar) shear panels, warped membrane panels, and a few triangles. Figure 8 shows a portion of the idealization in greater detail. As in most analyses of this sort, the applied loads enter at the structural node points. Their values are obtained by assuming that the air loads and the inertia loads associated with the models described previously are distributed to the structural nodes by simple beaming action. There are some obvious gross assumptions involved in such procedures, but the process is consistent with the accuracy with which the applied loads themselves are known.

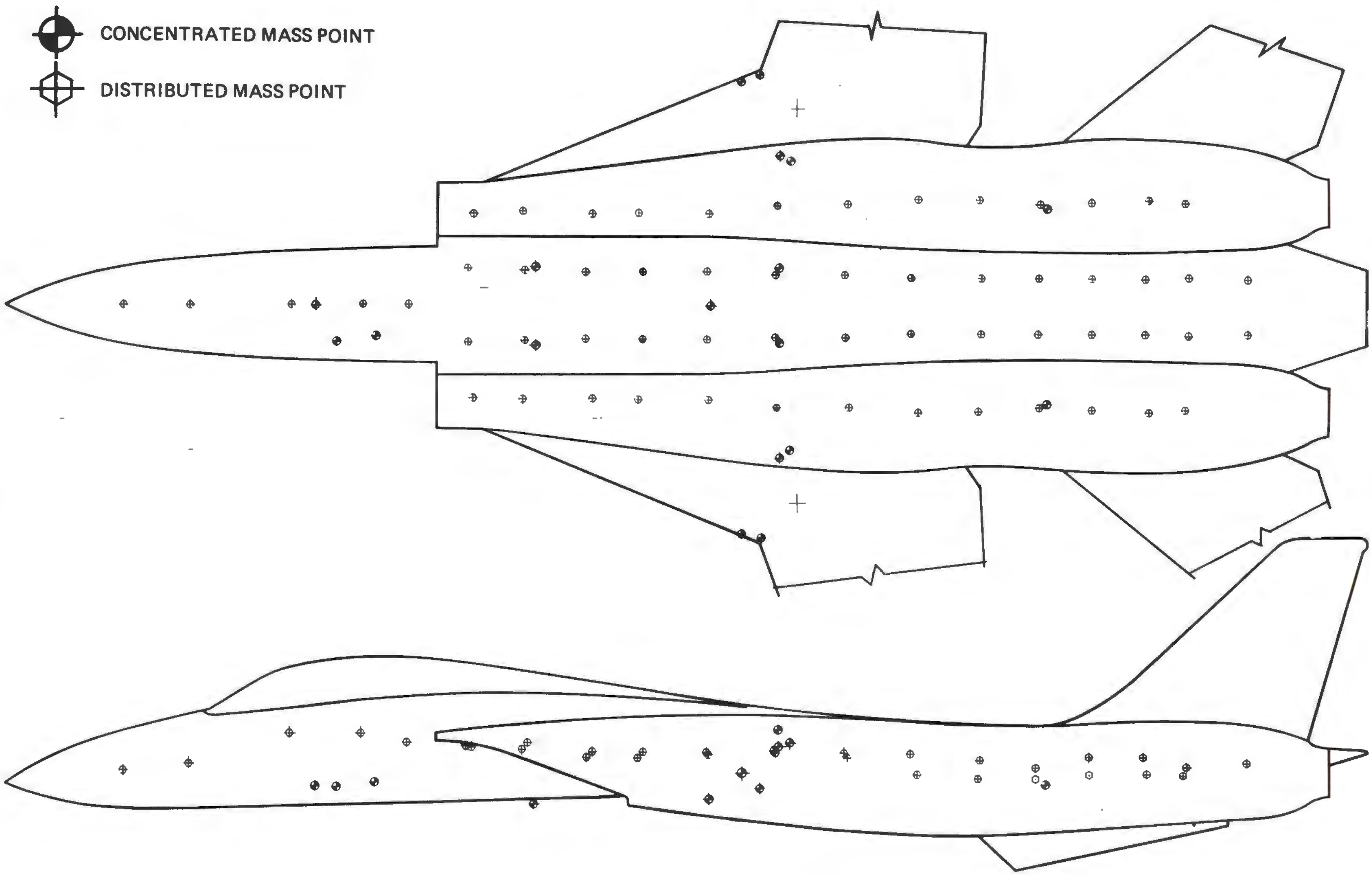


Figure 5 Fuselage Weights Model

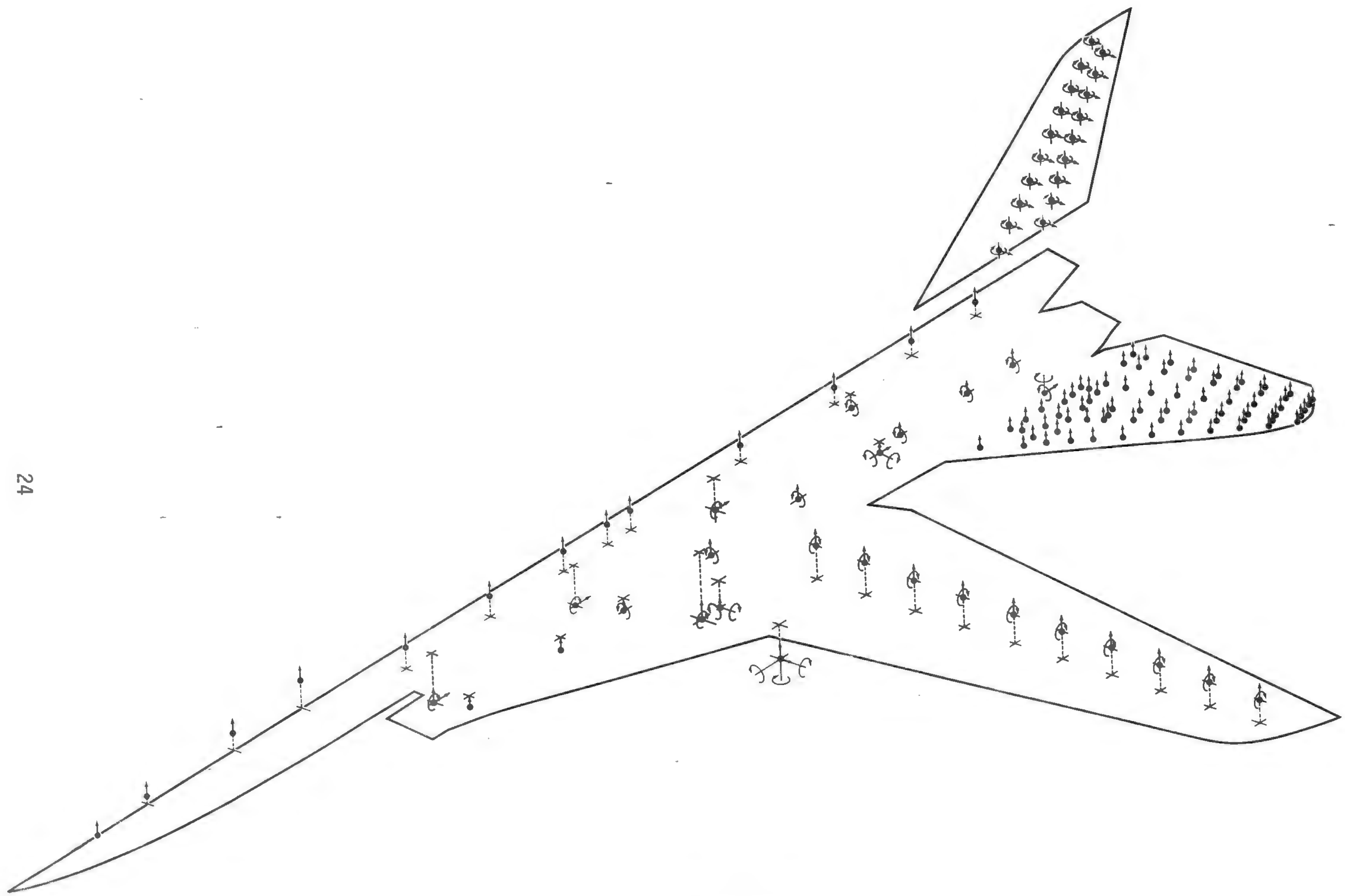


Figure 6 Flutter Model

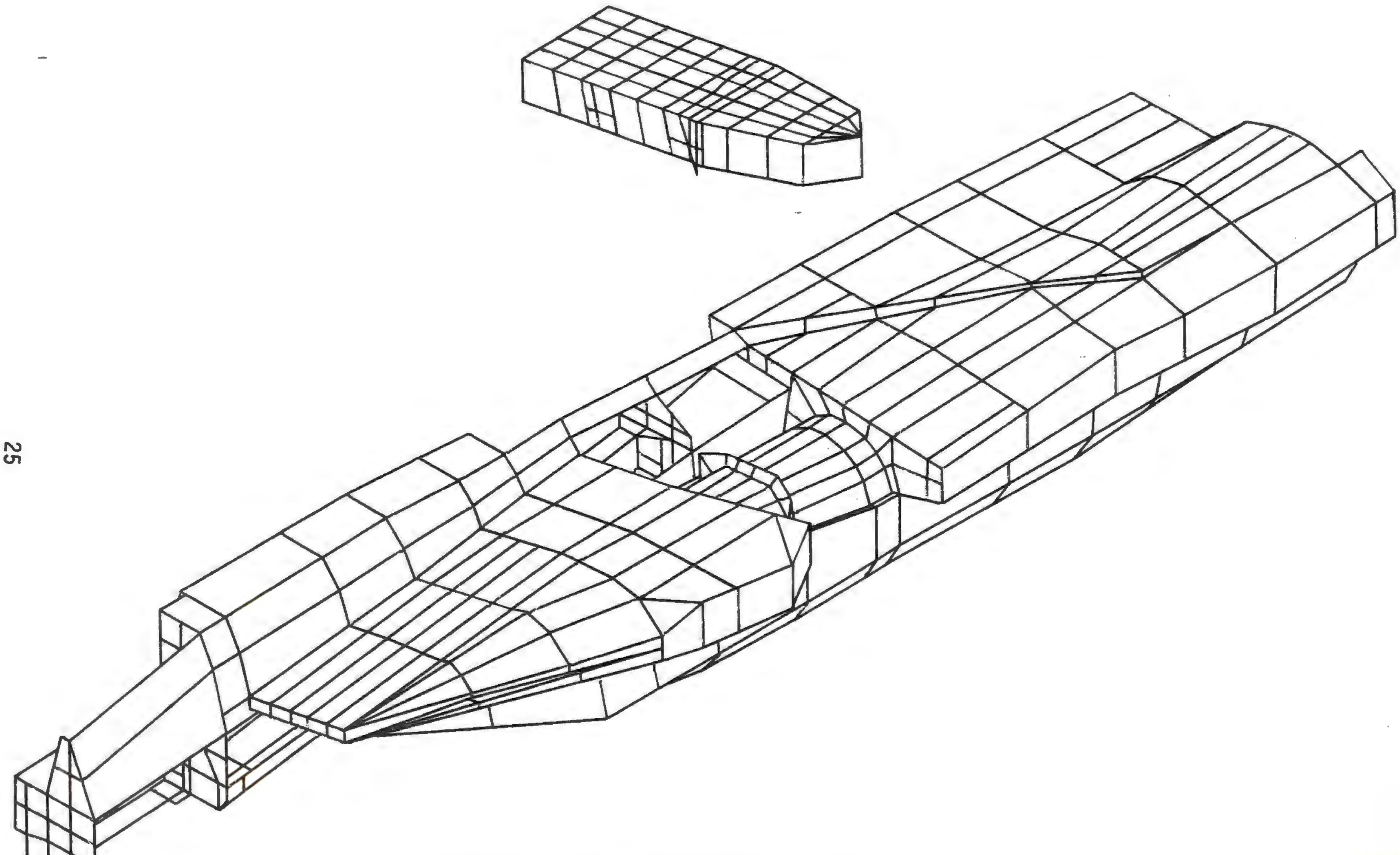


Figure 7 Fuselage Structural Idealization

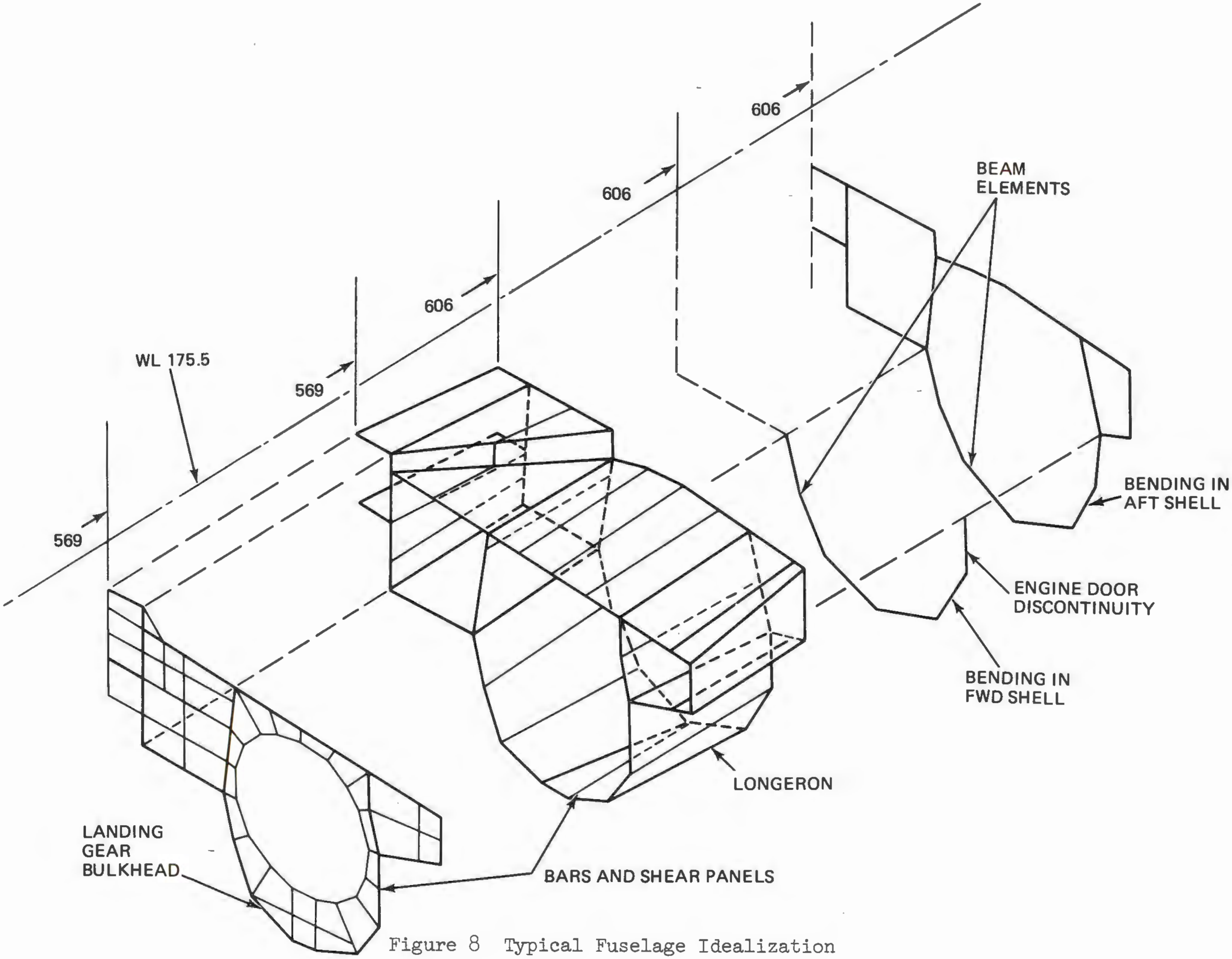


Figure 8 Typical Fuselage Idealization

The wing center section has also been idealized somewhat more elaborately in another model for its detail design. The wing outer panel is of high aspect ratio, and is conventional in its design except for the pivot region. Figure 9 shows its planform, and the region of the primary structure idealized by a finite element model. The remainder, including leading edge, tip and moveable surfaces, is analyzed by conventional methods based upon engineering beam theory.

The fin and rudder are also conventional, and are treated similarly to the wing outboard of the pivot. Again, a finite element model is used for only a portion of the structure, in this case, that adjacent to the fuselage attachments, because of departures from engineering beam theory in this region.

The stabilizer is a low aspect ratio surface which pivots about a shaft fixed to the fuselage. Beam theory is marginal in this case, and a finite element model for the entire primary structure would thus be preferred even if it were not for the boron fiber covers. The stabilizer structural arrangement and its corresponding finite element model are shown in Figures 10 and 11.

These models have been supplemented by many other finite element models which represent smaller regions of structure previously described but in greater detail. The wing pivot region is an obvious example. The principal fuselage bulkheads comprise additional cases.

Loads Calculations

The design conditions that are critical for the F-14 are primarily the flight maneuver conditions, and arrested landing and catapulting. The flight maneuver calculations are made originally with simplified airframe flexibility effects included. In later iterations, more refined aeroelastic corrections are introduced. From the calculated flight maneuver time histories, critical values of gross air and inertia loads are determined. As mentioned previously, five different wing sweep positions are covered in the loads work. Thus, the number of maneuver conditions to be considered is increased approximately by a factor of five, as compared to a fixed wing aircraft. These gross loads are then distributed to the structure in accordance with the air loads and weights models previously described by means of appropriate transformation matrices.

As for the arrested landing and catapulting conditions, here the critical loads are induced in the structure through the arresting hook and landing gear forces. (The catapulting loads in all of our modern Naval aircraft are applied through the nose gear.) Consequently, in carrying out the necessary time history calculations, the main and nose gears must be carefully modelled, because their nonlinear load-stroke and inertial characteristics enter into the determination of the loads in a fundamental way. Airframe flexibility effects are also significant, and are included as well.

