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# Mechanical and Analytical Screening of Braided Composites for Transport Fuselage Applications

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## INTRODUCTION*

Techniques developed for the textile industry are now being applied to the manufacture of composite structural parts with advanced fibers. Textile technology provides a process for introducing through-the-thickness fiber reinforcement in a single step. Furthermore, structural textile preforms can be formed near to the final shape of the desired composite component. Consequently, there is a great deal of interest in the manufacture, design, and analysis of composites with new fibrous reinforcements. Braided composite materials are one of the advanced material forms which are under investigation in Boeing's Advanced Technology Composite Aircraft Structures (ATCAS) program. The overall objective of this work is to evaluate braided composite technology for applications to a commercial transport fuselage. The ATCAS braided composite studies are being performed at Boeing Helicopters in conjunction with the Fibrous Materials Research Center at Drexel University.

Studies on the effects of process variables and fiber architecture on the mechanical performance of textile composites aid in determining suitable applications. The application to structural components, such as attachment fittings and frames, requires that the material form exhibit sufficient through-the-thickness strength, damage resistance, and the ability to be formed in a near net shape manufacturing process. The fiber architecture of braided composites is known to increase damage resistance and out-of-plane strength, although the precise amount of through-the-thickness fiber reinforcement required to improve these properties, without excessively degrading in-plane properties, is not known.

The first objective of the ATCAS braiding study is to show the feasibility of braiding near net shape structural components. The second objective, which is also manufacturing related, is to show the feasibility of fabricating these near net shape preforms into composite components using both thermoplastic and thermosetting resins. In addition, the critical processing parameters inherent to both processes will be identified and optimized in order to determine the best possible processing conditions. The third objective is to evaluate the structural performance of braided composites through a series of mechanical tests. The fourth objective is to develop an analytical model which accurately predicts the behavior of braided structures. The fifth and final objective is to identify potential structural applications for braided composites.

This paper summarizes the mechanics of materials progress in support of a goal of understanding the application of braided composites in a transport fuselage. Composites consisting of both 2-D and 3-D braid patterns are investigated. Both consolidation of commingled graphite/PEEK and resin transfer molding of graphite/epoxy braided composite processes are also studied. Mechanical tests examine the following composite properties: unnotched tension, open hole tension, compression, compression after impact, in-plane shear, transverse shear, out-of-plane tension, bearing, and crippling. Analytical methods are also developed and applied to predict the stiffnesses and strengths of test specimens. A preliminary study using the test data and analytical results is performed to assess the applicability of braided composites to a commercial transport fuselage.

The four main areas of focus in the ATCAS braiding study to be discussed here are: 1) Design and Formation of 2-D and 3-D Braided Fabrics for Advanced Composites, 2) Manufacturing Braided Composite Parts, 3) Mechanical Testing of Braided Composites, and 4) Analysis of Braided Composite Structures.

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Textile preforming plays an important role in the development of cost effective, high damage tolerant structures. With a broad supply base and a wealth of well-established mechanisms for fiber orientation, pre-shaping and pre-placement of matrices, textile preforming gives composite design engineers an additional degree of freedom in the optimization of structural composites. As shown in Figure 1, there is a large family of fiber architectures created by different preform fabrication techniques.

| | **Basic direction of yarn introduction** | **Basic formation technique** |
|---|---|---|
| Weaving | Two (0°/90°)<br>(warp and fill) | Interlacing (by selective insertion of 90° yarns into 0° yarn system) |
| Braiding | One (machine direction) | Intertwining (position displacement) |
| Knitting | One (0° or 90°)<br>(warp or fill) | Interlooping (by drawing loops of yarn over previous loops) |
| Nonwoven | Three or more (orthogonal) | Mutual fiber placement |

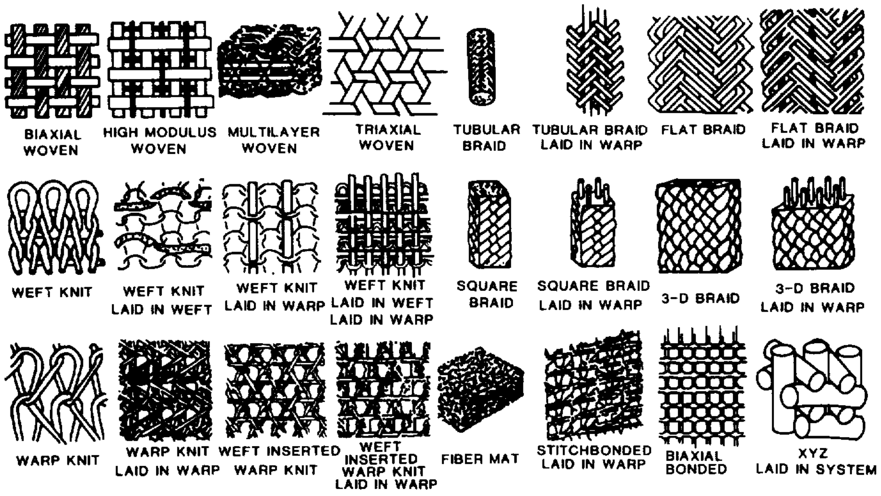


FIGURE 1.

