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DESIGN CONSIDERATIONS FOR FIBER COMPOSITE STRUCTURES

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by C. C. Chamis

ABSTRACT

An overview of the design methodology for designing structural components from fiber composites is presented. In particular, the need for new conceptual structural designs for the future is discussed and the evolution of conceptual design is illustrated. Sources of design data, analysis and design procedures, and the basic components of structural fiber composites are cited and described. Examples of trade-off studies and optimum designs are discussed and a simple structure is described in some detail.

Key words: Fiber composites, Design, Structural Engineering Composites, Reinforcement Review

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by C. C. Chamis[1] A.M.

INTRODUCTION

Future demands for land and conservation of natural resources will require revolutionary structural design concepts in designing residential, commercial, industrial, and other types of structures. Dismantling, transporting, and relocating large structures will probably be important design considerations. The emphasis will be on modularity, ease of construction, shortest time possible between building start and occupancy, ease of dismantling and replacement, and reuseability.

The advantages of such structural design concepts are numerous from social, environmental, and economic considerations. Reallocation of land and relocation of the structure within a region or neighborhood would be possible. This will lead to material conservation and could conceivably deter neighborhood and urban decay. Difficult problems arising for large massive structures would be avoided and elaborate and time-consuming erection procedures would not be required. Remodeling could be readily accomplished and incorporating several small structures into a larger complex, when the need arises, would be possible.

Structures of fiber composites are of light weight and are amenable to modular form and complex shapes. These characteristics make

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them primary material contenders in the aforementioned types of structures. The objective of this paper is to present a synopsis of the design methodology available in designing structural components from fiber composites.

The general design concept, sources and types of design data, analysis methods and their capabilities, and design procedures are described. Illustrations of basic structural components and shapes are given. Types of joints, parametric designs, and optimum designs are discussed. A simple three-dimensional truss is described in some detail.

EVOLUTION OF DESIGN

The evolution of any design results from a requirement or desire to satisfy either a known or agreed upon need. In this sense, design of structures is mission oriented even though the term mission has not been used by structural designers. Several decisions precede the definitization of any specific design objective. Some of these decisions are schematically illustrated in Fig. 1. For example, modular-type construction for low cost housing evolved from the need of having suitable and inexpensive housing for low income families.

Selection of the material for the modules for low cost housing is governed by whether the material under consideration satisfies the specific requirements (meet local codes, inexpensive, ease of fabrication, human factors, etc.). To establish whether the material selected meets the specific requirements depends on the availability of the following and other information: necessary design data, design methodology and fabrication technology. In the case of structural fiber composites, considerable design data have been accumulated and the design methodology has been generated as will be discussed subsequently. The fabrication and construction technologies are available as is evidenced from the achievements cited in (1-6).[2]

Large amounts of data for the various composite systems available (S-Glass/Epoxy, Boron/Epoxy, Graphite/Epoxy, etc.) have been generated. These data have been compiled and are available in several sources, such as books, hand-books, reports, conference proceedings, etc. An extensive list of many of these sources was given in (7). Additional references are cited in Appendix II-Bibliography where they have been grouped by source.

The types of data found in these sources include: elastic and thermal properties, strength, fatigue, creep, impact, temperature, and other environmental effects, etc. Some of these sources include information and data on partial or complete designs. Practically all of the references cited in Appendix II are readily available.

STRUCTURAL ANALYSIS METHODS

The methodology for analyzing complex structures and/or structural components subjected to complex loadings has been extensively developed in the last few years. This development has resulted primarily from the tremendous progress in computer technology and the advent of the finite element method of analysis. Many of the sources which deal with analysis and design methodology were given in (7).

General and special purpose computer programs of structural and stress analysis are an invaluable asset to structural designers. Some

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[2]Numerals in parenthesis refer to corresponding items in Appendix I - References.

of these programs are available in leading consulting engineering firms and various industrial and institutional computer centers throughout the country. Many of these programs are available through time sharing systems. A partial list of general and special purpose structural-stress analysis computer codes and their sources is given in Table 1. Documentation on the capabilities and limitations of these codes is readily available from the sources cited in Table 1. The general purpose codes usually are designed to handle a variety of structures and structural components. This generality, however, introduces some inefficiencies in both computer storage and running times. Special purpose codes usually are designed to handle specific structures or components under restricted loading conditions. As a result, they are efficient in both computer storage and running times.

The general purpose computer program NASTRAN (8) is selected herein as an example to illustrate the capabilities of such codes. The various types of analysis that NASTRAN is designed to handle are listed in Table 2. The types of finite elements available in NASTRAN are shown in Fig. 2. As can be seen from both Table 2 and Fig. 2, the code possesses considerable generality and a great potential. Three other factors make NASTRAN even more attractive. These are:

(1) NASA has created a NASTRAN office at Langley Research Center, Langley Field, Virginia which has the responsibility of maintaining and updating NASTRAN within the foreseeable future.

(2) The 15.1 NASTRAN level available after April 1972 will contain 10 more finite elements in addition to those shown in Fig. 2.

(3) The NASTRAN office has scheduled annual conferences of NASTRAN users where advantages and disadvantages of the code are

discussed and recommendations for possible improvements are made.

Typical structures which have been analyzed by NASTRAN are shown in Figs. 3-7. Additional examples are found in (9).

Judicious use of both general and special purpose computer codes can save considerable time in the design process and therefore result in considerable cost reduction.

General and special computer codes require input data for material and section properties. For the case of composite materials, it is convenient to generate material and section properties using composite micromechanics, macromechanics, and laminate analysis (7). All of these can be incorporated in computer codes (10).

BASIC STRUCTURAL COMPONENTS, JOINTS, AND OPENINGS

Any structure, regardless how complex, is an assemblage of basic components such as truss, beam, frame, membrane, plate, and shell. Basic components have been successfully designed and fabricated using fiber composites. (See schematics, Fig. 8.) Design criteria for basic components have also been generated. For example, design formulas for preventing column and lateral beam buckling are given in (11).

Basic components from fiber composites can be combined to form special structural components. Some of these are illustrated in Fig. 9. Additional ones are given in (1 and 2) and in many of the references cited in appendix II.

Joints and openings are two general types of discontinuities in structural members. Joints interconnect the structural members in the structure. Nonstructural design considerations such as plumbing, heating, etc. require structural components to be subjected to cut-outs and openings. The methodology for designing for these discontinuities in fiber composite structures has been the subject of intense research in recent years (12-18). The primary tool of analysis has been the finite element method. Typical examples of adhesively bonded joints are shown in Fig. 10, and for mechanical joint analysis in Fig. 11. The stress distribution around openings is shown in Fig. 12. It is significant to note in Fig. 13 that nonuniform stress distribution exists around the hole due to the anisotropic material behavior. Through-the-thickness shear stresses also exist due to the heterogeneity (18).