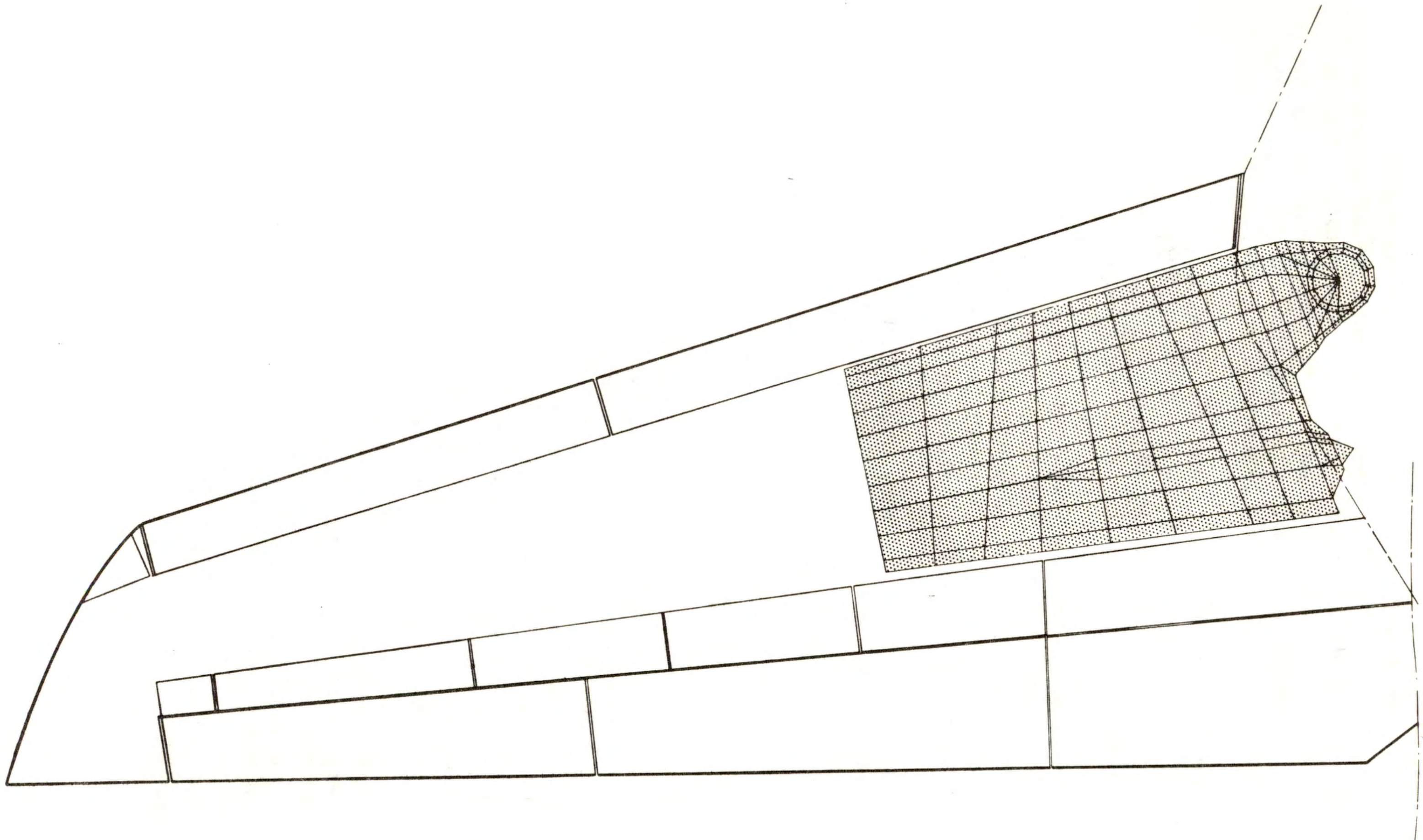


Figure 9 Idealized Wing Structure

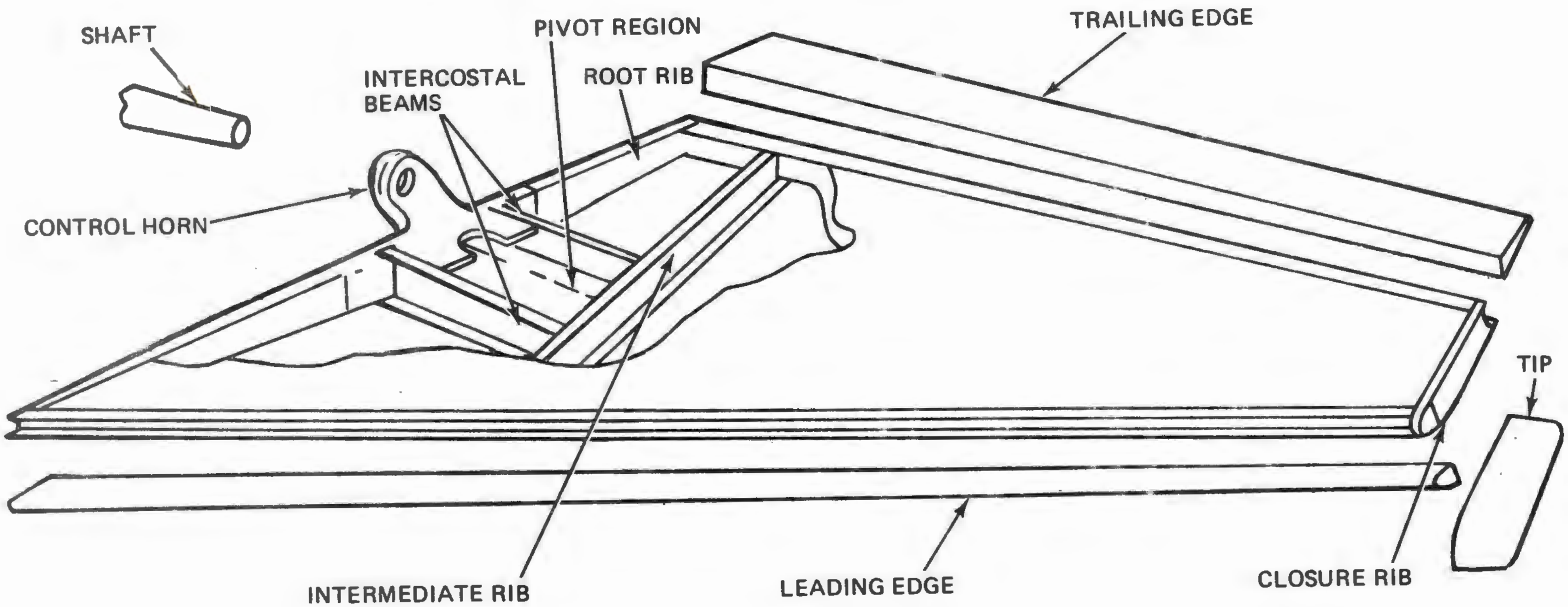


Figure 10 Exploded View of Stabilizer

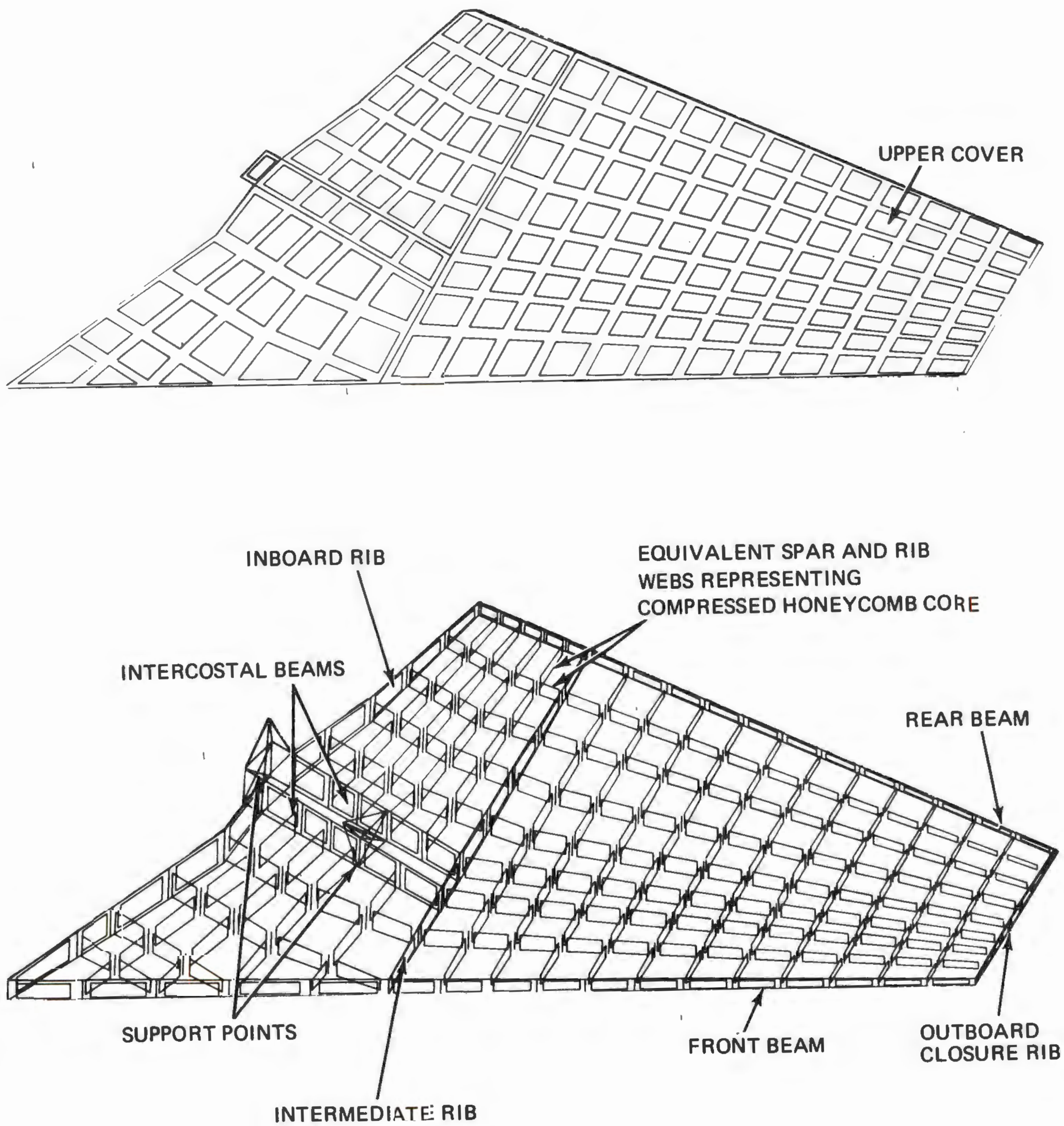


Figure 11 Stabilizer Idealized Structure

Analysis Iterations

As I have emphasized previously, structural design is an iterative procedure in which one of the analyst's tasks is to provide timely evaluations as the design progresses. In the case of the F-14, a review of the timing of the various analysis iterations that were done should be of interest. I have summarized these for the fuselage in Table 1.

As shown in this table, the time between the F-14 contract go-ahead and first flight was twenty three months, a very short period for such a sophisticated design. During this period, four major fuselage analyses were conducted. The first one was pretty crude, and actually began before contract go ahead. The next two were progressively more complex, and were completed prior to release of major structural drawings. The fourth was completed prior to first flight. All but the first of these analyses involved the 4 types of models I've been talking about -- loads, weights, dynamics, and structures -- and included all the steps that were needed to go from basic design requirements to internal structural loads.

Similar analysis iterations took place for the wing and vertical tail. As for the stabilizer, its design was fixed much earlier than would normally be the case, because of the use of the new material - the boron fiber/epoxy composite - in the covers. This was done in order to permit additional lead time for early completion of its static and fatigue testing, well before the aircraft's first flight.