## CLASSIFICATION OF BRAIDED STRUCTURES

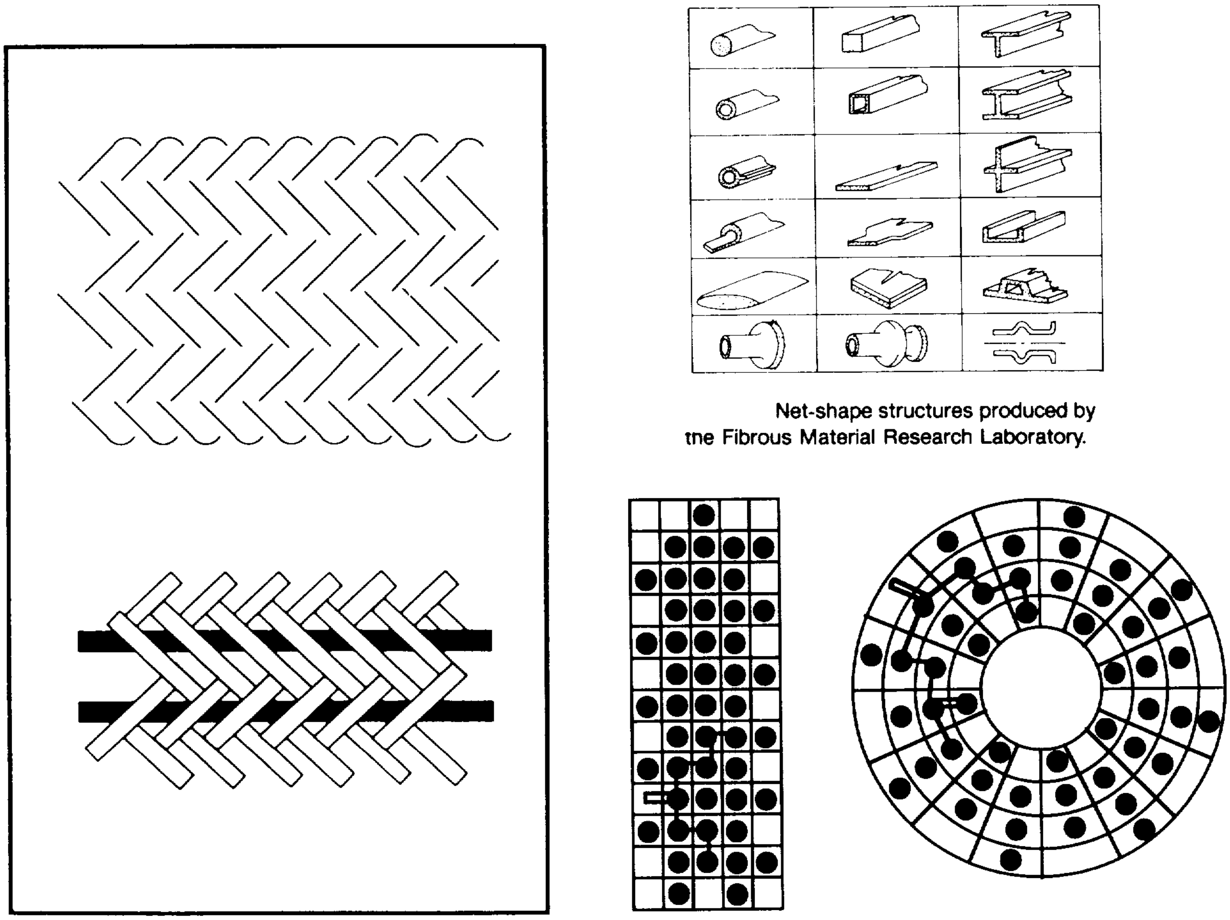
Braided structures can be generally classified into 2-D and 3-D braids. 2-D braided structures consist of two (or three, in the case of triaxial braids) yarns in the through thickness direction, whereas 3-D braids have three or more yarns in the through thickness direction. Both 2-D and 3-D braids can be fabricated into generic tubular and rectangular forms as well as many other complex structural shapes as shown in Figure 2.

| PARAMETER | LEVELS | |
|---|---|---|
| DIMENSION OF BRAID | 2-D | 3-D |
| YARN AXES | BIAXIAL, TRIAXIAL | MULTIAXIAL |
| SHAPING | FORMED SHAPES | NET SHAPE |
| DIRECTION OF BRAID | HORIZONTAL | VERTICAL, INVERTED VERTICAL |
| CONTROL MECHANISM FOR CARRIER MOTION | POSITIVE | JACQUARD |
| BRAIDING TYPE | CIRCULAR | FLAT, JACQUARD/SPECIAL |

FIGURE 2.

