COMPOSITE MATERIAL TECHNOLOGY 1990

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FOREWORD

Composite materials are often termed the material of the future. Regardless of whether the composite is fiberglass, boron–epoxy laminate, metal matrix tape or reinforced ceramic, design options exist that have no precedent in conventional ferrous and nonferrous material technology. By judiciously choosing the composite fiber or skewing the individual lamina of a laminated structure, a material can be designed to resist a given loading without altering the geometry of dimensions of the structure. This is in contrast to the historic alternatives of altering the structural dimensions, attaching grids or machining ribs.

The needs of the aerospace industry led to the development and acceptance of composite materials. Low weight, high strength and great rigidity were of paramount interest to military aviation. These same qualities are also in demand in many non-military applications. As a consequence, composites are becoming more pervasive in industries which hitherto have depended on steel and aluminum for their basic structural needs.

No blessing is without its problems. So it is with composite materials. Directional strength properties are not always completely understood or appreciated. Thus mis-designs or incorrect analyses have and will continue to occur because of ignorance of the basics of material anisotropy. Failure mechanisms are more complex and, in fact, delamination of laminated composites is not only of primary concern but also without counterpart in conventional type structures. Generally accepted theories of failure such as have been developed for ferrous and nonferrous materials are nonexistent for composite materials. This is especially true for fatigue. The difficulties of mass production and of joining composite components to other parts of a structure create a special class of problems which often are included under a general heading of "Composite Manufacturing Technology" and whose solutions are critical to the general acceptance of composite materials as an economically feasible alternative to conventional materials.

The problems associated with composite materials which have been discussed in the preceding paragraph are by no means inclusive. However, the advantages and promise of composite materials are so great that obstacles to their general use are being overcome by unprecedented efforts in research and development in industry, the universities and government laboratories. The results of these activities are being communicated to the technical community by publications, conferences and symposia.

The composite material symposium at the Energy-Sources Technology Conference and Exhibition (ETCE) is sponsored by the Petroleum Division of The American Society of Mechanical Engineers (ASME). It is a statement of the importance of this material to the petroleum and energy-related industries. To further emphasize this importance, the ASME transactions journal, *Journal of Energy Resources Technology* (JERT), also has a policy of encouraging and accepting papers in composite technology. Ideally, the papers and presentations in the journal and symposium should be directly applicable to the needs of the petroleum and energy industries. Certainly such papers are eagerly sought. However, because of the existence of important fundamental problems with composite material technology, it is not always possible, feasible or desirable to deny presentration of basic research results in a forum that is focused to a particular application. Thus the present symposium as well as JERT will present and publish results that could be construed as basic science or mechanics. Ultimately, the objective of both the symposium and the journal is to provide an array of information, both basic and applied, to the petroleum and energy-related engineering communities that will allow the utilization of composite materials to their maximum advantage without jeopardizing the safety of the structure.

The present symposium volume contains four main sections, namely: Design; Failure, Strength and Buckling Analysis; Material Properties; and Micro and Macro Mechanics. Each of the sections is equally important, though an individual reader may show preference of one over others. What is important is that the volume contains a wide spectrum of papers, providing information to the designer, user and researcher on the properties and use of composite materials.

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ABSTRACT

Utilizing a detailed examination of the numerous design decisions in the design of a complex composite aircraft part, it is shown that the dependence of the design process on manufacturing issues is uniquely strong in the design of composite parts and assemblies. Although this dependence is true for design in general, it is amplified by the high degree of coupling between functional and production requirements which characterize the utilization of composite materials. The findings presented in this paper point to a methodology for designing with composites. Furthermore, a model for study of other design activity is suggested by the useful insights developed by this approach.

INTRODUCTION

In this paper, we present a model of the design process that captures the complex relationships between the variables that describe the product and those that characterize production techniques in the design of products using fiber-reinforced composite materials. Jansson [1] describes the design process as an interaction between concept development and configurational formulation. His methodology suggests transforming the problem into its simplest and most fundamental form. He then presents a model in which the design process is an iterative process between two spaces - concept space and configuration space. New ideas and concepts are created within the former while they take form into a physical configuration in the latter. Physical configuration here does not merely represent shape but rather denotes the conversion of a concept into a physical solution. We will discuss the relationships between design and manufacturing variables, in this context primarily configurational in nature, in design with fiber-reinforced composite materials. At this level of representation, conceptual variables are primarily treated as external inputs to the process.