The flutter analyses that were conducted proceeded along conventional lines. As is customary, the wing and empennage structures were first designed for strength and then checked for flutter. The checks made followed the structural design iterations, and increased in complexity until finally, the complete airplane model of Figure 6 was used. The result was a very small amount of weight added to the stabilizer early in the program for increased torsional stiffness. Very small weight increments were also required in the wing outer panel and in the upper region of the fin, and thus the F-14 has an almost negligible weight penalty for flutter.

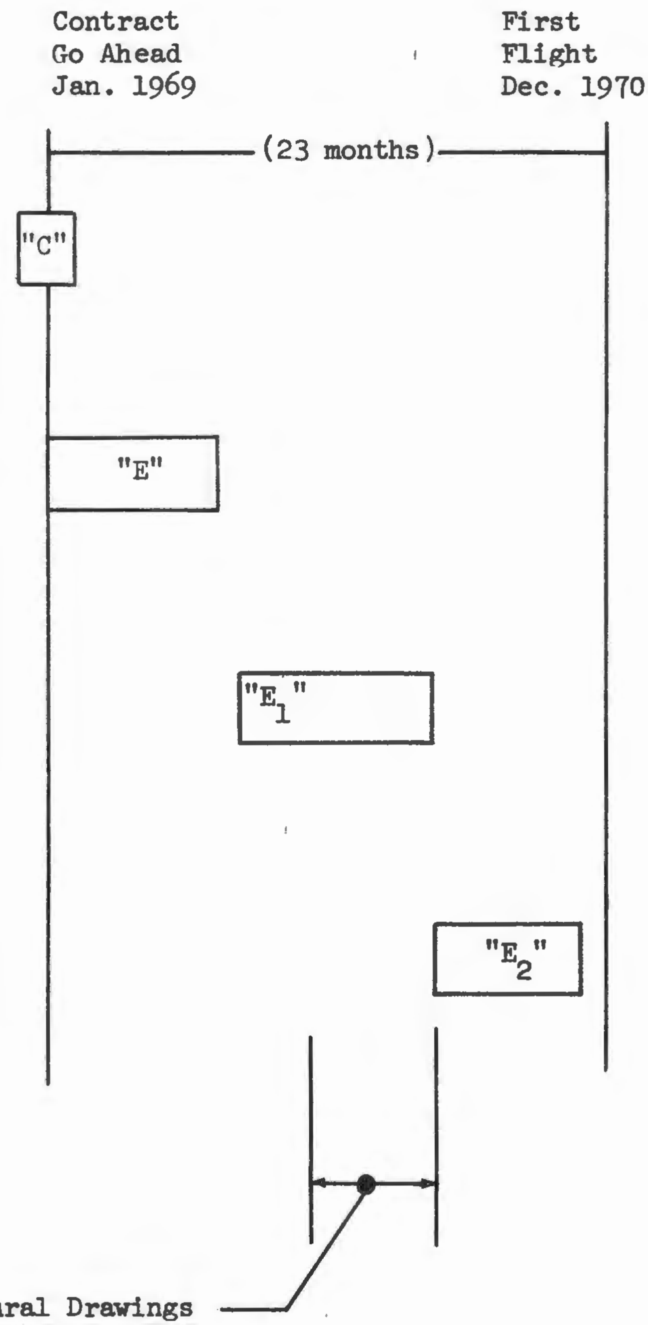
Use of Internal Loads Rather than Stresses

It may have been noticed that in discussing the role of the automated methods used in supporting the F-14 structural design, I have always referred to the goal as calculating the internal loads needed for sizing primary structure. I have specifically avoided any mention of stress distributions as such. There is a very important reason for this.

I have tried to emphasize, all along, how often the design will change during its more creative stages. It is therefore inevitable that the analyses will always lag behind; we just can't keep changing them instantaneously to keep up with the changes in design. Also, because of necessary simplifications, a given idealization may not have represented the structure precisely, even before any changes in design took place. Under these circumstances, the stress analyst frequently has to "make do" with somewhat obsolete analysis results. What he needs to do is put a portion of a large redundant structure,

TABLE 1

F-14A FUSELAGE ANALYSIS TIME LINE



Simplified idealized fuselage structure employing one quarter as many elements as in Figure 6; crude preliminary applied loads

More refined fuselage structure, including configuration changes, similar to Figure 6; refined preliminary flight loads & preliminary rigid body ground loads

Updated fuselage structure and flight loads, elastic structure used in determination of ground loads and response to same

Further updated fuselage structure; flight loads based upon wind tunnel pressure distributions; ground loads as in previous iteration (Total of 100 design conditions)

Release of Major Structural Drawings

say a bulkhead, in equilibrium, and size it for the loads acting upon and within it. If he has internal loads, then even if the real structure is somewhat different from that for which the redundant analysis was performed, he can still make assumptions and go ahead with his work. However, if all he has are stresses, he's in deep trouble.

This reality of the design procedure is so important that at Grumman, we convert the results of our standard displacement analyses into the older force method form for use by our stress analysts. By this I mean results in the form of bars with axial force varying along the length, and shear panels subjected to shear flows only.[4] If we had not hit upon this expedient, Grumman might still be using the force method in support of structural design.

Preparation of Structural Models

No doubt the most creative task associated with any redundant structure analysis is the selection of the structural model. Unfortunately, it can also be one of the most laborious.

Early in a design, before the structural details have become established, one has available only the external lines of the vehicle. At this stage, the designer requests of the contour development people that appropriate sections through the fuselage or wing, or whatever, be drawn for his use. (Most of the aerospace companies, including Grumman, now have fairly extensive automated drafting systems for such purposes.) The analyst and the designer then rough out a primary structure configuration within these external contours. As for the member sizes, their selection can be a major task. They are chosen based upon whatever information is available or can be conveniently obtained - results of previous analyses, engineering beam theory calculations, pure estimates based upon past experience, etc. In this work, estimates of the applied loads for the more critical conditions obviously are necessary. And if one has an automated fully stressed design capability available, it can be tremendously helpful in sizing the members. One can simply start the fully stressed design calculations with unit areas or gages for all members.

Later on in the design, when structural layout drawings become available, new structural idealizations are developed. Even at this time, however, some departures from the actual structural configuration are usually made. Examples of this are the simplification of complex fastening details between major parts, "lumping" of stringers and frames, etc. Regardless of the degree of refinement of the model, it must be translated into nodal geometry, topology (i.e., how the members are interconnected), and member sizes, for submittal to the computer. On the F-14, this translation was done very laboriously by hand. The idealized structure in each case was then plotted by the "Orthomat," an automated drafting machine, to provide a visual check on the input data. This is certainly an area where further automation would appear to be most cost effective.

Graphical Display of Output

One of the F-14 fuselage analyses mentioned earlier consists of approximately 3000 elements for the half structure, and is subjected to 100 design conditions. When one considers that there are two bar end loads for each bar, four shear flows for each panel and up to twelve end loads and moments for each bending element, the sheer volume of the printed results is quite disheartening to the person who has to use them. To make it as easy as possible to use results such as these, we have done two things. First, we have listed the output so that it is as convenient as we can make it. Figure 12 shows the portion of fuselage between stations 569 and 606. Figure 13 shows the corresponding member loads by condition, while in Figure 14, the member loads are ranked by condition according to maximum positive and negative values. The other thing that we have done is to display the results on a DD-80, and make hard copies from its microfilm output. Figure 15 represents a fuselage station cut just aft of station 668. The trailers leading to a number identify cap loads, while the numbers written along the members represent shear flows. Sketches like Figure 15 were produced for all loading conditions and for cuts forward and aft of each bulkhead, as well as for the bulkheads themselves. As for displacements and distortions, Figure 16 shows these for the bulkhead at station 668. Similar DD-80 plots were made for all bulkheads and all design conditions. They were a big help in understanding the way in which the structure carries its loads. The graphical display of outputs such as these is very cost effective, and seems certain to be pushed everywhere.

Another application of computer graphics consisted of partial use of the Orthomat as an aid in plotting vibration mode shapes of the previously described dynamics models. As an example, Figure 17 shows a symmetric fuselage-bending mode. In this application, the Orthomat plotted only the original undeflected grid and the corresponding displacement vectors. As an expediency, the deflected grid was then drawn in by hand. Even so, it was a tremendous aid in plotting the 480 mode shapes that were required because of the variety of sweep angles and fuel conditions to be considered.

Structural Optimization of the F-14

The design iterations of which we have spoken, including the final sizing of primary structure, really refer to an attempt at structural optimization. It is the time honored engineering approach. How near the structure comes to optimum depends upon many things - first and foremost, the ingenuity of the engineers doing the work, but also upon the tools available to them and the time allotted for their application.