Combinations of adhesively bonded and mechanical joints are also possible. The type selected will obviously depend on the particular design. The additional reinforcement required around the opening is readily determined from the stress analysis (19).

TRADE-OFF STUDIES AND OPTIMUM DESIGN

Trade-off or parametric studies serve a very important role in preliminary designs for sizing structural components and selecting materials. In this approach, the desired function such as section modulus, structural index, moment capacity, member weight, etc. are plotted as functions of design variables. Combinations of design variables for optimum values of the desired function are easily selected from these plots. Trade-off studies are very useful in designing with structural fiber composites.

Representative examples of parametric studies are shown in Fig. 13 for panel buckling, Fig. 14 for a freely excited beam, and in Fig. 15 for a stringer-flange section. Additional examples are available in the conference proceedings cited in Appendix II.

The design of any structural component or structure can be cast into a linear or nonlinear, inequality and/or equality constrained mathematical programming problem by making suitable assumptions. The optimum design is then found by seeking the optimum of the mathematical programming problem using powerful minimum (maximum) searching algorithms (7).

Optimum design results of a graphite-fiber/resin composite stiffened cylindrical shell are given in Fig. 16 from (20), and for boron-fiber/resin panels in Fig. 17 from (21). Additional work in optimum design of fiber composite structures is reported in (7, 22, 23, and 24).

The concepts of optimum design have also been applied with respect to material and processing variables. An example wherein the internal burst pressure of a pressure vessel is computed with respect to material and processing variables is illustrated in Fig. 18 from (25). An example of a thermostructural panel is discussed in (7).

SIMPLE STRUCTURE

A support truss for the 30-foot-diameter parabolic antenna dish of the NASA Applications Technology Satellite (ATS) is required as shown in Fig. 19(a). This truss must be as light weight as possible and must have negligible longitudinal dimensional changes in the (-256^{o} to 200^{o} F) outer space temperature range. The truss will resist approximately 160 kips of compressible load and will be 172 inches long.

Unidirectional graphite-fiber/resin composites are strong, low in density, and have very low thermal coefficient of expansion. Typical properties of the material selected for the truss are given in Table 3. The final truss design as described in (26) is as follows: (Refer to Fig. 19(b).) (1) eight support tubes 2.69 inches o.d. by 170.16 inches long; (2) a stabilizer ring located 83.135 inches from the instrumentation platform; and (3) two struts located approximately 40.0 inches from the instrumentation platform plane as shown in Fig. 19(b). The ends of the support tubes are bonded to Ti 6Al 4V fittings with Hysol 934 epoxy adhesive. The support tube material consists of a 13-ply composite layup with the following sequence progressing from the i.d. toward the o.d.:

(a) 1 ply 2002M graphite/epoxy 83° nominal thickness 0.008

(b) 11 ply 2002M graphite/epoxy 0° nominal thickness 0.086

(c) 1 ply S901 glass/epoxy 90° nominal thickness 0.006

A glass cloth reinforcement layer is placed at the fitting attachment locations on the o.d. of the tubes for the purpose of being able to machine the o.d. to a tight tolerance to give the tubes added reinforcement and to better match thermal coefficient of expansion between the tubes and the fittings.

The stabilizer ring is made up of eight 2024-T3 tubular struts with 7075-T73 adhesively bonded end fittings which in turn are attached to the truss support tubes through a bolted joint to the Ti 6Al 4V titanium fittings.

The struts are square 2024-T3 aluminum tubes with 7075-T73 adhesively bonded end fittings which in turn attach to the truss support tubes through adjustable Ti 6Al 4V titanium fittings.

The tubular truss members were designed to meet material compressive strength and Euler buckling requirements. The corresponding safety factors are approximately 3.4 and 1.1, respectively.

As can be seen from the above simple structures, with fiber composites we have strength, stiffness, light weight, and thermal dimensional stability. In addition, suitable end fittings for load transfer and component interconnection can be designed.

CONCLUDING REMARKS

1. The methodology for structural and stress analysis of large and complex structures, and structural components made from conventional and fiber-composite materials is available.

2. Considerable design data for fiber composites has been compiled.

3. The technology for the fabrication of structural shapes, complex parts, panels, and modules from fiber composite materials has been developed.

4. Various ingenious means of building and erecting structures and structural modules from fiber composites are possible.

5. Solutions to difficult problems of fire resistance, building codes and human factors associated with fiber composites are in the process of being worked out.

6. The time has come for the designers of residential, commercial, industrial, and other structures to become more imaginative and inovative in conceiving structural configurations, which will provide convenience, comfort and beauty, while conserving natural resources.

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TABLE 1

Computer Codes - General Purpose

Code Name	Source
ANSYS	Westinghouse Tele Computer
ASKA	University of Stuttgart, Germany
ELAS, SAMIS	Jet Propulsion Laboratory COSMIC-University of Georgia
ICES, STRESS, STRUDL	MIT and other time sharing Computer Systems
MAGIC	Bell Aerospace, AFFDL-Wright Patterson AFB
NASTRAN	COSMIC-University of Georgia

Computer Codes - Special Purpose

SPNOZ/CYLNOZ	Franklyn Institute
STRU-PAK	CDC
FMA	COSMIC-University of Georgia

TABLE 2

Current NASTRAN Capabilities

Static Analysis
- Basic static analysis
- Static analysis with inertial relief
- Static analysis with differential stiffness
- Nonlinear geometry and material

Buckling

Dynamic Analysis
- Normal mode
- Transient response
- Frequency and random response
- Complex eigenvalue analysis

TABLE 3

ATS Truss Material Properties, Average Stiffness Values (26)

Parameter	-256^{o} F	77^{o} F	200^{o} F
Longitudinal Modulus (psi$\times 10^{6}$)			
Tension	25.3	26.2	25.8
Compression	25.6	23.3	22.8
Transverse Modulus (psi$\times 10^{6}$)			
Tension	1.2	0.95	1.0
Compression	2.5	1.80	1.5
Major Poisson's ratio	0.30	0.28	0.35
Shear Modulus (psi$\times 10^{6}$)	1.63	0.657	0.369

Average Strengths

Parameter	-256^{o} F	77^{o} F	200^{o} F
Tensile Strength (psi$\times 10^{3}$)			
Longitudinal	>82.2	132.7	113.20
Transverse	5.69	6.30	5.60
Compressive Strength (psi$\times 10^{3}$)			
Longitudinal	111.9	96.7	92.7
Transverse	35.8	31.3	20.6
Interlaminar Shear (psi)	11,019	10,430	7,864