The study is based on a project involving conceptual re-design of the F-16 horizontal stabilizer [2]. Subsequent to completion of the project, we reviewed the decision-making process that led us to the final design. In doing so, we made some interesting observations that suggest a methodology for designing with composite materials. We will first describe the model in detail, discuss our observations, and then illustrate the model through examples.

RELEVANT LITERATURE

Despite a thorough search of the literature, we have not been able to find any papers that deal with design methodology specifically for composite materials. Many researchers have recognized the need to consider product and process design concurrently. Jakobsen [3] discusses a design procedure for integrating shape, material, and production method in making a product that fulfills functional requirements. The procedure involves a sequential and iterative investigation of function, shape, material, and production method. A set of six possible sequences are suggested, all starting with functional requirements. No recommendations are made regarding the suitability of any particular sequence for a given design problem. Krolewski and Gutowski [4] discuss the effect of automation of the fabrication process on part costs for composite materials. They state that many of the current methods of advanced composite automation, with the exceptions of pultrusion and filament winding, may not be cost-effective. They argue that composite parts must be designed for manufacturability and that new flexible processes must be developed to manufacture them.

IDENTIFICATION OF VARIABLES AFFECTING DESIGN REQUIREMENTS

In order to develop the model, we start by examining the functional and production requirements in the design of parts using composite materials. Composite materials become a viable alternative mainly in products that require low weight and high structural performance. The primary functional requirements are therefore comprised of desired strengths and stiffnesses. The main production requirements on the other hand, consist of desired production rate, repeatability, and tolerance. Some of these terms may need clarification. Production rate may be specified as the number of parts required per unit time or as the time required to produce one part. There is a subtle difference between the two specifications; the former depends on the ability to run parallel processes that produce the same part (e.g. use two filament winding machines since one cannot achieve the required part production time) whereas the latter is a function of the design, material, and process variables only. Repeatability refers to the ability to maintain consistent quality from part to part.

Satisfaction of the functional and production requirements depends on our choice of material, process, and design configuration. Table 1 lists the major variables that characterize this choice. The functional requirements are met by a suitable selection of material composition, material form, fiber orientation, and physical configuration. Satisfaction of the production requirements is dependent on the proper choice of fiber orientation, physical configuration, material form, and manufacturing process. An explanation of these terms follows.

In order to take advantage of the superior structural properties of the fiber, it is important to process the composite material such that the fibers are oriented optimally with respect to the loading directions. Fiber orientation is thus a key variable that affects both functional and production requirements. Material composition refers to the fiber type, matrix type, and fiber-matrix interface. The material may be available in various forms such as woven comingled fabric which may be used for thermoforming or as individual tows for filament winding. Thus, material form limits the structure of the material that is used in the manufacturing process. From this, one may also infer the fiber length, which has an impact on the mechanical properties of the material. Physical configuration here is more narrowly defined to be the variable that represents geometrical features of the design. We include both overall shape (such as a tapered I beam) as well as specific details (such as an angle at the flange) in our definition of physical configuration. The parameters of the manufacturing process (such as rate of winding for a filament winding operation) are represented by the variable listed as 'Manufacturing Process' in Table 1. Both fabrication of individual parts and subsequent assembly of the parts are included in our definition of the manufacturing process.

MODEL DEVELOPMENT

Let us now examine how the model in Figure 1 can be developed. First, we list all the requirements in the top row. In this case, we have chosen to specify structural performance as the main functional requirement. Also, we specify production rate and repeatability as the dominant production requirements. Since we have not specified any details for these requirements, the description at this stage is universal. However, the final design must satisfy these requirements and therefore they cannot be compromised. The requirements may be specified in terms of a single value or a range of acceptable values.

We also specify two additional requirements - geometry and cost. If the composite part has to be assembled to other parts in the structure, some other issues need to be considered. For instance, the part has to fit within the geometrical envelope specified by the adjoining components and must satisfy assembly constraints. These requirements are recognized in Figure 1 under the heading 'geometry'. In addition to satisfying the constraints outlined above, we also try to optimize various 'costs' in the design. Cost here refers to any objective function that we may wish to minimize. Thus, weight and dollars are two different types of cost.