## UNIQUENESS OF BRAIDED STRUCTURE

Braided preforms were selected for this study because of their unique combination of damage resistant capability and ability for near net shape and net shape manufacturing. These interesting combinations of formability and toughness are a result of the intertwining nature of the yarns in a braided structure. As shown in Figure 3, the bias yarns contribute to a high level of resistance to shear and torsional deformation. The ability to introduce 0° lay-in yarns further enhances the design flexibility of braided preforms.


Net-shape structures produced by the Fibrous Material Research Laboratory.

**2-D Braid** **3-D Braid**

FIGURE 3.

## INTEGRATED DESIGN AND MANUFACTURING

In order to provide a solid foundation for the engineering design and large scale manufacturing of braided components, an integrated approach was employed [1]. This integrated approach is supported by three levels of modelling including processing (topological), fiber architecture (geometrical), and performance (mechanical) modelling. The flow chart of the engineering design framework is shown in Figure 4.

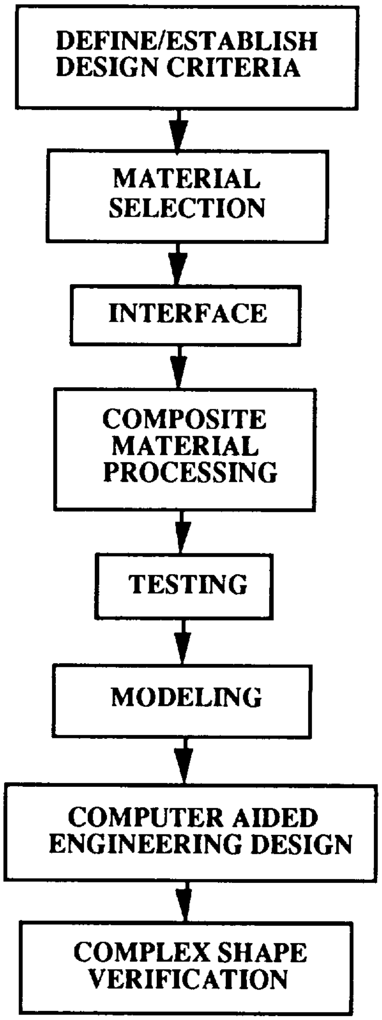


FIGURE 4.

# DESIGN OF BRAIDED PREFORMS

The design of the braided preforms was based on the governing equations for braiding, which relate fiber volume fraction to yarn geometry and braiding parameters as shown below in Figure 5.

2-D Braid:

$$d_o = \frac{Mn_{ply} A_y}{(\pi \text{ T } V_f \cos\theta) + T}$$

$$d_i = \frac{Mn_{ply} A_y}{(\pi \text{ T } V_f \cos\theta) - T}$$

where

$d_o$ = outer diameter; $d_i$ = inner diameter
T = fabric thickness; M = # of carriers
$A_y$ = yarn cross-sectional area; q = braiding angle
$N_{ply}$ = # of plies per bobbin; $V_f$ = fiber volume fraction.

3-D Braid:

$$V_f = \frac{N_y D_y}{9 \times 10^5 \rho A_c \cos\theta'}$$

where

$V_f$ = fiber volume fraction; $N_y$ = total # of yarns in the fabric

$D_y$ = linear density;
q = interior yarn angle
$= \tan^{-1}\left(\frac{(1+K^2)^{1/2} \tan(\theta')}{K}\right)$
where $K = \frac{\text{track movement}}{\text{column movement}}$
$\theta'$ = surface braiding angle.

**FIGURE 5.**

The overall manufacturing goal of the ATCAS braiding study in Phase A was to develop a consolidation process and resin transfer molding process that consistently produced high quality braided composite parts. The schematic of the approach followed to achieve this goal is shown below in Figure 6. This approach was used for both thermoplastic consolidation and resin transfer molding.

The first step was to design and manufacture the necessary tooling for the fabrication process. Once this was accomplished, a set of processing conditions were chosen and an optimization cycle began. A trial run was made with the chosen processing conditions, and the quality of the fabricated composite part was then determined by a number of quality assessment tests. After evaluation of the test results, necessary changes to the critical processing parameters were made. Following the optimization of the processing parameters (i.e. when the quality of the part could no longer be improved), fabrication of the braided composite specimens began.