Thermal Coefficients of Expansion	-320^{o} to 125^{o} F
Longitudinal in./in./^{o}F	-0.22×10^{-6}
Transverse in./in./^{o}F	16.8×10^{-6}

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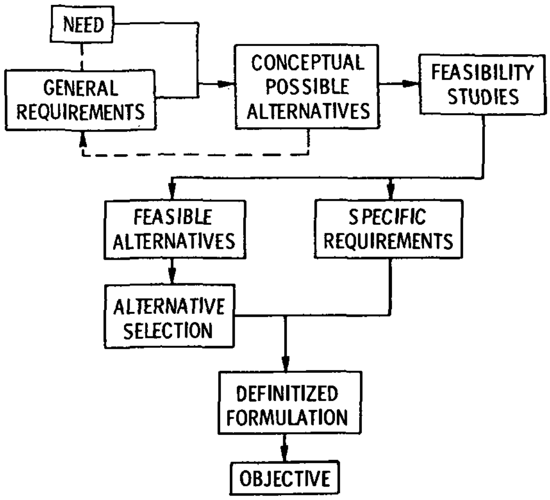
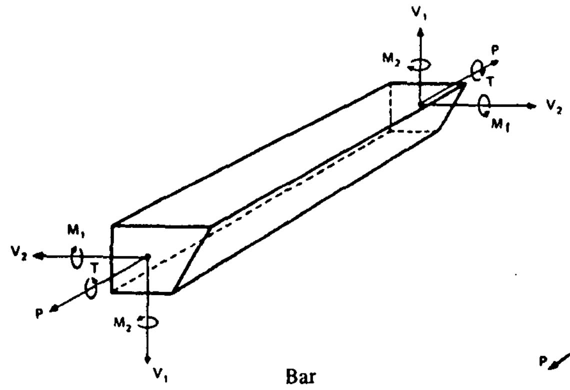
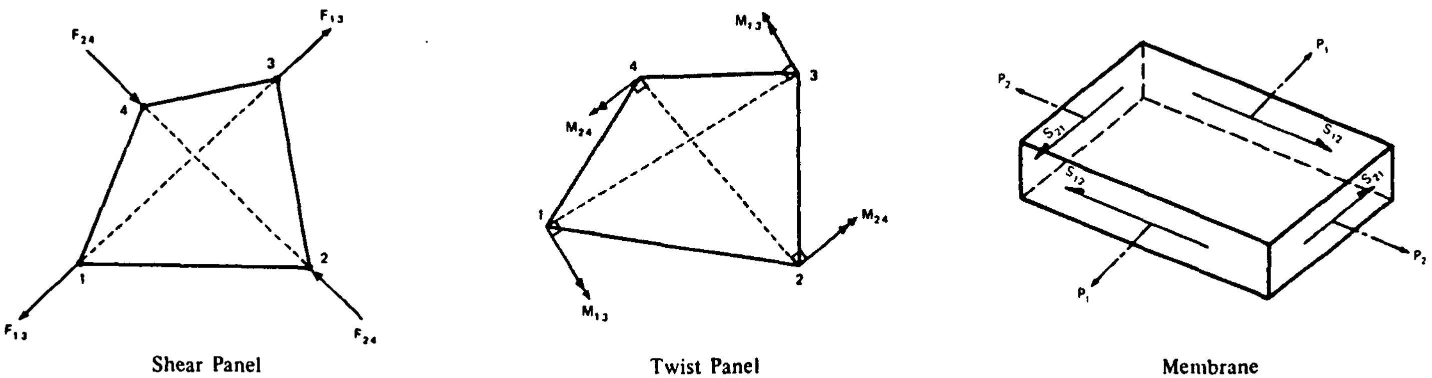


Figure 1. - Mission or system design schematic.

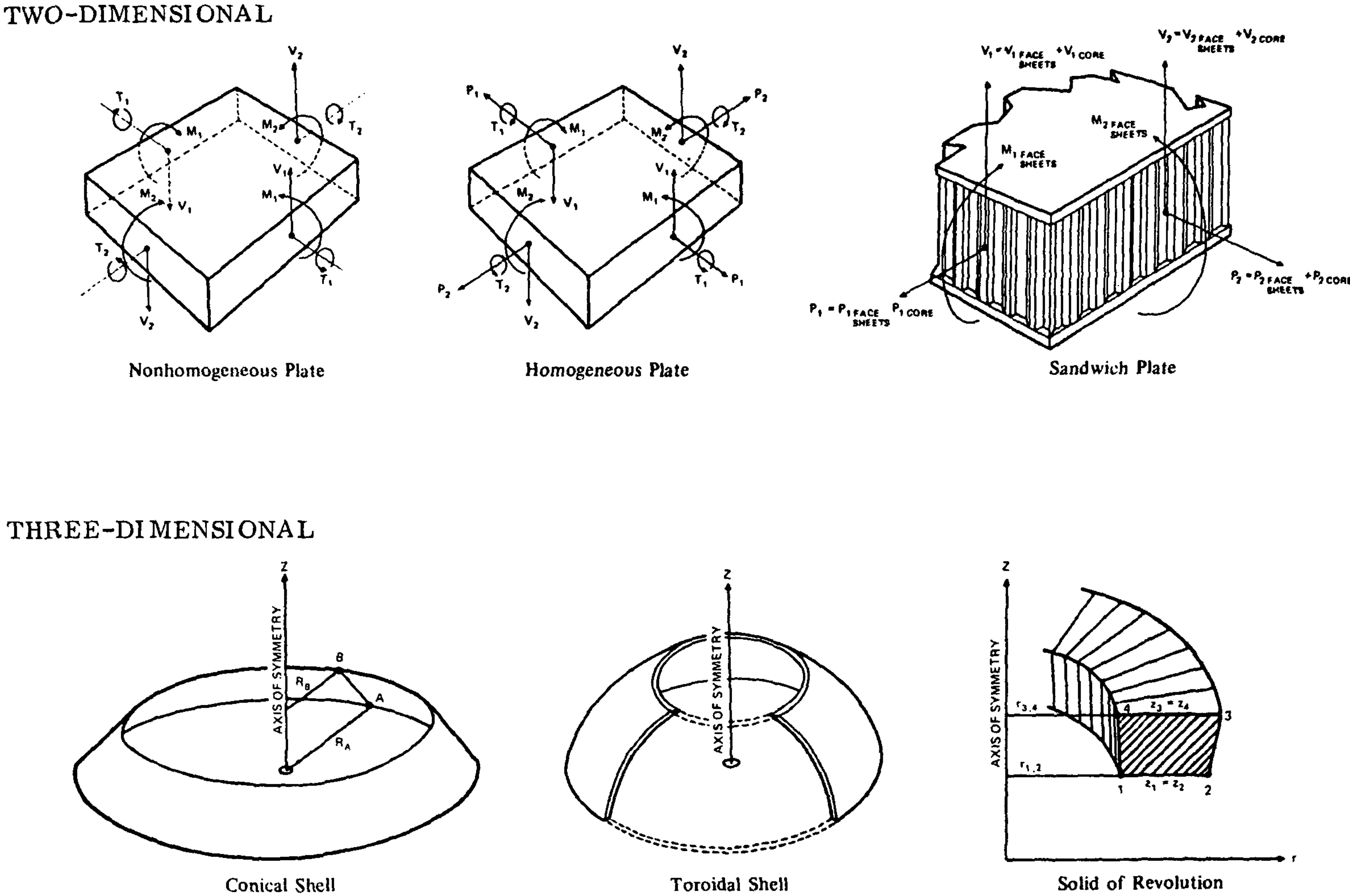
ONE-DIMENSIONAL



TWO-DIMENSIONAL



(a)



(b)

Figure 2. - NASTRAN elements (8).