Next, we list all the variables that characterize the design at any stage of the design process. This list is depicted as the last row of variables in Figure 1 and consists of a specification of the design configuration, the material, and the manufacturing process.

In order to discuss the unique placement of the 'fiber orientation' variable in Figure 1, we must refer again to Table 1. In this table, three of the variables listed under production requirements also influence the functional characteristics of the design. We will denote this subset as 'Coupling Variables'. In the case of metals, the coupling is mainly through the physical configuration since they involve a less complex set of material options and a fairly well understood set of processing techniques. The degree of coupling is higher for composite materials because of a greater number of Coupling Variables. We note that fiber orientation is the only Coupling Variable that is not specified as part of the design output (last row of variables in Figure 1). We therefore include it in Figure 1 as a separate variable.

We now move on to the development of constraining relationships between the different variables, also referred to as nodes. These relationships are depicted by the arrows from node to node. While recognizing the fact that each of the variables perhaps constrains all the others (i.e. there should be a bi-directional arrow between every node), we select those relationships that appear to dominate the design process and represent the flow of constraint information which ultimately leads to the final design. Dominant relationships are those that form the focus of the decision process at any given stage. Identification of such relationships is important in order to handle the complexity caused by the coupling. Consider for instance the selection of the fiber orientation. The desired load-carrying capability has a major impact on the selection whereas production rate has little impact on the decision at this stage. Therefore, the relationship between the load and the fiber orientation is a dominant relationship while the relationship with production rate is secondary or weak.

Design in general constitutes a sequence of divergent ideas and constraint-driven convergence to solutions. For instance, the structural requirements and the capabilities of the manufacturing process constrain the range of acceptable fiber orientations. In such cases, a material with better structural properties (e.g. graphite fibers instead of glass fibers) would offer the same structural performance while allowing a wider range of fiber angles. The relaxation of the fiber orientation constraint may in turn allow consideration of other configurations and manufacturing processes. In Figure 1, the only relationship that relaxes a constraint is that between material choice and fiber orientation. Not depicted here are the many divergent processes by which new ideas are injected into our model.

OBSERVATIONS

We believe that all critical constraint relationships have been captured in Figure 1. We now list some observations that emerge from the diagram. These observations are significant in the development of some generalized guidelines for design with composite materials. Firstly, note that the only arrow leaving the physical configuration node leads to the processing node. This implies that any change to the physical configuration of the product must be followed by an investigation to check if producibility has been affected. Secondly, the physical configuration and the processing nodes are extremely busy, thereby emphasizing the need to address both aspects simultaneously and early in the design process. Finally, we observe that fiber orientation plays a major role in design with composites as it directly affects both the satisfaction of the functional requirements as well as the producibility of the part.

The importance of considering processing issues early in the design of the part cannot be emphasized enough. Although this statement is true for design in general, it is especially relevant to design with composite materials because of the high degree of coupling illustrated by the number of Coupling Variables. Further, many composite products require custom manufacturing techniques. In other words, the process itself has to be designed. We can think of this as two concurrent design processes, each imposing constraints on the other. Design of the product is therefore dominated by the limitations of the production technique.

EXAMPLE: F-16 Horizontal Stabilizer Design

We shall now proceed to a discussion of the conceptual re-design of the F-16 horizontal stabilizer which was the subject of design exercise from which this paper emerged. Specific design decisions made during the project are used to clarify the model presented above.

The horizontal stabilizer for the F-16 currently consists of two graphite-epoxy skins separated by an aluminum corrugated substructure which tapers along the span in two directions and follows the airfoil contour along the chord (Figure 2). Further details about the current design and a comparison with the earlier honeycomb design are given by Butcher [5]. The substructure is manufactured by a two-step drop hammer process. The substructure is then riveted to the skins. Although the corrugation is structurally a very good design, there are several problems associated with the production process. The material is formed to the limits of the process in order to create the necessary double curvatures (3D curvatures) in the part. Further, the properties of the rolled sheets of aluminum (used in the forming operation) are highly sensitive to the direction of rolling. Thus, the material is effectively non-isotropic for this application, and the sheets have to be lined-up within fairly tight tolerances for the forming process.