We have seen that in the case of the F-14 fuselage, both the idealized configuration and the applied loads varied from one model to the next. Nevertheless, to the best of their ability, the analysts made use of the information gained from each model to size the structural members of the next model downstream. The fully stressed design program that we had operational at this time did not include a bending element, which was essential in idealizing the

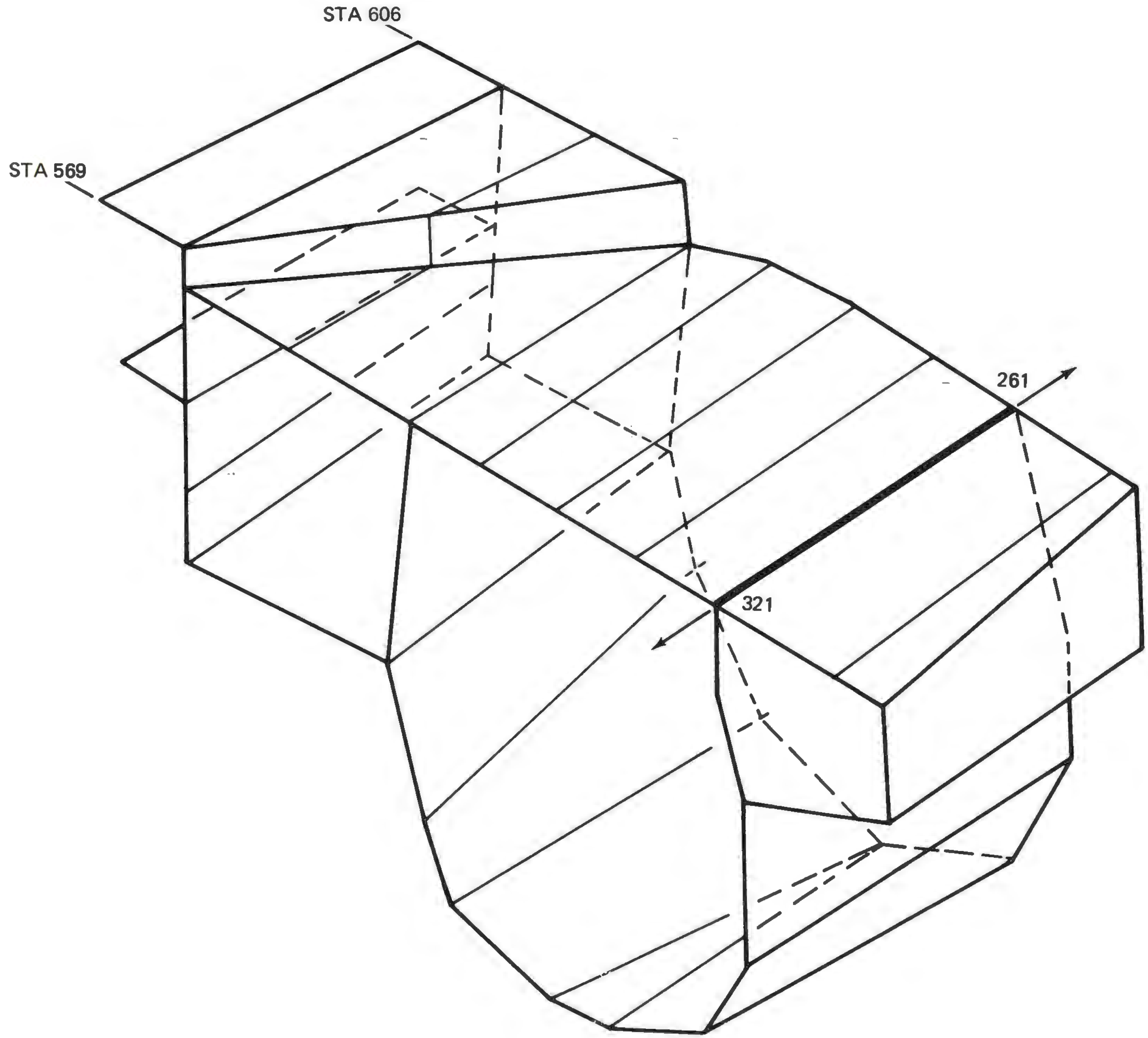


Figure 12 Typical Fuselage Section

F14-A E2 AFT FUSELAGE INTERNAL LOADS COND 61-90(FLIGHT)

TABLE E001.2 NODE LOADS - F.S. 569 TO F.S. 606

AT NODE	FROM NODE	MAX	MIN	CONDITION 61L	61R	62L	62R	63L	6
319	259	63L	80R	0.	0.	-7.	-7.	3.	
319	320	75R	72L	7194.	7282.	6900.	6981.	-10351.	-102
320	319	71R	70R	19779.	19585.	19780.	19981.	7339.	757
320	260	63R	82L	0.	0.	-6.	-6.	3.	3
320	321	71R	70R	19778.	19563.	19780.	19980.	7324.	7564
321	320	72R	69R	19421.	19514.	19845.	19933.	9985.	1010
321	261	61L	70L	79085.	78008.	72162.	71064.	36041.	3496
321	322	71L	90L	8338.	8306.	7599.	7562.	3629.	36
321	345	81R	70R	18229.	18259.	17952.	17979.	8437.	84
322	321	89R	72R	-5864.	-6027.	-6105.	-6271.	-7998.	-81
322	262	77L	86L	4863.	4835.	4038.	4009.	1010.	98
322	323	72L	89L	-528.	-642.	-454.	-573.	5072.	495
323	322	68R	75R	-31837.	-32369.	-29763.	-30301.	-936.	-153
323	264	77L	86L	9219.	9090.	6991.	6856.	1580.	145
323	327	76R	69R	9298.	9346.	9321.	9368.	2630.	26
323	347	68R	75R	-13967.	-14175.	-12329.	-12537.	1262.	1
324	326	75R	68R	2033.	2043.	1772.	1782.	-929.	-
324	265	63R	80L	-0.	-0.	-4.	-4.	2.	
324	345	78L	77R	-7.	-6.	-6.	-6.	-11.	
326	324	68R 63	75R	-2033.	[illegible]	-1772.	1782.	929.	

Figure 13

F14-A E2 AFT FUSELAGE INTERNAL LOADS COND 61-90(FLIGHT)

TABLE E001.2 NODE LOADS - F.S. 569 TO F.S. 606

AT NODE	FROM NODE	RANK - COND NO IN ( ) 1	-1	2	-2
319	259	3.(63L)	-12.(80R)	3.(63R)	-12.(82R)
319	320	15201.(75R)	-11564.(72L)	15114.(75L)	-11520.(72R
320	319	31698.(71R)	-17252.(70R)	31686.(72R)	-17242.(69R
320	260	3.(63R)	-10.(82L)	3.(63L)	-10.(82F
320	321	31688.(71R)	-17248.(70R)	31677.(72R)	-17239.(69
321	320	30291.(72R)	-16608.(69R)	30262.(72L)	-16545.(6
321	261	79085.(61L)	-48241.(70L)	78833.(79L)	-47865.(
321	322	12579.(71L)	-6206.(90L)	12532.(71R)	-6190.(
321	345	22825.(81R)	-14859.(70R)	22753.(81L)	-14828.(7
322	321	7066.(89R)	-13557.(72R)	7008.(89L)	-13426.(72
322	262	8944.(77L)	-4442.(86L)	8357.(78L)	-3566.(85
322	323	8691.(72L)	-4353.(89L)	8635.(71L)	-4303.(89
323	322	18704.(68R)	-39820.(75R)	18463.(68L)	-39291.(75
323	264	12937.(77L)	-9443.(86L)	11784.(75L)	-8427.(88
323	327	9735.(76R)	-4129.(69R)	9722.(75R)	-4091.(69L
323	347	10730.(68R)	-19121.(75R)	10635.(68L)	-18915.(75L
324	326	2609.(75R)	-1538.(68R)	2599.(75L)	-1533.(68L
324	265	2.(63R)	-6.(80L)	2.(63L)	-6.(80
324	345	15.(78L)	-11.(77R)	15.(77L)	-11.(63
[illegible]	[illegible]	1538.(68R)	-2609.(75R)	1533.(68L)	[illegible]9.(75L