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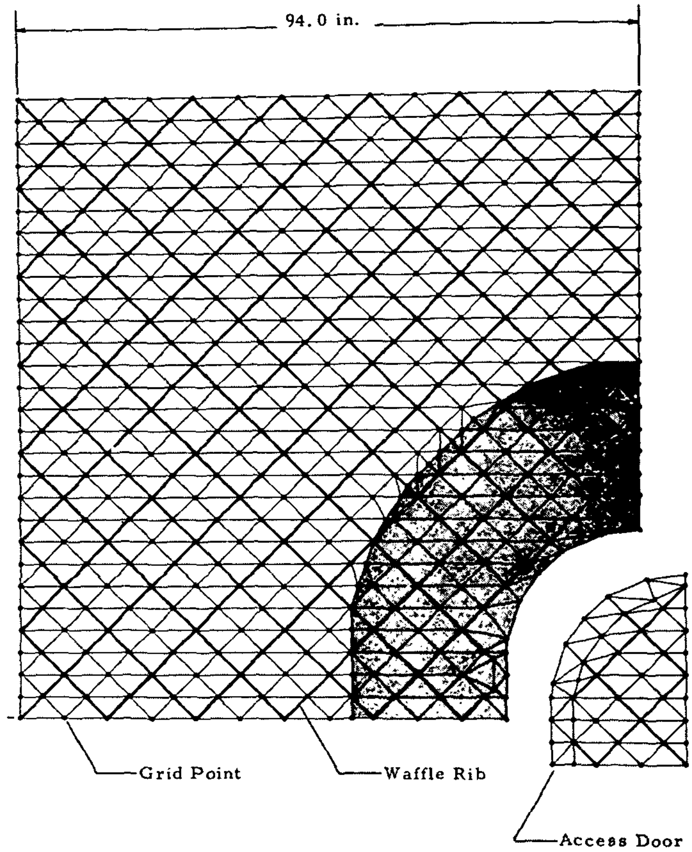

Figure 3. - Skylab workshop access door model.

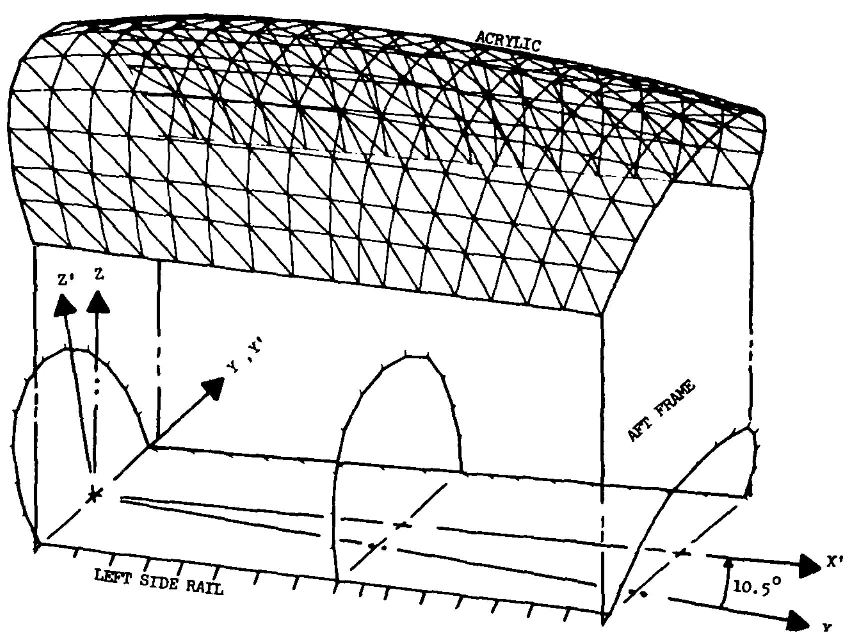

Figure 4. - Exploded 3 dimensional view of the canopy model.

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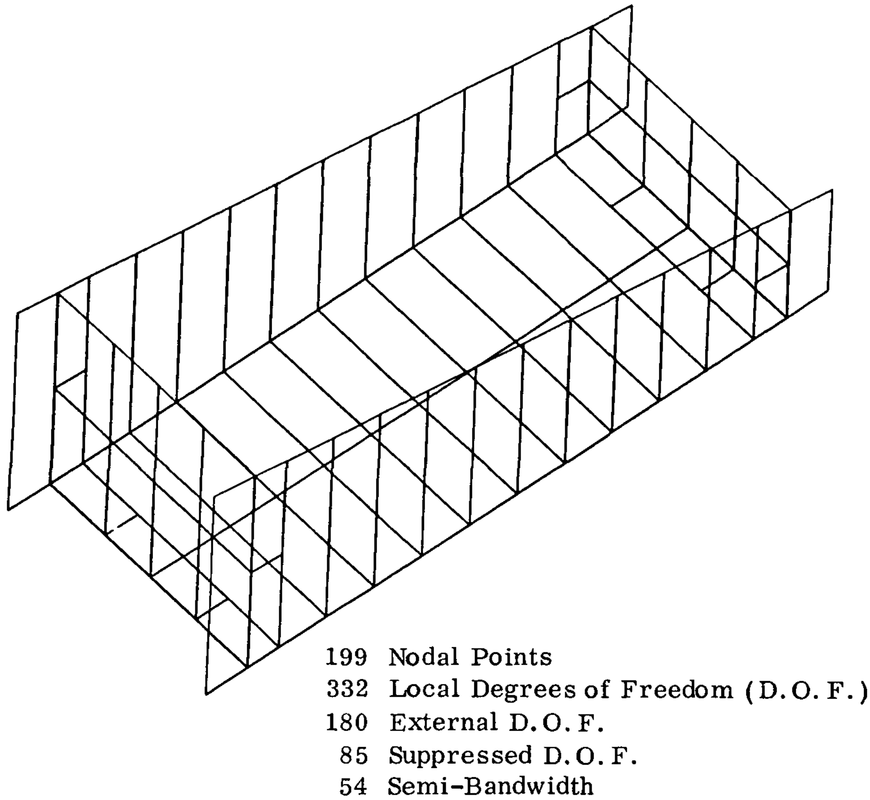

Figure 5. - Characteristics of box type substructure.