A result of these complications is that the post-process elastic springback is difficult to predict. Consequently, the positions of the rib spars (refer to Figure 2) vary with each piece, leading to a variation in the locations of the rivet holes. In such cases, robotic drilling of the rivet holes is replaced by a manual drilling operation. Furthermore, the thickness of the skin is not a constant and varies depending on the number of layers of tape at any point. Therefore, the depth of the rivet hole also varies and each hole has to be manually sized before riveting. Together, the location and sizing of the rivet holes result in a highly labor-intensive assembly process.

The manufacturer was interested in investigating the use of fiber-reinforced composite materials to produce the substructure. Thus, the problem definition for our study was to design a composite substructure that would eliminate many of the problems currently faced with the aluminum piece and to recommend the proper manufacturing process to be employed in the production of the new design.

The main functional requirement is the load-carrying capability of the substructure. The primary forces acting on the horizontal stabilizer are bending loads caused by the lift, which can be up or down, on the stabilizer surfaces. The skins are designed to resist the tensile forces caused by bending. Thus, the main task of the substructure is to transfer the shear between the top and bottom skins. The major concerns that defined our production requirements were the desired production rate and the repeatability of the process (the ability to achieve consistent quality). Finally, the design had to meet specified constraints arising from the geometry of the envelope (airfoil shape and distance between skins). Weight was a major cost factor that we wished to minimize.

The initial problem formulation was to transform the given loading into a specification for preferred fiber orientation. For a pure shear case, the principal stresses act in the +/- 45 directions. The maximum strength of fiber reinforced composites is along the direction of the fiber. Therefore, the desired fiber orientation is +/- 45 degrees with respect to the vertical. This step marked our first design decision and is illustrated by the arrow from structural requirement to the fiber orientation in Figure 1.

The existing substructure is an aluminum corrugation which tapers in along the span in two directions and follows the airfoil contour along the chord. We generated a list of possible manufacturing techniques to produce a composite corrugated substructure based on the constraints imposed by the physical configuration and the desired fiber orientation. From a rudimentary analysis, the complications faced in the manufacturing a composite corrugated substructure forced us to consider more automatable manufacturing processes. This now became our dominant constraint. Filament winding is one of the few highly automated processes which allow some control over placement of fibers in order to obtain desired fiber angles. Therefore, we decided to investigate the application of filament winding to produce a more manufacturable configuration. Long, tapered boxes with quasi-rectangular cross-sections follow as the obvious choice (Figure 3).

A more detailed analysis showed that due to the taper, the fiber orientation across the boxes would vary along the span. As a result, we had to compromise our earlier restriction on fiber orientation. There is a second effect that arises due to the taper. After the winding process is completed, the cross-sectional area of the material already wound must remain constant over the length of the mandrel (Figure 4). Therefore, as the effective diameter (or circumference of the mandrel) reduces, the total thickness of the layers must increase in order to lay the same amount of material. The circumference of our box-shaped mandrel decreases toward the tip of the stabilizer. The resultant increase in thickness at the tip violated one of the geometric constraints (distance between skins at the tip). Since the geometric constraint was specified in the problem statement, it could not be compromised. We therefore had to re-evaluate our manufacturing options.

Since fiber orientation was difficult to achieve through filament winding, we decided to select a material form that already had the fibers oriented in particular directions. The chosen material form was a number of layers of woven fabric with most of the layers oriented to give +/- 45 degree fiber angles. Therefore, we now had to find a physical configuration that would yield the desired fiber orientations along the vertical planes. Notice that material form is now constraining the possible physical configurations.

If we drape the woven cloth around a box-shaped mandrel, the optimal fiber orientation is only achieved on one of the vertical sides. Also, from a shear strength consideration, the top and bottom of the box provide little support. However, they contribute significantly to the weight of the structure. The strength-to-weight criterion now prompted us to select a configuration that would reduce the amount of material being placed on the top and bottom. Since the horizontal part of the substructure is not a shear-carrying member, the theoretical minimum suggests purely vertical sections. When we considered the processing of such sections, it became evident that assembly of the fabricated sections to the skin might only require a horizontal flange. Thus, the process constrained our configuration to one that resembles C-sections.

We still had to decide the production technique, and this again led us back to processing. Since the chosen configuration, material, and material form satisfied the structural and geometric constraints, the dominant criteria for selection at this stage were repeatability and production rate. After generating several alternative means of producing C-sections and evaluating them based on all cost and global criteria, we selected thermoforming as a suitable process.