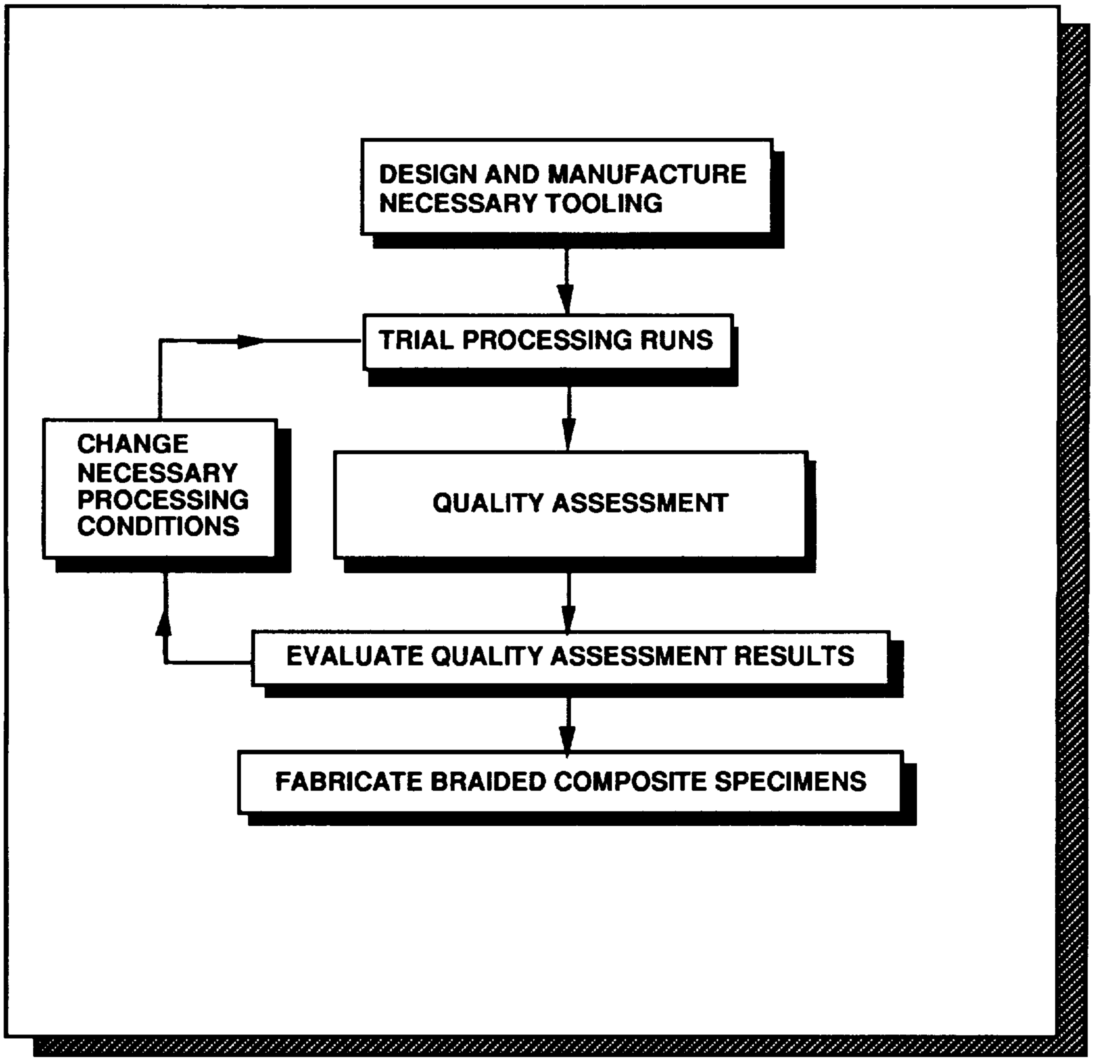


FIGURE 6.

Consolidation of thermoplastics is one of the two fabrication techniques used in this study. The material system used in this fabrication process was AS4 graphite/PEEK commingled hybrid yarn. The processing challenge that needed to be overcome using this material system was to achieve complete uniform wet-out of a composite preform.

Commingled yarns were chosen to be one of the material systems investigated in this study for a number of reasons. First of all, commingled yarns are currently the only way of braiding thermoplastic composites, and an evaluation of a braided thermoplastic system was desired in this study. Secondly, commingled yarns are inherently flexible and drapable which makes them easy to braid. Finally, high quality composite parts can consistently be fabricated using commingled yarns.

The design of the tooling for the high pressure/high temperature environment of thermoplastic consolidation must be done properly in order to prevent warpage and achieve dimensional accuracy of the fabricated composite. A universal tool consisting of a base plate, rails, and caul plates was designed for the flat specimens. Individual tools were designed for the more complex-shaped specimens. The universal and complex-shaped tool assemblies are shown with the autoclave in Figure 7.