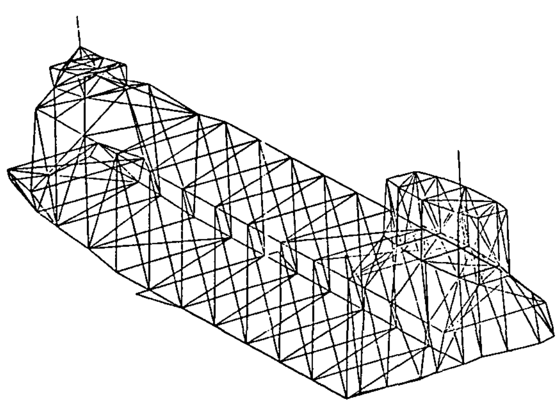

Figure 6. - Vertol helicopter fuselage.

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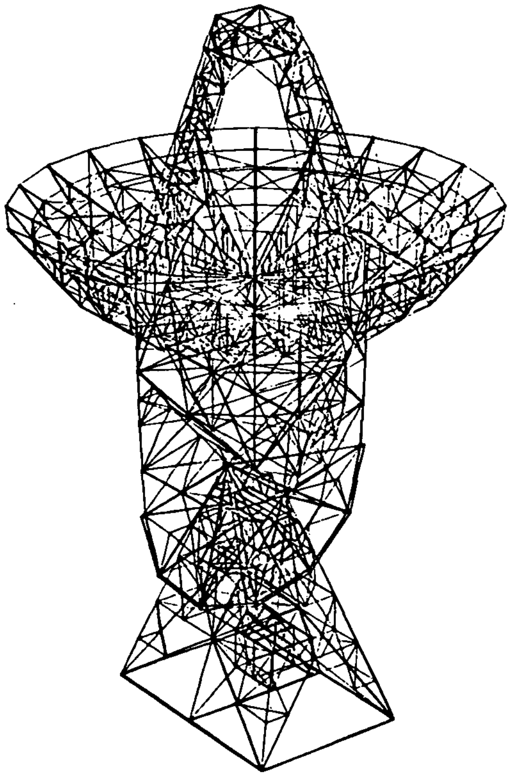

Figure 7. - Stereoscopic view of Rosman antenna.

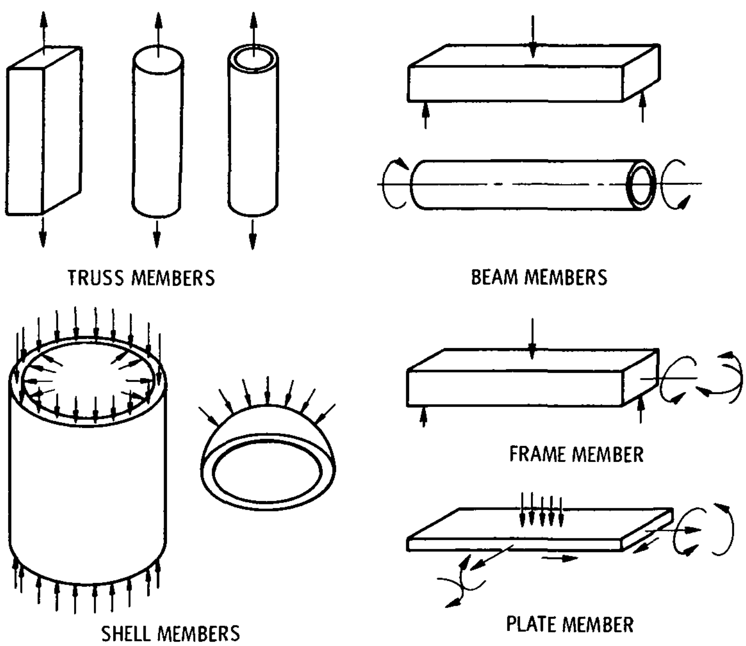

Figure 8. - Typical structural components.

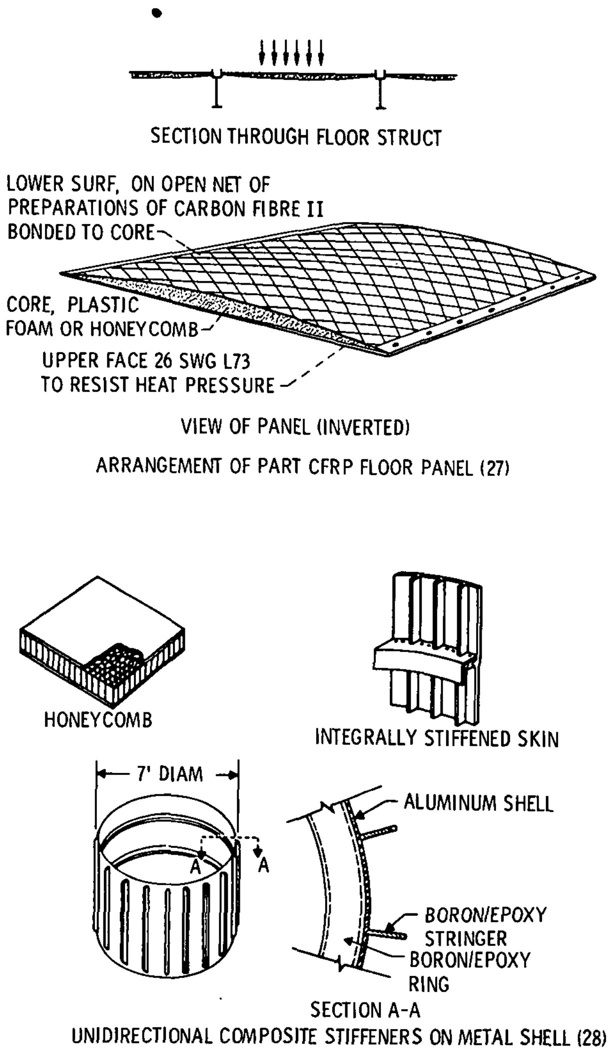

Figure 9. - Structural wall configurations.