CONCLUSIONS

It is our belief that Figure 1 represents the design process with composite materials in general. Several aspects of this model are noteworthy. The main motivation for using composite materials is the high strength-to-weight ratio that these materials offer. To take advantage of this property, the fiber should be oriented in the directions of the desired properties. As is evident from our case study, the fiber orientation also plays a major role in determining the set of possible fabrication processes. Therefore, it is a key Coupling Variable for composite product design.

Next, we observe that the only arrow leaving the physical configuration node leads to processing. This is highly significant since it suggests a methodology whereby the designer should always consider the process whenever the configuration is altered. As a result, the design process will always terminate at the processing node. This is because any alteration of a design variable imposes a return to this node in order to ensure that processing limitations have not been violated.

Finally, notice that the processing node is the hub of much of the design activity depicted in the diagram. This implies that processing constraints drive a number of decisions in the design process. The suitability of a process is also highly sensitive to changes in other variables such as physical configuration or desired fiber orientation. The designer should therefore attempt to integrate the configuration, material, and manufacturing process through innovation not only in the design of the product but also in the design of the process. This is in sharp contrast to most conventional design applications where the process is fairly well understood and is therefore selected rather than designed.

As mentioned earlier, it is possible to specify constraint relationships between each of the nodes in Figure 1. Many of these relationships, however, would represent weak interactions. Dominant relationships can be identified easily if the model is kept simple. This simplicity is achieved by neglecting all weak interactions while generating the model. Thus, we are left with the major constraints that drive the design process.

In general, much attention has been focused on the need to pull manufacturing considerations up toward the front end of the design process. Such a need is particularly evident when designing with composite materials. In our study, the manufacturing process was not only an integral aspect of the design but was constantly the driving constraint that dictated the configuration of the product. Although it is less evident when designing with homogeneous, isotropic materials such as metals, here too, manufacturing plays a critical role. Often, poor designs result from consideration of manufacturing issues only after the functional requirements of the design have been satisfied, that is, only after the physical configuration is finalized. Problems downstream usually lead to a set of separate solutions, resulting in a "patched-up" final design. Such problems may be avoided by considering fabrication issues up front in the conceptual design loop.

ACKNOWLEDGEMENTS

We wish to acknowledge the contribution of General Dynamics, Fort Worth in providing the horizontal stabilizer design project to our graduate design class and the generous assistance given by them throughout the semester.

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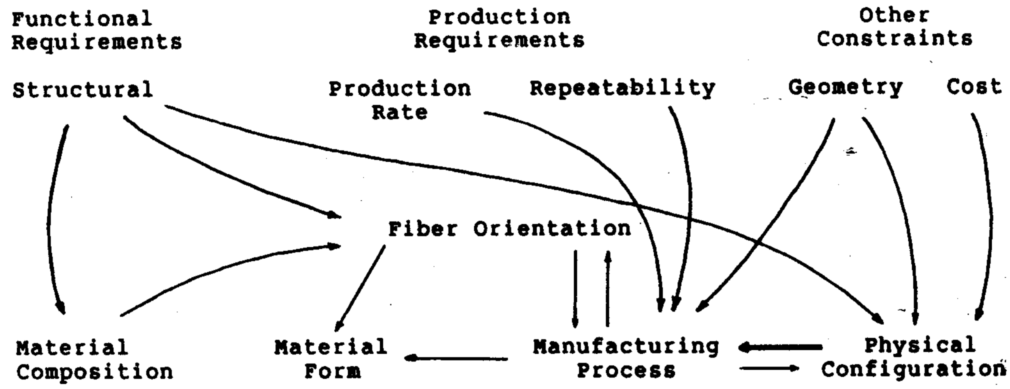