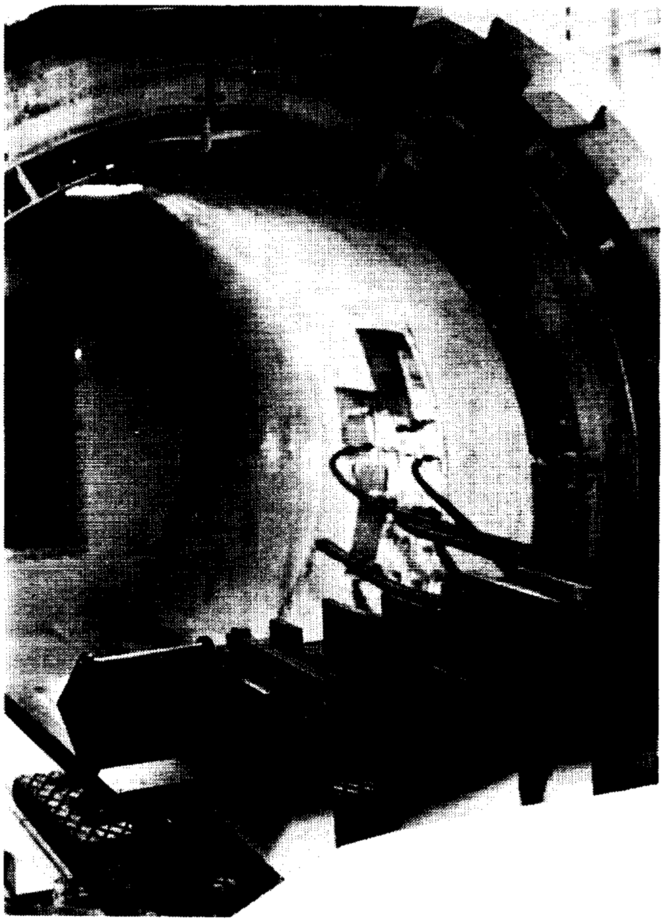


FIGURE 7.

The critical parameters involved in the thermoplastic consolidation process had to be identified and optimized in order to determine the best possible processing conditions. The critical processing parameters for thermoplastic consolidation were identified as follows: part temperature, heat-up rate, cool-down rate, dwell time, pressure, and ramp-up pressure rate. The optimized consolidation cycle is shown in Figure 8a.

In determining the optimized consolidation cycle, many trial runs were made using different combinations of processing parameters. The quality of the fabricated composite parts was evaluated after each trial process. The techniques used to determine part quality included fractography studies, void content testing via resin digestion and digitized micrograph analysis, C-scans and X-rays. A photomicrograph of the cross-section of a part fabricated with the optimized consolidation cycle is shown in Figure 8b.

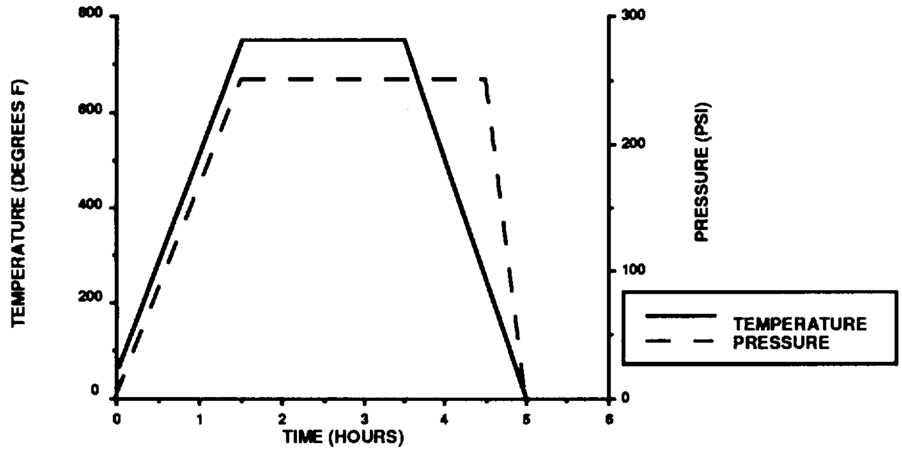


FIGURE 8a.

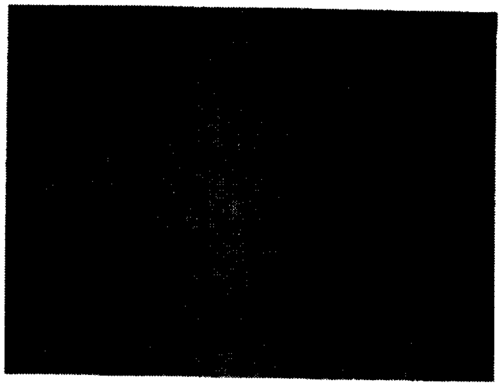
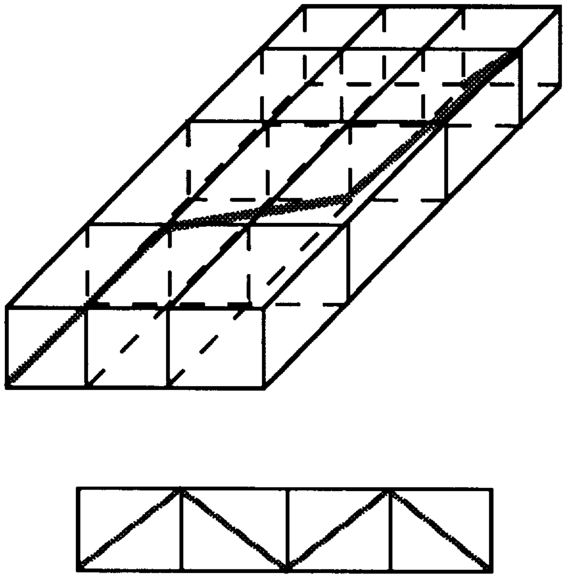


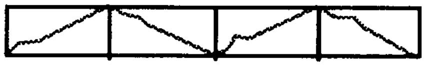
FIGURE 8b.