Figure 14

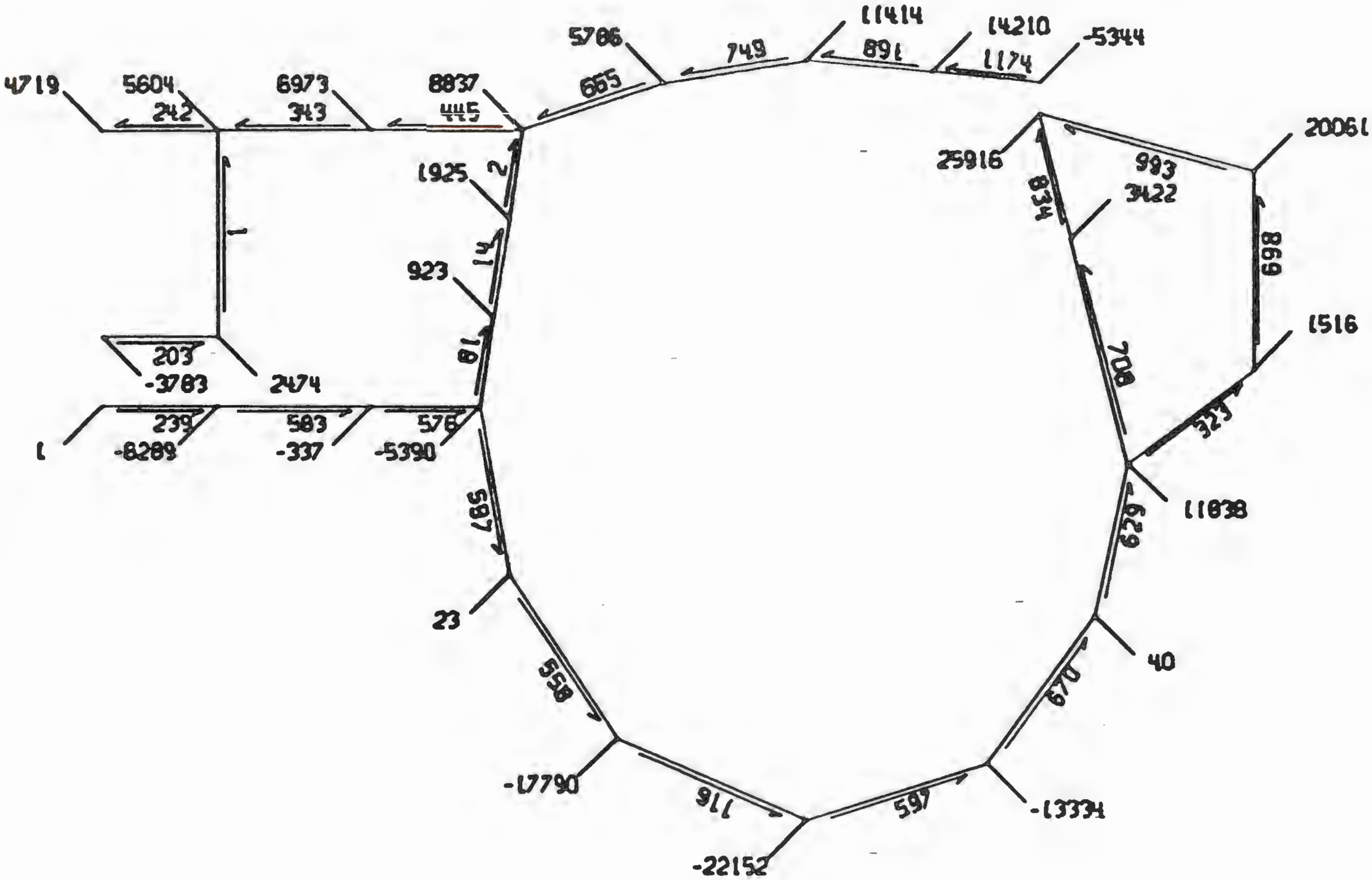


Figure 15 Internal Loads at Station Cut Aft of FS 668

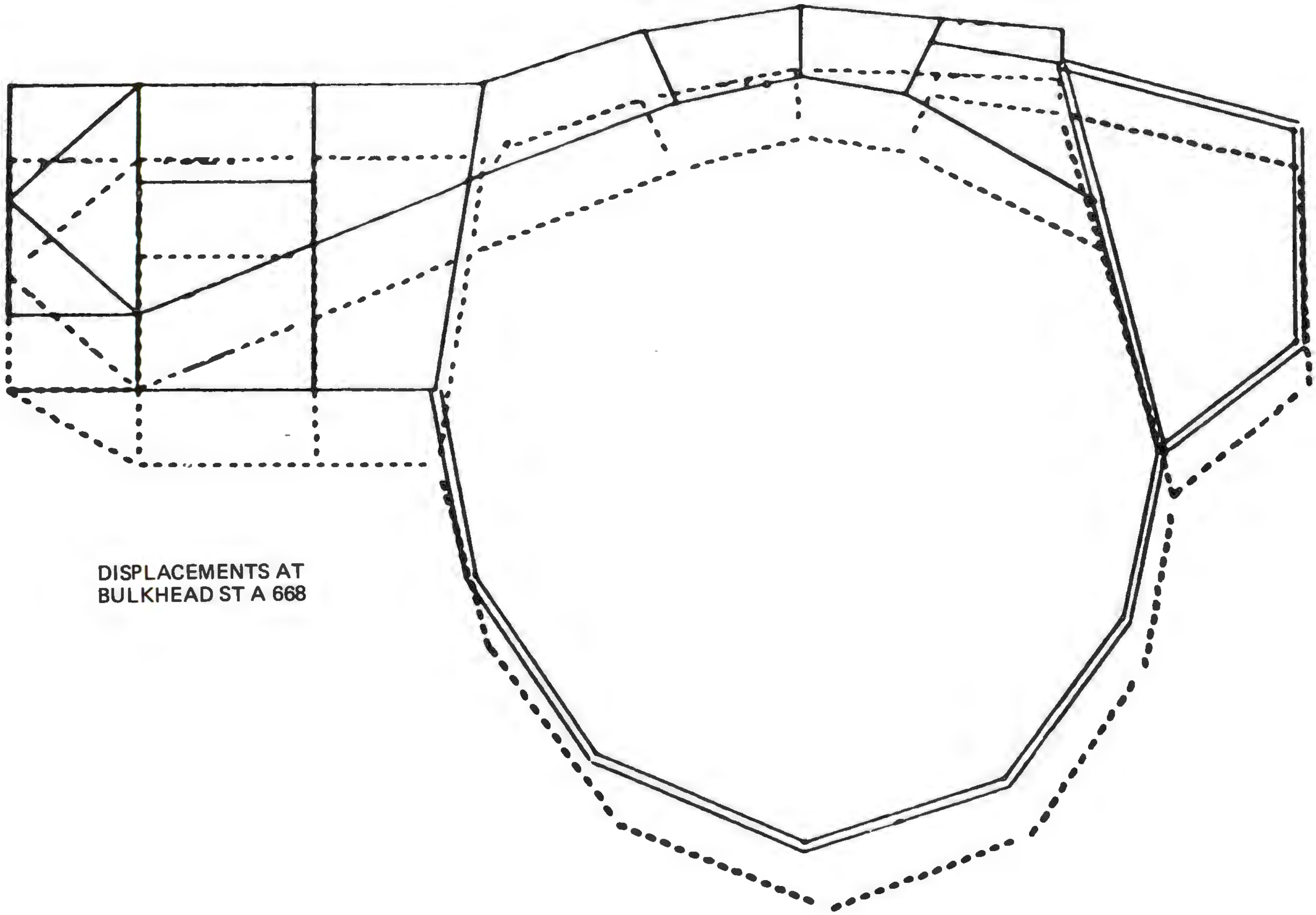


Figure 16 Displacements at Bulkhead ST 668

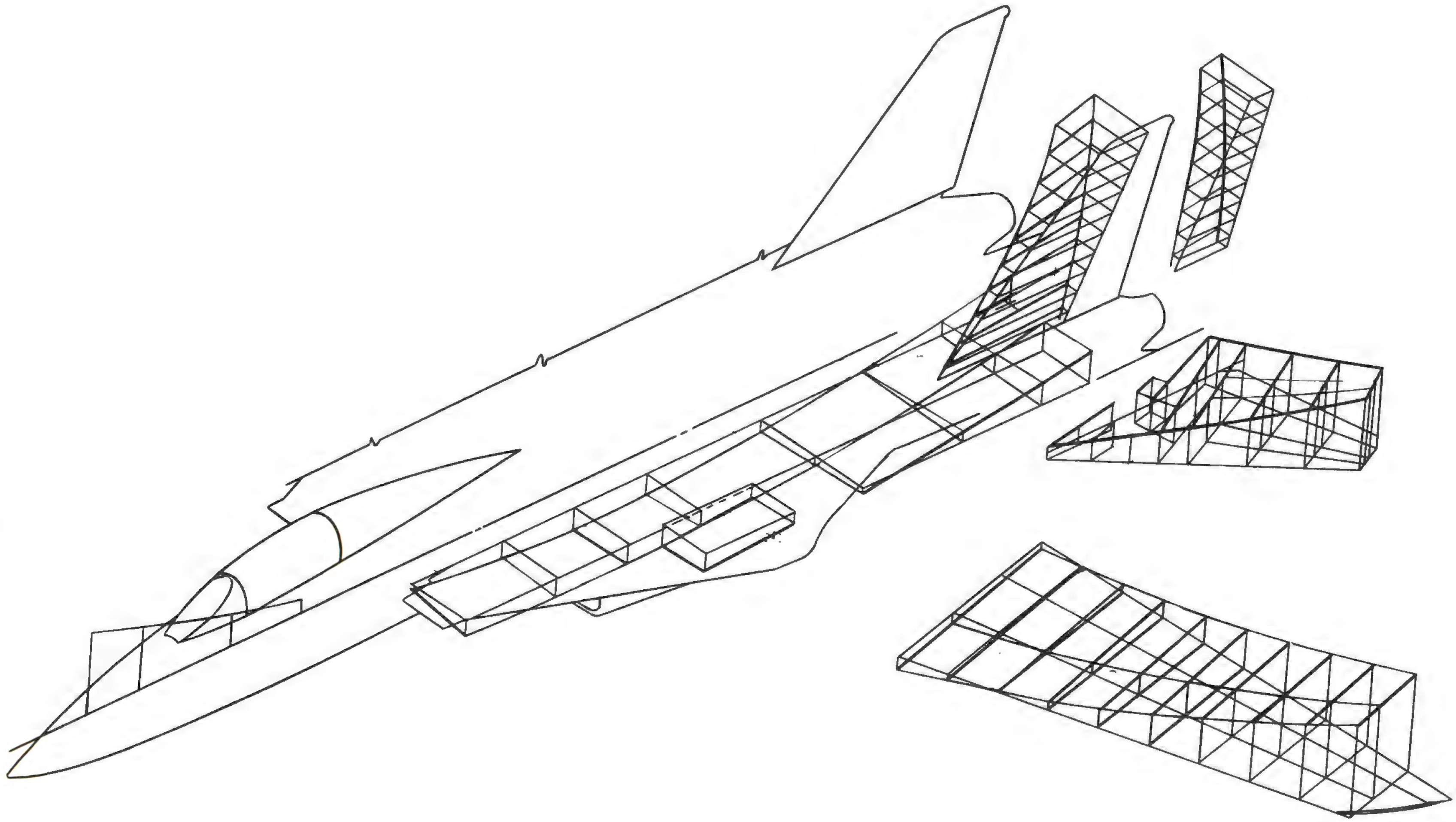


Figure 17 Second Airfame Vibration Mode

fuselage. Thus the use of fully stressed design was not even considered. This element deficiency has since been remedied in ASOP (Automated Structural Optimization Program). However, there are many other practical problems that remain in the optimization of fuselage structures, such as introducing the appropriate frame design criteria. It may still be a while before we are really ready to approach this task in any automated fashion.

In the case of the stabilizer, the situation was somewhat better. Because of the nature of the structure, it was logical to idealize it primarily by bars and anisotropic membrane elements. (See Figure 11). Thus it could be handled by an existing fully-stressed design computer program developed for wings and empennages. It was only necessary to add to the program a capability for selecting optimized boron epoxy layups according to a suitable allowable strength criteria. This work has already been discussed[5] and so will not be repeated here. However, one observation should be made. Even after attempting to introduce realistic minimum sizes into the fully stressed stabilizer design, the weight of the actual structure as built was far above that of the idealized structure. Specifically, for the main box the ratio of weights was 1.51, while for the covers alone, it was 1.28. The differences can all be accounted for in joints, splices, fasteners, adhesives, bearings, fittings, etc. The point is that a surprisingly large proportion of actual primary structure weight is not included in its corresponding finite element idealization.

The fully stressed design program also was used effectively on the titanium wing center box. It was not used on the wing outer panel, largely again because of the unavailability of a bending element in the program. The latter was needed in idealizing the wing covers adjacent to the pivot region.