Fig. 1 Design Process Model

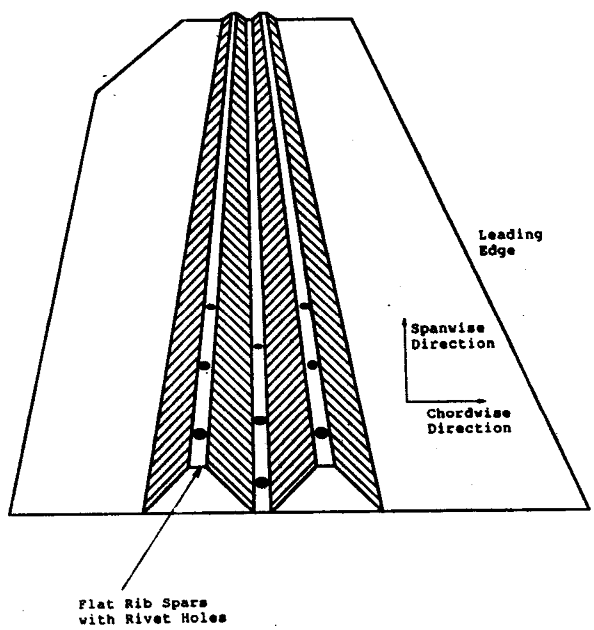

Figure 2. Corrugated Horizontal Stabilizer Substructure

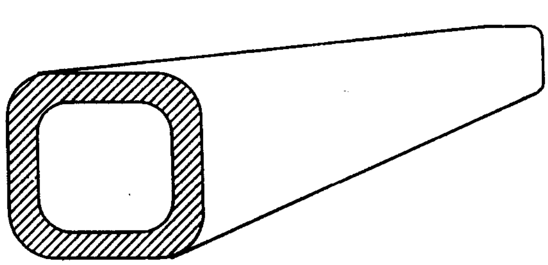

Figure 3. Tapered Quasi-Rectangular Boxes

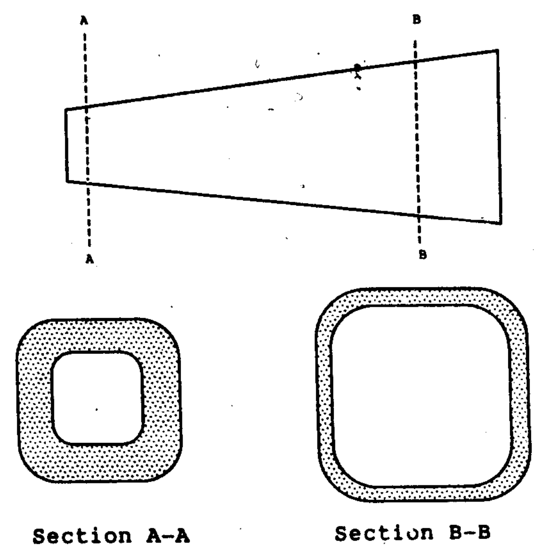

Figure 4. Effect of Taper on Material Thickness

Section A-A Depicts Thickness at Tip
Section B-B Depicts Thickness at Root

TABLES

FUNCTIONAL REQUIREMENTS	PRODUCTION REQUIREMENTS
1. Material Composition	1. Material Form*
2. Material Form *	2. Physical Configuration*
3. Physical Configuration *	3. Fiber Orientation *
4. Fiber Orientation *	4. Manufacturing Process

*Denotes Coupling Variables

TABLE 1: VARIABLES AFFECTING DESIGN REQUIREMENTS

EFFICIENT CUTOUT DESIGNS IN FIBER REINFORCED COMPOSITE STRUCTURES

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ABSTRACT

The ensuing work focuses on the effects of various cutout designs in fiber reinforced composite flat panels. Stress/strain information obtained through the use of a finite element program, PATRAN, with numerical solutions performed in ABAQUS. Variations of cutout shape, and cutout proximity to one another have been evaluated. The square cutout causes the lowest stress concentration. The hexagonal cutout, which removes unstressed fibers around the hole, intensified the stress higher than the square, yet lower than the circular cutout. This phenomena may be only particular to the single load case and material/fiber orientation.

INTRODUCTION

The use of composite materials is increasing throughout the aerospace industry. The demand for superior performance requires that aircraft must eliminate excessive weight. The high unit cost of composite application warrants restraint, especially when the designer does not have an in-depth structural property database.

One area of critical design is cutouts. Typically the cutouts are of circular geometry for isotropic material. By utilizing the smooth curve of the circle, stress flow lines follow a smooth path thus greatly reducing stress concentration factors about the hole. Conversely, anisotropic materials have directional properties, where a fiber reinforced composite will withstand higher tensile loading along the fibers orientation path. The side view of an isotropic material web, would maintain the circular cutout design. However, examine the fiber reinforced composite web with ± 45 fiber layup with an 'isotropic cutout' in Figure 1.