The effect of the thermoplastic consolidation process on the internal fiber architecture of the preforms was an area of concern that was addressed. The effect of consolidation on the fiber architecture was observable by braiding a copper-coated graphite tracer fiber tow into the preform. The preforms containing the tracers were X-rayed before and after consolidation in order to detect any changes in fiber architecture that might have occurred.

The first effect observed was the variability in part thicknesses of the composite parts. The final part thickness is difficult to control when preforms are not made by automated machines (i.e. the bulk factor cannot be accurately controlled when manual steps are involved in the braiding process). The X-rays also showed that there was a significant reduction (30%) in through-the-thickness angle in the 3-D preforms. Although this is a drawback, the reduction in through-the-thickness angle can be calculated if the initial preform thickness and final composite part thickness are known. Another observation made from the X-rays was the presence of fiber kinking and fiber waviness. When the preform was compressed during fabrication, the fibers kinked around the areas of fiber interlocking. A schematic of an X-ray illustrating the effects mentioned above is shown in Figure 9.



BEFORE CONSOLIDATION



AFTER CONSOLIDATION

FIGURE 9.

## FABRICATION OF BRAIDED COMPOSITES BY RESIN TRANSFER MOLDING

Resin transfer molding was the other fabrication technique used in this study. The preform material used in this fabrication technique was AS4 dry graphite fibers. The resin system chosen for the process was DPL-862, which is a new resin system developed by Shell. This resin system was chosen for the following five reasons: excellent structural properties, retention of structural properties in a hot-wet environment, low viscosity, lack of a styrene, and reasonable cost. The processing challenge of this fabrication technique was to move resin uniformly through a highly interlaced structure with a high fiber volume fraction (61%).

Resin transfer molding was chosen for this study for the following reasons: RTM uses materials in their lowest cost form, the finished product of RTM is dimensionally accurate in all directions, and RTM is a low cost, high rate process that is versatile and repeatable. A schematic of the RTM process used in this study is shown in Figure 10.

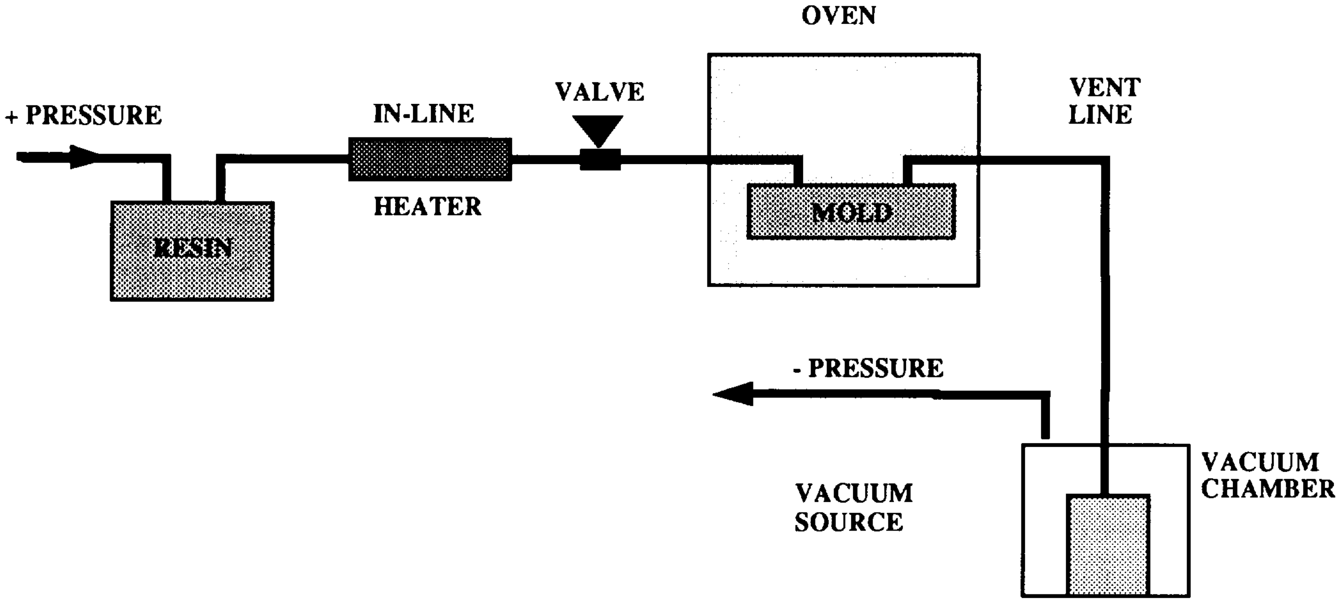


FIGURE 10.

In order to determine the best possible resin transfer molding conditions, the critical parameters of the process were identified and optimized as follows: a resin temperature of 200°F, an inlet line temperature of 225°F, a mold temperature of 250°F, and a vent/exit line temperature of 250°F. The details of the molding process are given below in Figure 11.

In determining these processing conditions an optimization cycle similar to the one used for the consolidation of the graphite/PEEK preforms was used. Many of the same manufacturing issues addressed in the thermoplastic consolidation technique are currently being investigated.