Concluding Remarks on the F-14 Design Analysis

It would be an exaggeration to say that the design of the F-14 is representative of all modern American fighters. After all, with the exception of the F-111, the F-14 is the first of the only two new fighters we've had in the last fifteen years. (The F-15, now being designed by McDonnell Douglas, is the other.) Nevertheless, one can conjecture that the F-14 program contains elements of what lies ahead for most new aircraft of its type.

By far the most important F-14 design constraint was the short time available from contract go ahead to first flight. This, in combination with the requirement to do the applied loads work effectively for five different airplanes because of the variable sweep feature, absolutely dictated that the design analysts employ the systems approach in the determination of internal loads for sizing structure. By use of the IDEAS system, it was possible for them to make their inputs sufficiently early to provide a sound basis for changes in design during its more creative stages.

USE OF IDEAS IN PRELIMINARY DESIGN

As discussed previously, the first IDEAS application has been to the F-14, during the period from contract go ahead to first flight. More recently, we have used the system for preliminary design purposes on the Earth Orbital Shuttle. It would be inappropriate to go into detail on this work at the present time; however, some of the highlights can be mentioned.

Grumman, in partnership with Boeing, currently has a contract with NASA titled "An Alternate Space Shuttle Concepts Study." During our investigations last winter, we became convinced that the orbiter's main propellant liquid hydrogen tanks should be mounted externally to the fuselage. See Figure 18. The tanks could then be jettisoned while the vehicle is still in orbit, thus reducing the latter's overall size and weight for reentry. NASA was interested in the concept, but was concerned about the possibility of undesirable dynamic effects. To establish credibility for the design, it became essential to evaluate its dynamic behavior.

The specific problem of most concern was the response of the vehicle to sinusoidal variation of the thrust load during first stage of boosted flight. As in all "piggy back" arrangements, there is a primary interaction between longitudinal excitation, such as variation in engine thrust, and transverse response. (This effect is almost completely absent in the Saturn/Apollo vehicle.) In the case of our shuttle configuration, the long, flexible, end supported, LH_2 tanks were especially suspect.

In order to carry out the investigation, we first had to come up with a sufficiently realistic dynamic model of the coupled orbiter/booster vehicle. The booster was relatively easy to model, because of its extremely simple structural arrangement and load paths. The orbiter was something else. Because of the provisions necessary for payload, various internal "floating" tanks for liquid propellants, and transfer of thrust load from booster to orbiter during first stage boost - as well as the external hydrogen tanks - the orbiter structural arrangement was much more complex. The idealized structure correspondingly had to be more detailed.

Based upon the preliminary layouts available for our H3T configuration, (Figure 18), we roughed out node locations and topology for a complete, idealized orbiter/booster structure. The total number of structural elements employed (bars, beams, shear panels, etc.) was 1763, of which 92% were in the orbiter. Preliminary applied loads for various design conditions were obtained, and distributed to the idealized structural components. In the case of the orbiter wing and fin, beginning with completely arbitrary distributions of material, fully stressed designs were obtained by use of the ASOP program. For the fuselage, member sizes were first selected by the stress analysts using conventional design procedures. An analysis was then run, and based upon the results, the structure was resized. The resized fuselage structure was then used to compute flexibilities in the subsequent dynamics calculations.

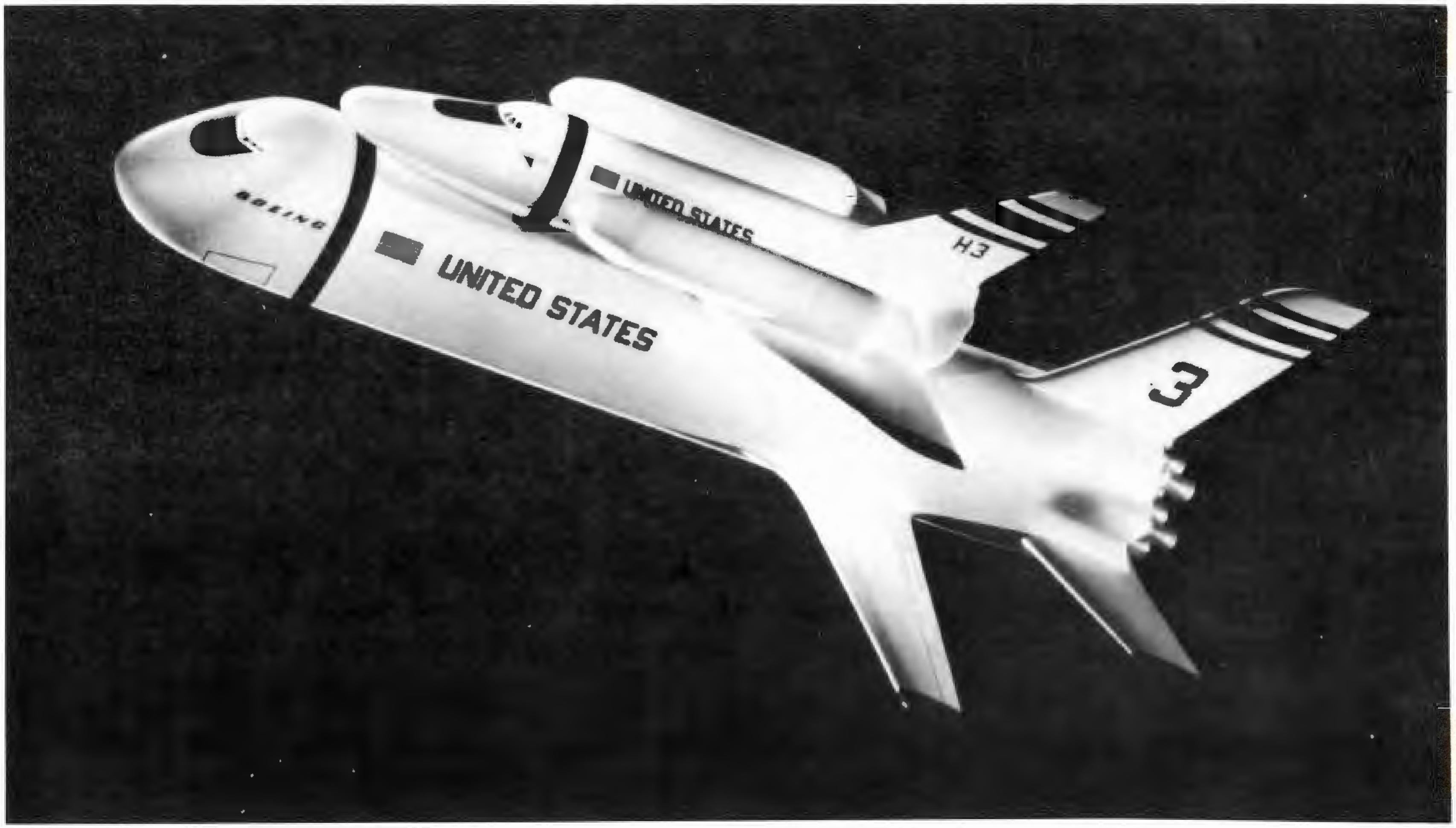


Figure 18 Grumman/Boeing External Hydrogen Tank Space Shuttle

Mass and inertia idealizations had been obtained concurrently, together with the necessary transformation matrices. It was now possible, using selected portions of IDEAS, to carry out all of the matrix manipulations required. These included coupling together the booster and the fuselage, wing and fin of the orbiter, transforming the structural influence coefficient matrices to conform to the dynamics model, obtaining the normal mode characteristics, and finally obtaining the desired response to sinusoidal variations in booster engine thrust.

The results of the investigation were very gratifying. They were completed on schedule and indicated that the external hydrogen tanks presented no additional dynamic problems. Of course the analyses also yielded all of the usual static structure information - internal loads, deformations, etc.

Once the preceding objectives had been met and the pressure was off, we went back and applied the ASOP program to the orbiter fuselage idealized structure. This time we started out with completely arbitrary member areas, skin gages, etc., i.e., set equal to unity, together with specified minimum sizes and simplified strength allowables. Because the latest applied loads, as used in this calculation, were different from those employed earlier, a direct comparison with the earlier, hand resized results was not possible. However, there was now a drastic reduction in the new weight of the frames relative to the external shell structure. Before being able to place any confidence in such results, we shall have to examine the failure criteria employed for the frames much more closely.

CURRENT DEFICIENCIES AND FUTURE TRENDS

Structural Optimization

Earlier in this paper, I have tried to show that, from a practical design point of view, it is still a struggle merely to obtain internal loads in primary structure on a time schedule that is attuned to the needs of the designer. Traditionally, once the internal loads are known, the analyst and the designer use them to resize the structural members as required. An essential ingredient in the redesign is a good knowledge of the failure criteria and the accompanying allowable stresses to be employed; of course these will depend upon the nature of the various structural elements and their loadings. Member resizing is customarily based upon the ratios of the predicted stresses to these allowables. However, the method is not applied rigidly. Also involved are the judgements of the analyst and designer as to what constitutes a well-balanced design, taking into account good manufacturing practices, etc. This is followed up by a reanalysis check whenever possible.

A very normal, evolutionary improvement in this procedure is to automate the resizing, based upon the stress ratios just mentioned. Of course, this is the motivation that has led to the inclusion of fully stressed design features in a number of computer systems recently reported in the literature - a recent version of W. D. Whetstone's original SNAP program[6] and NASA Langley's DAWNS program[7], to name a few in addition to the Grumman references cited earlier. All these programs have the characteristic that between analysis cycles, the structural elements are either resized to carry some prescribed allowable stress in at least one design condition, or are at their specified minimum sizes. In most cases, the stress ratio is based upon some average stress that can be identified for each element. The Grumman programs are different in that for the skin portion of a semi-monocoque structure, the individual element stresses are combined into "nodal stresses."[3,4,5] In our experience, this leads to smoother distributions of material than the average stress approach. In either event, after a small number of analysis and redesign cycles, say five, the structural weight and material distribution usually settle down, so that further recycling causes negligible improvements. When one considers that the idealized structure weight may only represent on the order of two thirds of the equivalent actual primary structure weight (as in the case of the F-14 stabilizer), the last percent or so of idealized structure weight saved may be relatively meaningless.