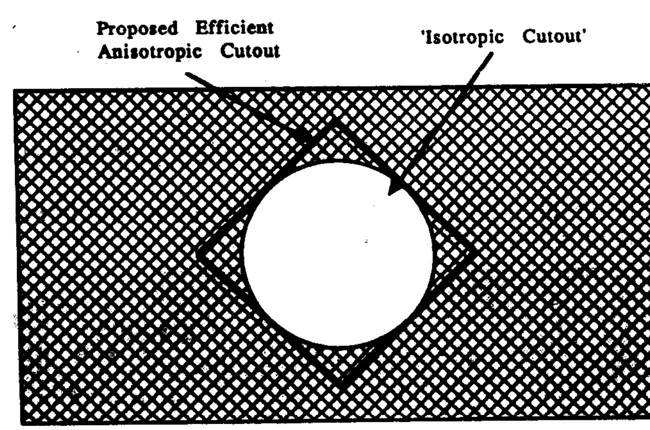


FIGURE 1 - _+/-45 Fiber Reinforced Composite Web

By superimposing a diamond cutout over the circular, it is observed there is no additional fiber breakage, yet the net cutout area is larger. Using this analogy, a more efficient cutout design for composite structures may be achieved, while maintaining structural integrity.

The excess area which is removed with a diamond cutout, contains fiber sections which would be unloaded in a stress field. These unstressed fibers create an effective resin rich area. A resin rich area, in composite structures compounds stress fields, producing high stress concentration factors around the cutout. To reduce the stress concentration, it is necessary to eliminate resin rich areas.

NUMERICAL METHODS

Numerical analysis was performed through the use of two commercial software packages. PATRAN was implemented to generate the finite element mesh, material properties, loading and boundary conditions. ABAQUS was used for post-processing, numerical solving. All solutions have been developed using plate/shell theory, corresponding to S8R5 elements in ABAQUS.

Modeling of test coupons was restricted to one panel received from Hercules. The panel was AS4/3501-6 graphite/epoxy with $[+/-18_5/90_{10}]_s$ layup and the following laminae properties:

$$E_{11} = 20.2 \text{ Msi}$$
$$E_{22} = 1.60 \text{ Msi}$$
$$G_{12} = 0.69 \text{ Msi}$$
$$\nu_{12} = 0.3$$
$$h = 0.0052'' \text{ (cured ply thickness)}$$

The panel was segmented into five equal specimens and modeled as shown in Figures 2 - 5.

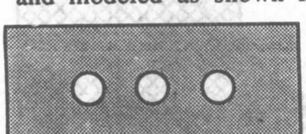
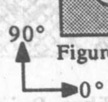


Figure 2 - Circular Cutout



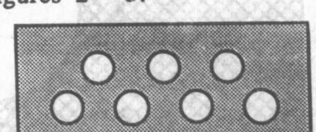


Figure 3 - Staggered Cutout

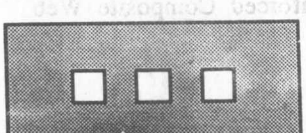


Figure 4 - Square Cutout

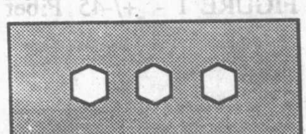


Figure 5 - Hexagonal Cutout

The fifth panel, without any cutouts, is a control specimen. The coupons were each 10.00" x 1.910" size. All of the cutouts were started as 0.5" diameter circular holes, then the excess material was removed to shape the respective cutout geometry. The square cutout maintains 0° and 90° sides with respect to the loading axis. The hexagonal cutout parallels the +/-18° fibers along the top and bottom cut, and 90° along the side cuts.

Because of the symmetry in each coupon, they were not modeled as full test specimens. This also reduces required computer time. With the exception of the stagger hole coupon, all models were made from the upper right quarter of the test specimen. The stagger hole coupon was modeled in the right half since it did not have quarter symmetry. The portion of each panel which was not modeled, is merely a mirror image of the portion modeled. See Figures 6 - 9. All models were loaded in tension using equivalent nodal loading. The deformed shape for the staggered and square cutout coupons are shown in Figures 10, 11.