1.) Loaded preform in mold and verified vacuum integrity.

2.) Attached inlet and exit lines.

3.) Preheated mold and preform to 250°F. Mold cavity was held under vacuum to dry preform for 2 hours.

4.) Preheated resin and curing agent were mixed and desired under vacuum. (NOTE: At 250°F under approximately 30 in. Hg, the resin system boils. A slight decrease in vacuum solved this problem.

5.) Resin was then loaded into preheated pressure pot at 200°F.

6.) While maintaining full vacuum (30 in. Hg), inlet valve was opened to allow resin to flow to inlet port of mold. Vacuum was then decreased to approximately 10 in. Hg and positive pressure was applied to the resin (approximately 5 psi initially).

7.) When resin was witnessed at exit port, vacuum was reduced to zero and the pressure was increased to 20 psi.

8.) When an air bubble was observed in the free stream of resin contained in the exit line, the exit line was clamped and the resin pressure was increased to 40 psi.

9.) The mold was then blocked under 40 psi and the mold temperature was increased to 300°F to gel and cure resin.

10.) CURE CYCLE
Three hours at 300°F with slow cool down to room temperature.

**FIGURE 11.**

The primary goal of the experimental mechanical characterization of braided composites in Phase A of the Boeing ATCAS Program is to obtain a preliminary data base for 2-D and 3-D braided composites. The schematic of the approach followed to achieve this goal is shown below in Figure 12.

The first step of the approach was to set-up a test matrix that would allow the investigation of a variety of structural mechanical properties of both 2-D and 3-D braided composites. Selection of the material systems and internal fiber architecture configurations was also an important part of the effort The next steps were the design of the test specimens and definition of the test methodology that would properly determine the desired mechanical properties. The following two steps were manufacturing oriented. The processes which were used to manufacture the braided composite parts were optimized in order to consistently produce excellent quality parts for mechanical testing. After process optimization, the test specimens were fabricated. Following fabrication, the specimens were prepared and tested. The final step to this approach was the correlation between experimental data and predicted analytical results.

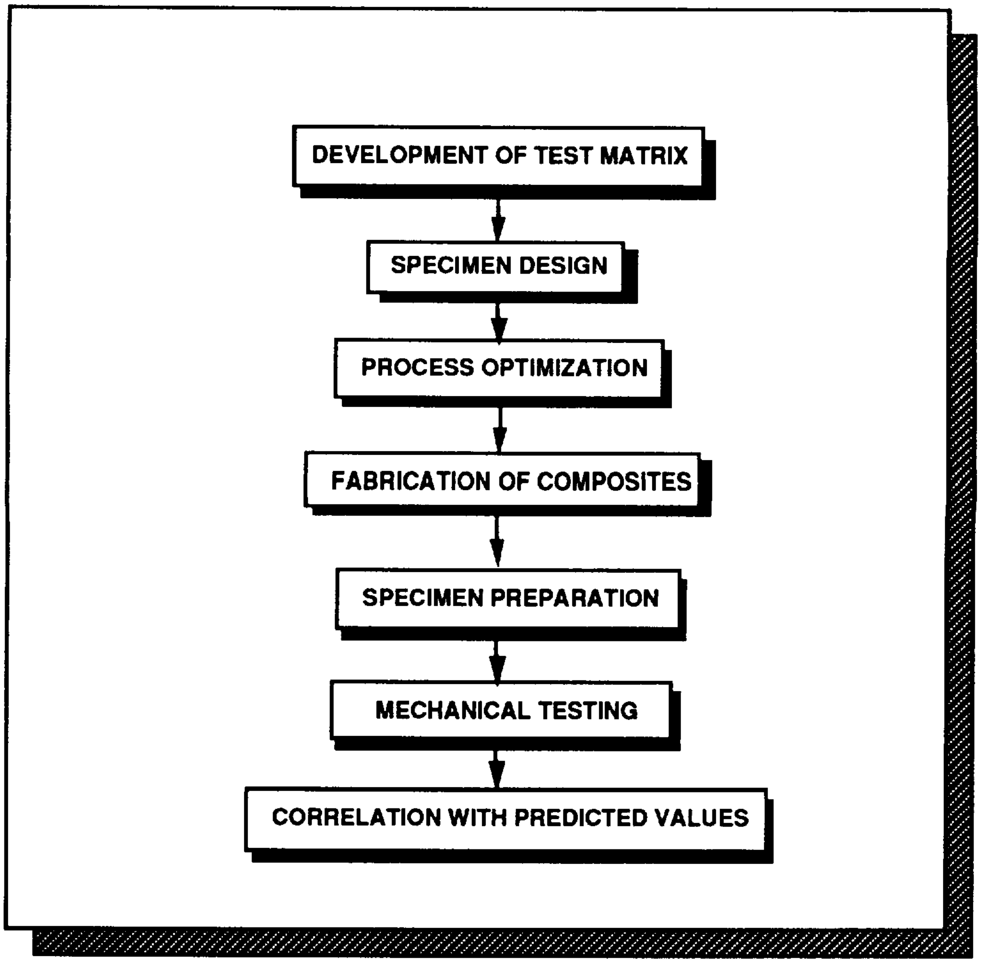


FIGURE 12.