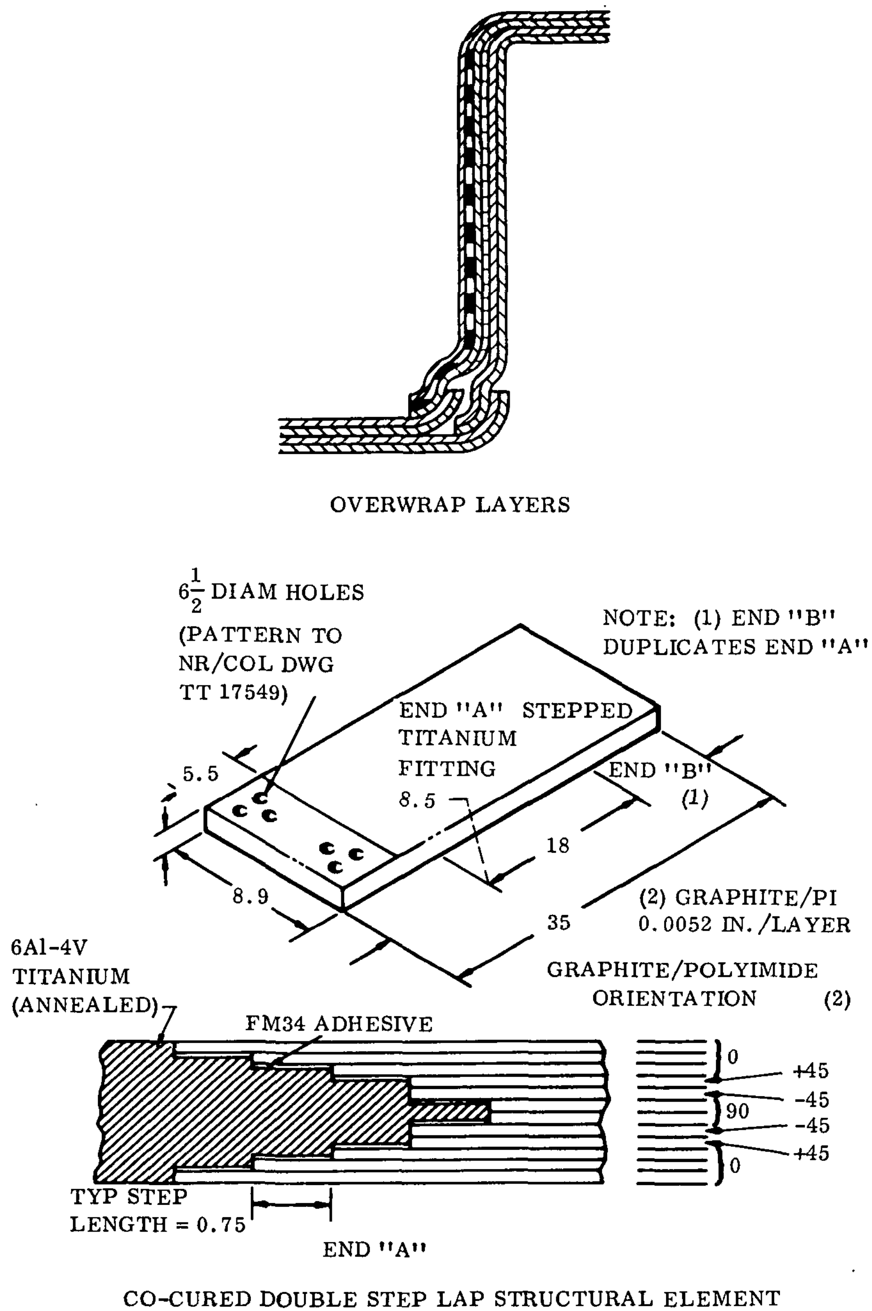

Figure 10. - Joints (29).

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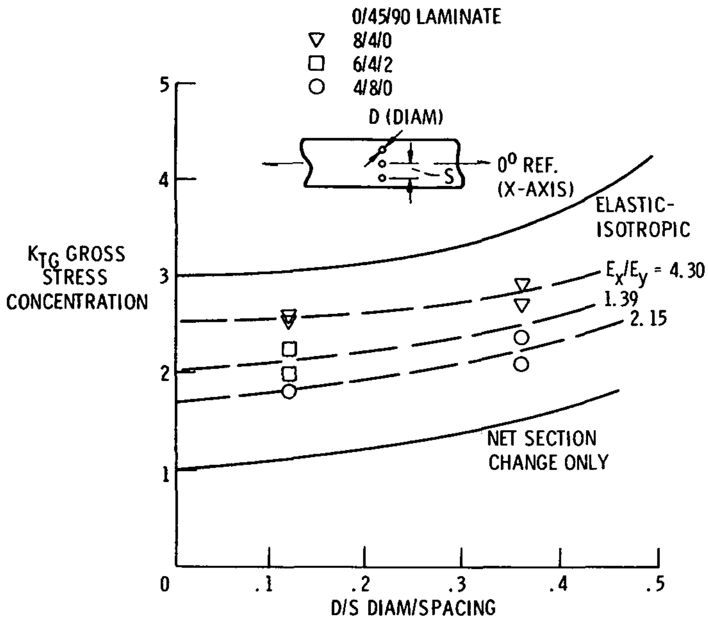

Figure 11. - Effect of holes in graphite composite (15).

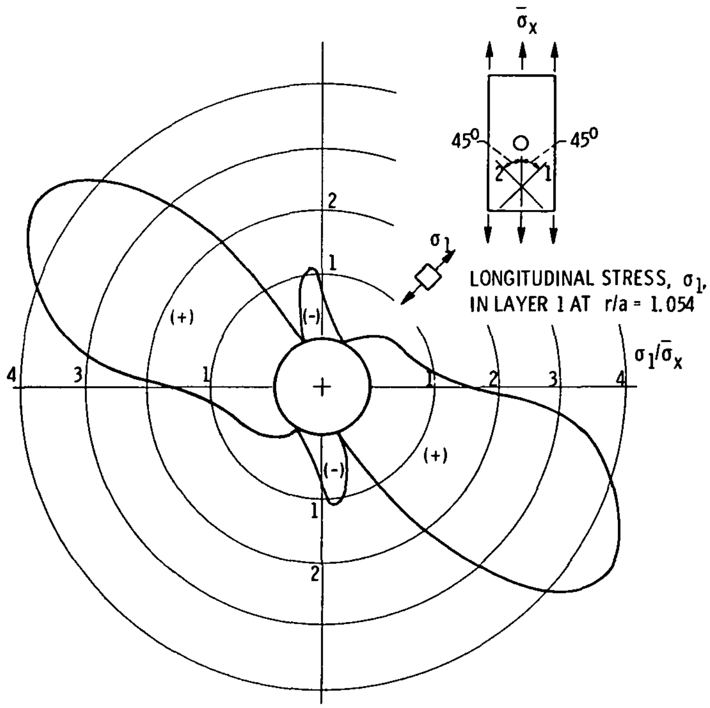

Figure 12. - Longitudinal membrane stress in layer near hole, $[45/-45]_S$ boron-epoxy laminate (18).