Theoretically, of course, one can argue that fully-stressed designs are not necessarily optimum even for strength critical structures. Perhaps as we gain more experience in the use of these procedures, we will encounter practical airframe design cases where fully-stressed designs are in fact significantly non-optimum. The writer doubts that this will be the case for wings, but fuselages could be another story. We just don't know. However, this possibility should not deter us from using the tool until we have a more optimum one to replace it. The latter could be a long time in coming; current projections of computer running times for reasonably large structures optimized by mathematical search techniques are still quite high.

Fox and Schmit[(8)] have suggested that the mathematical search approach could be made workable for such large idealized structures by abandoning the one to one relationship between the number of optimization variables and the number of finite elements employed. Instead, they propose that only certain key elements be optimized, and that one interpolate between them for the sizes of the other elements. Tocher and Karnes[(9)] have incorporated this interpolation concept into a mathematical search program which can handle structures up to 500 members in size, of which less than twenty percent of the members are actively optimized. They have applied it successfully to several relatively small structural components. It will be interesting to see whether this approach can be extended to larger structures in a practical way.

No matter what resizing algorithm eventually turns out to be best, it is only part of the story for strength critical structures. From a practical design point of view, a very significant part of the total methods development effort will have to go into delineation of all of the strength criteria and resulting allowable stresses that will be required. I referred to one especially sticky case of this previously, that of fuselage frames. Here stiffness rather than strength may be critical, and the situation will become further complicated if the fuselage skins buckle and go into partial diagonal tension. Compression allowables for stiffened panels such as are used in wing skins is another example. Fibrous composites and all of their applications is a whole new field. Fatigue allowables different from static strength allowables must be accommodated. Until features such as these are incorporated into the programs, their usefulness in practical applications will be severely limited. The allowables aspect of the work apparently has been given very little attention so far, at least in the literature.

Another matter of extreme practical importance is that of cost. More and more, in the current environment, weight penalties are being taken in order to reduce the overall price of a design. One illustration of this is simplified machining. By reducing the number of cuts in an integrally stiffened wing skin, for example, one can save on machining costs, and perhaps at a fairly small weight penalty. We ought to be thinking in terms of evaluating such alternatives by means of our optimization procedures.[(10)]

Up to this point, the discussion of structural optimization has dealt exclusively with strength as the constraint. This is as it should be - the first requirement for any aerospace vehicle is that it be able to carry the "static" loads applied to it. However, there are other constraints over and above strength that sometimes become critical.

Displacements as a constraint have been included practically from the beginning in the mathematical search work that has been done[(11)]. In the original work by Schmit, they have been treated exactly as the strength constraints, and travel in design space has been either normal to or parallel to the equal weight surfaces until the constraint surfaces have been encountered.

More recently, Venkayya et. al.[12] have suggested that travel normal to a deflection constraint surface - combined with travel associated with "scaling" the sizes of all structural members proportionately - would be preferable. In the examples examined to date, in combination with a suitable stress ratio algorithm for strength, the method appears to lead to designs that are generally competitive with those obtained by traditional mathematical search, and in significantly less computer time. It has been incorporated into and is operational in the ASOP program. Berke[13] has another interesting intuitive approach to the constrained displacement problem. The resizing algorithm is a very simple one which is theoretically correct only for statically determinate structures. It is somewhat analogous to the stress ratio algorithm of fully stressed designs, and is used iteratively in a similar fashion. Exploratory investigations conducted so far indicate that it may prove to be even more desirable than Venkayya's approach, from the point of view of computer running time.[14]

Vibration frequencies of aerospace structures can also impose design constraints. There have been a number of papers on this recently, of which the one by Rubin[15] is especially attractive. Here, one of the travel directions is normal to the frequency constraint surface - the other along the frequency constraint and directed so as to reduce weight. In order to be applicable in airframe structural design, strength constraints would have to be introduced as well.

Flutter is still another constraint. There have been a number of papers already in this area, of which Turner's[16] was the first. One of the most recent, by Rudisill and Bhatia[17], is very promising in that it provides the direct means for obtaining gradients to the flutter velocity constraint surface. Programs for optimizing directly for both strength and flutter could be of great practical assistance on many aircraft, particularly those designed for low maneuver load factors. These can be significantly flutter critical.

A constraint of special interest for the Space Shuttle is thermal stress. This one is especially tricky, because it could involve configuration changes. A common design approach to the thermal stress problem is to reconfigure the structure if possible, so that the thermal effects will be minimized. Perhaps, automated redesign procedures can help in this area too.

Integrated Design and Analysis Systems

Of course, other organizations in addition to Grumman are hard at work on automated design systems. We shall be hearing about the Boeing experiences on the 747 and the SST at this meeting. In addition, there is the NASA DAWNS program,[7] which is part of an exploratory development project currently under way at Langley. DAWNS integrates the structures and aerodynamics disciplines into an automated design operation, and it can be used in an interactive mode with a cathode ray tube display. Primarily for wing type structures, it could be the beginning of a very attractive tool for use in preliminary design.

Langley has other goals that extend far beyond DAWNS. Over the next five to ten years, in partnership with industry, they contemplate the development of a system called IPAD, Integrated Programs for Aerospace Vehicle Design.(7) It is intended to embrace all of the disciplines that we have discussed previously as being required in aerospace structural design. Perhaps the most significant improvement that they visualize is in the complete automation of the interfaces that exist between the disciplines, as well as automated access to all stored data. The goal thereby is to reduce the total cycle time for review of a given design from a period of months to one of weeks. In achieving this objective, an avowed guideline is that the system be sufficiently versatile and flexible that industry will want to use it. They are soliciting industry's participation in developing it, so that this can in fact take place. The plan that Langley proposes appears to be a desirable and necessary one. For any one company to develop such a system using only its own resources appears to be very unrealistic under current conditions.

Computer Graphics

Large scale batch mode analyses of the type discussed for the F-14 have already benefited substantially from the use of graphic aids. Thus far, most aerospace companies have concentrated their efforts for these large analyses in two areas:

Graphic Input Data Checking

Graphic Display of Results

In the first of these areas, commonly used techniques involve the use of automated drafting equipment, such as the Orthomat mentioned earlier, for display purposes. In addition, several companies have techniques for interactively displaying and correcting the input data for structural models. Lockheed in particular has done very interesting work along these lines, and will be reporting upon some of it at this meeting.

The second big payoff area is the graphic display of structural analysis output data. In past years the results of an analysis were generally in the form of huge computer listings containing internal load distributions. These were handed over to the structural analysis personnel for their use. The information usually was hand transcribed onto model drawings so that examination and use of the results could proceed. The time consuming nature of the work, of the order of many man months, dictated a better approach. Initially, automated drafting or plotting equipment was tried, but this was still very slow. More recently, devices such as the DD-80 and other similar machines have made an appearance. They are based upon display of results on a cathode ray tube plus microfilm recording, and are much speedier. A recent advance in high resolution microfilm plotting which enables reproduction up to 30" x 40" (the FR80) has made possible the display of results in larger segments of the model. In conjunction with computer programs that can search for critical conditions, display of results ready for input into final stress reports is now a normal mode of operation in several companies.

While all these methods have led to great cost and time savings in the area of large scale structural analysis, a major bottleneck still remains, namely in the initial preparation of the input data. New hardware configurations enabling the marriage of low cost graphics terminals, x-y digitizers, and hard copy devices now permit the generation of input data in the engineering areas, interactively, without resorting to former hand transcription, card punching, verifying and associated time consuming processes. By using these devices in conjunction with a time share computer one can generate input data tapes for future runs on a batch computer. Work in this area is currently under way and we believe there will be a great payoff in the next few years.

The large scale batch mode analyses discussed earlier basically require for their staffing specialists having rather distinctive aptitudes, training and experience. The smaller, more detailed analyses that accompany and compliment the large scale ones are less specialized. Here, the design analyst himself should be in complete charge from beginning to end. (Bulkheads and fittings are good candidate components.) In this situation the interactive programs centered about machines like the IBM 2250 are very attractive. By their use, the engineer at the console can first enter the input data describing the structure either by light pen or appropriate data cards. He then calls for a solution, and the results are displayed on the cathode ray tube. While the computer is still "on line," he makes any changes to the structure he desires and reanalyses. Lockheed has had such a system operational for several years for two dimensional structures.[18] Other companies have similar capabilities in various stages of development, and this tool should come into widespread usage in the next few years.

Another interactive computer graphics area under development in a number of organizations is the tie in of the preceding efforts with a master dimensions library. These systems, usually referred to as design drafting systems, generally start with a stored geometric definition of the external contours of the vehicle. A designer sitting at a console can call up desired sections of the aircraft, perform a modelling function, and exercise various engineering application programs to arrive at final detail designs. Drawings, including all details, may also be created at the scope. Following the creation of the drawing, hard copy can be obtained via a flat bed plotter, high resolution computer output microfilmer or high speed laser-type plotting equipment. The full exploitation of such techniques appears years away, but several aerospace companies already have made sufficient progress to be marketing systems of this type.

CONCLUDING REMARKS

As indicated at the outset, my basic goal has been to portray the role of the design analyst during the evolution of an aerospace structural design, and the analysis tools that he needs to do his work. There is one principal idea that I have tried to develop and that I hope I can leave with you. It is that the design process and the analyses that must accompany it cover a wide range of technical specialties. Each specialty plays a vital role, and if any one of them falters, either schedules will not be met, or what is more likely, design decisions will be made on schedule, but they will be based upon incomplete information. We must be realistic. Our methods development work must focus, more effectively than heretofore, upon those areas where we are most deficient. If our industry is to become more competitive in the world marketplace, these are the areas where we should be expending a major portion of whatever resources are available for analytical procedures.

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