RESULTS

The results, namely the maximum stress values and corresponding stress concentration factors, are summarized in Table 1. The square cutout causes the lowest stress concentration. The hexagonal cutout, which eliminates unstressed fibers around the hole, provides higher stresses than the square, and yet lower than those of the circular cutout. The staggered cutout arrangement indicates a rise in stress concentration due to the proximity of cutouts.

FINITE ELEMENT RESULTS / CUTOUT GEOMETRY	MAXIMUM STRESS (PSI)	STRESS CONCENTRATION $K = \frac{\text{max. stress}}{\text{applied stress}}$
Circular	12556.	3.5
Staggered	11614.	4.6
Square	9053.	2.5
Hexagonal	11183.	3.1

Table 1 - Numerical Results

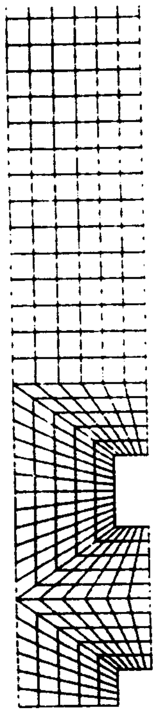


Figure 8 - Square Cutout Finite Element Mesh

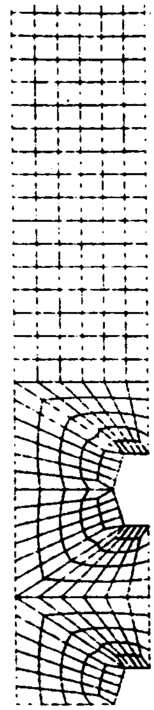


Figure 9 - Hexagonal Cutout Finite Element Mesh

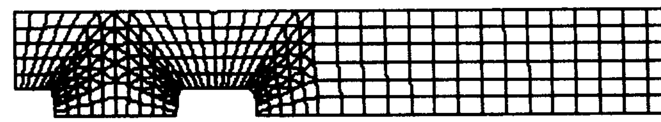


Figure 10 - Square Cutout Deformed Shape

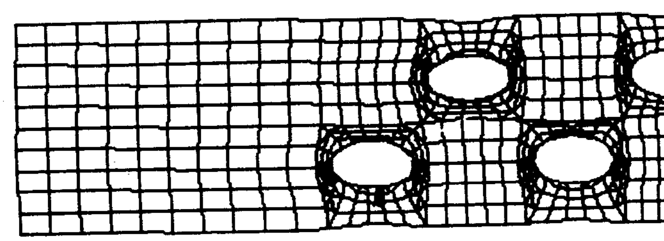


Figure 11 - Staggered Cutout Deformed Shape

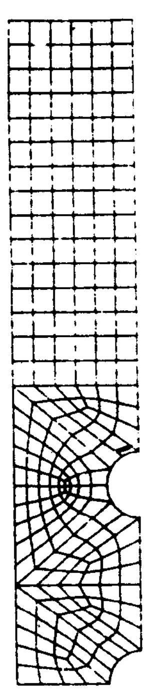


Figure 6 - Circular Cutout Finite Element Mesh

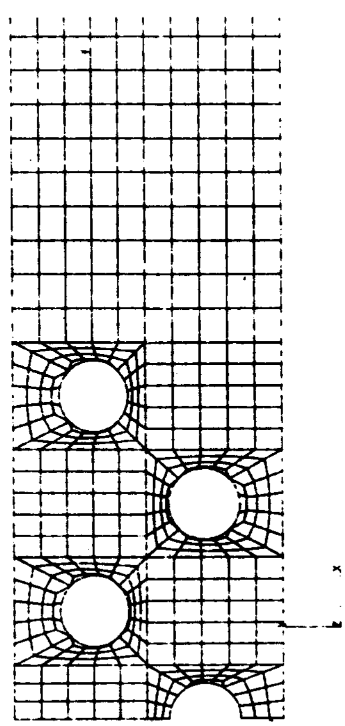


Figure 7 - Staggered Cutout Finite Element Mesh

Clearly, these results only pertain to the tension mode loading. Also, results are only relative to the particular layup and material properties of the graphite/epoxy system. These results are preliminary, and continued modeling and mesh regeneration must be performed. Specimen coupon testing is also necessary and is underway.

REFERENCES

PATRAN: Registered trademark of PDA Engineering, PATRAN Division, Costa Mesa, California, March 1988

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