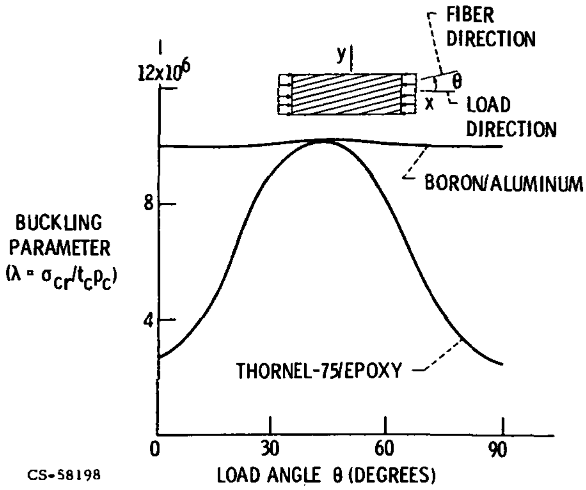

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Figure 13. - Specific buckling stress of two fiber composites plates - simply-supported four edges. FVR = 0.5. (a/b) = 2. (30).

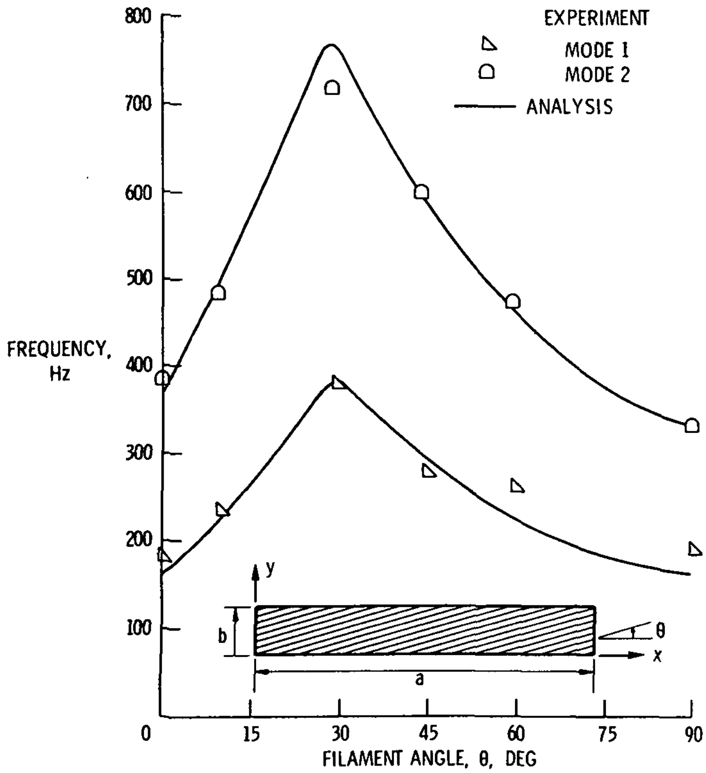


Figure 14. - Free variation with filament angle of natural frequencies of first and second plate-type modes (a/b = 7) (34).

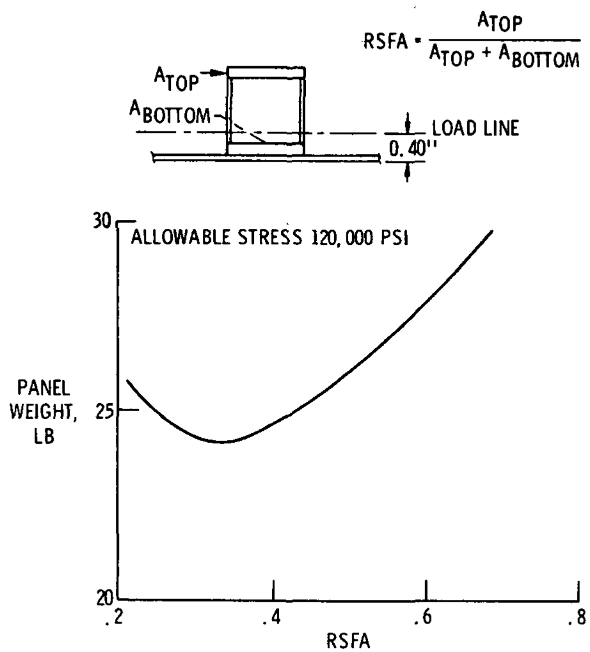
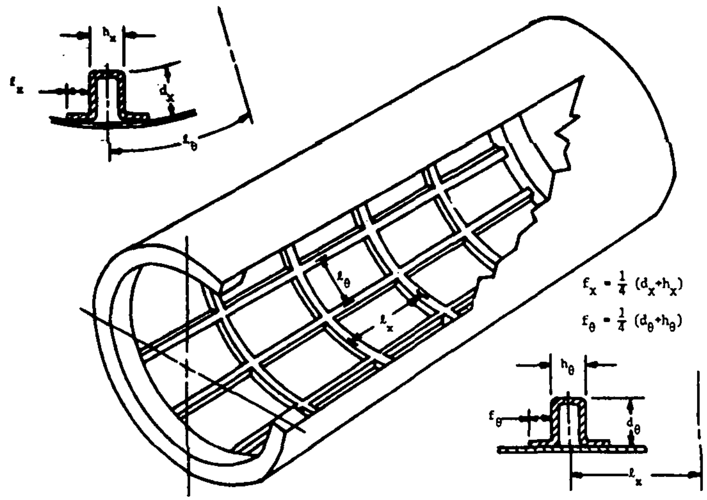
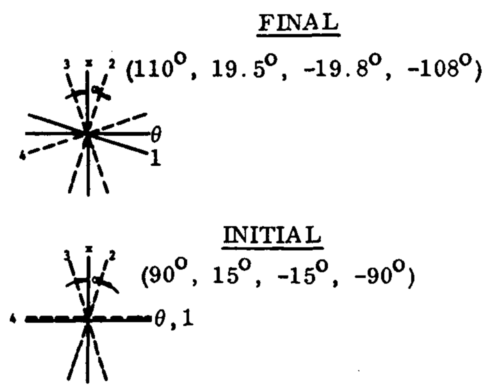


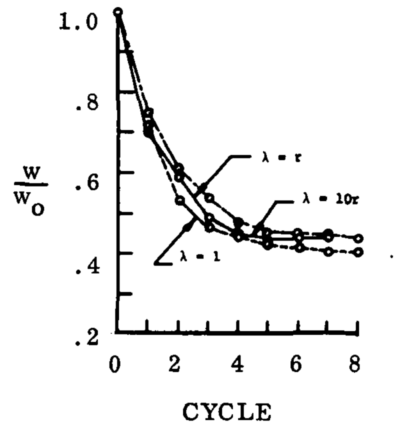
Figure 15. - Stringer flange area proportion versus panel weight high-modulus graphite-fiber/epoxy composite (32).



(a)



(b) INITIAL AND FINAL PLY ORIENTATIONS IN SKIN, 4-PLY SKIN SHELL UNDER AXIAL COMPRESSION.



(c) WEIGHT REDUCTION AT EACH CYCLE FOR VARIOUS λ VALUES, 2-PLY SKIN AXIAL COMPRESSION.

Figure 16. - Optimized design variables for an integrally stiffened cylinder with hat cross-section stiffeners (20).

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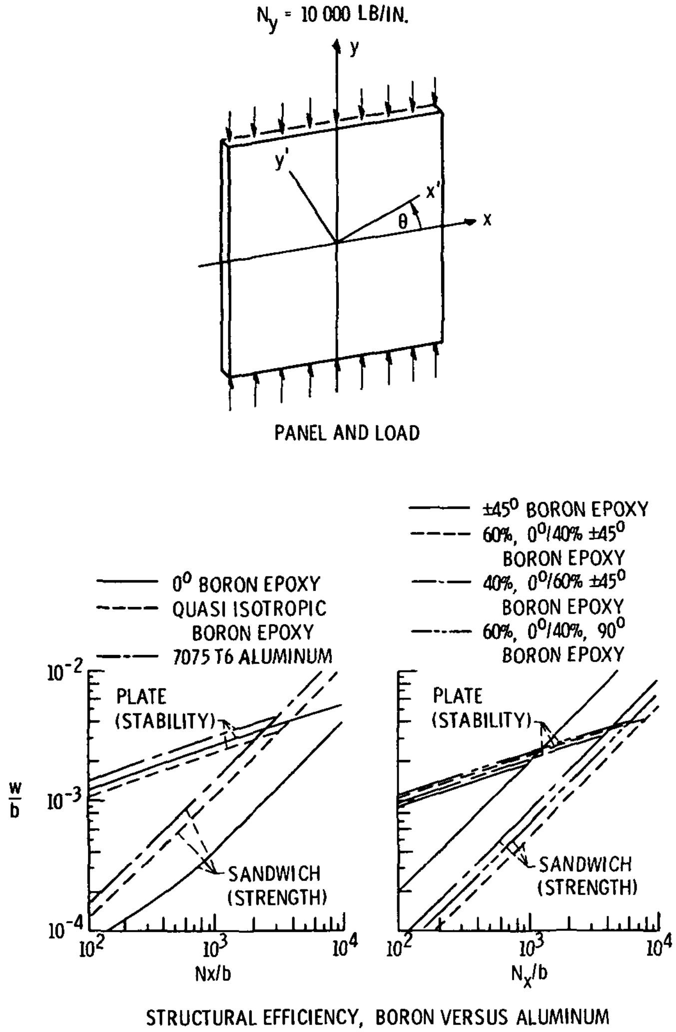

Figure 17. - Optimum design of boron/epoxy panel (21).

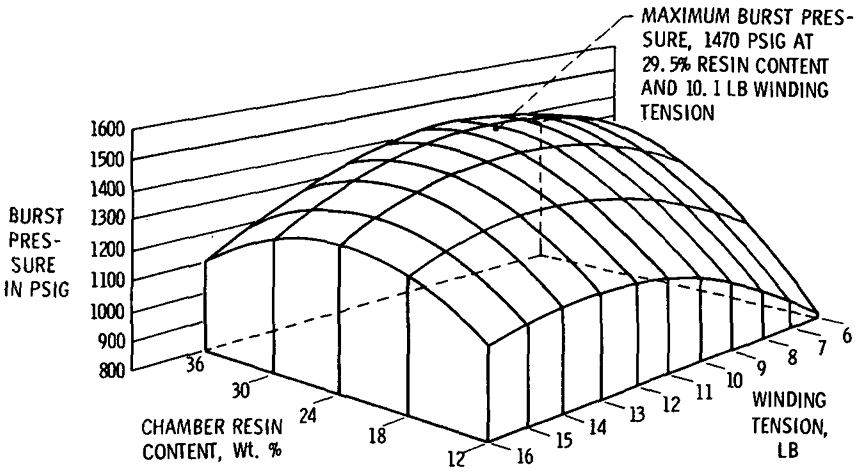

Figure 18. - Optimization of burst pressure of internally pressurized pressure vessel w/R to material and processing variables (25).

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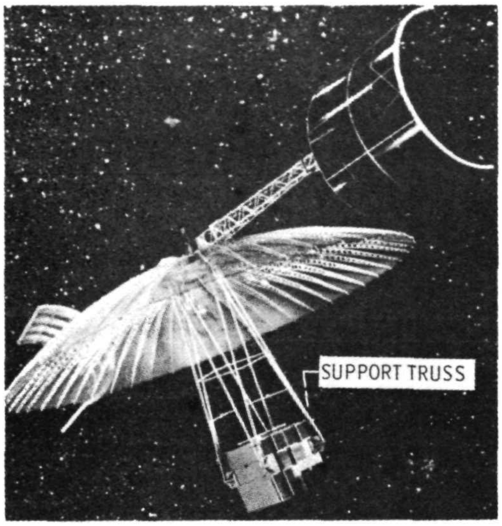
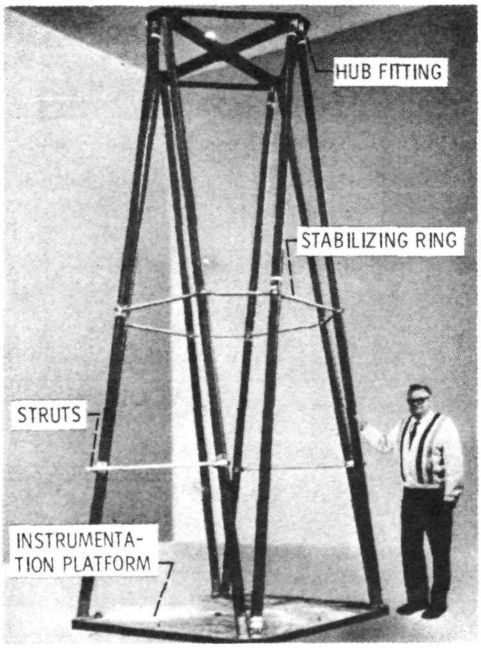


(A) NASA ATS COMMUNICATIONS SATELLITE.



(B) GRAPHITE COMPOSITE SUPPORT TRUSS.

Figure 19. - 3-D satellite support truss (26).