# BRAIDED COMPOSITES TEST MATRIX

The test matrix for braided composites was developed to fulfil five objectives. The first objective is to examine the response of braided composites to different types of loading conditions since collection of braided composite mechanical properties is needed to build a much needed data base. The second objective is to compare the mechanical response between 2-D and 3-D braided composites because the effect of through-the-thickness reinforcements on in-plane and out-of-plane properties must be examined. The third objective is to compare the mechanical response between braided composites containing different polymer resin systems. The fourth objective is to observe the effect of different fiber architectures on the mechanical response of braided composites. This objective will bring some insight to the dilemma of determining the precise amount of through-the-thickness fiber required to improve out-of-plane properties and damage resistance without excessively degrading in-plane properties. The fifth and final objective of the test matrix is to compare the mechanical properties of the braided composite systems with traditional laminated composite systems.

Figure 13 illustrates the braided composite test matrix which lists the nine different types of mechanical tests used in this study. The test matrix consisted of 123 test specimens, 57 two dimensional braided specimens and 66 three dimensional braided specimens. Two different internal fiber architectures were investigated. Fiber architecture "A" consisted of 60% braided yarns at a braiding angle of 20° and 40% in-laid longitudinal yarns; fiber architecture "B" consisted of 100% braided yarns at a braiding angle of 35°. The test specimens in the matrix consisted of two different material systems: an AS4 fiber/PEEK thermoplastic system, and an AS4 fiber/epoxy RTM resin. All test specimens were designed to contain a 61% fiber volume fraction.

| | 2-D BRAIDED SPECIMENS | | | | 3-D BRAIDED SPECIMENS | | | |
|---|---|---|---|---|---|---|---|---|
| | A | | B | | A | | B | |
| TYPE OF TEST | PEEK | RTM | PEEK | RTM | PEEK | RTM | PEEK | RTM |
| UNNOTCHED TENSION | 3 | 3 | 3 | | 3 | 3 | 3 | 3 |
| OPEN HOLE TENSION | 3 | 3 | 3 | | 3 | 3 | 3 | 3 |
| UNNOTCHED COMPRESSION | 3 | 3 | 3 | | 3 | 3 | 3 | 3 |
| COMPRESSION AFTER IMPACT | 3 | | | | 3 | | | |
| IN-PLANE SHEAR | | | 3 | | | | 3 | |
| TRANSVERSE SHEAR | | | 3 | 3 | | | 3 | 3 |
| TRANSVERSE TENSION | | | 3 | 3 | | | 3 | 3 |
| BEARING | 3 | 3 | 3 | | 3 | 3 | 3 | 3 |
| CRIPPLING | 3 | | | | | | | |
| TOTALS | 18 | 12 | 21 | 6 | 15 | 12 | 21 | 18 |

NOTES:

A - BRAIDING GEOMETRY OPTIMIZED FOR END LOAD [ 60% BRAIDED AT 20 DEGREES, 40% 0 DEGREES]

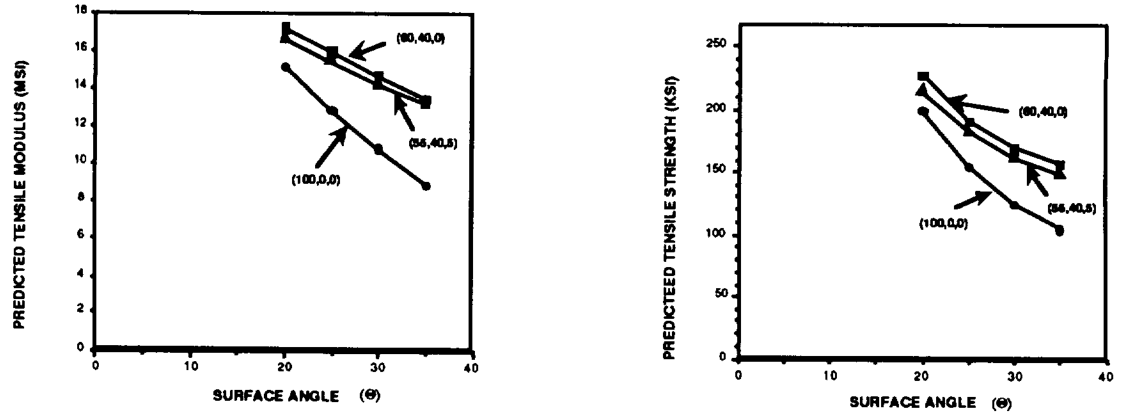
B - BRAIDING GEOMETRY OPTIMIZED FOR SHEAR [100% BRAIDED AT 35 DEGREES ]

FIGURE 13.

# OPTIMIZED FIBER ARCHITECTURE FOR END LOADS AND SHEAR LOADS

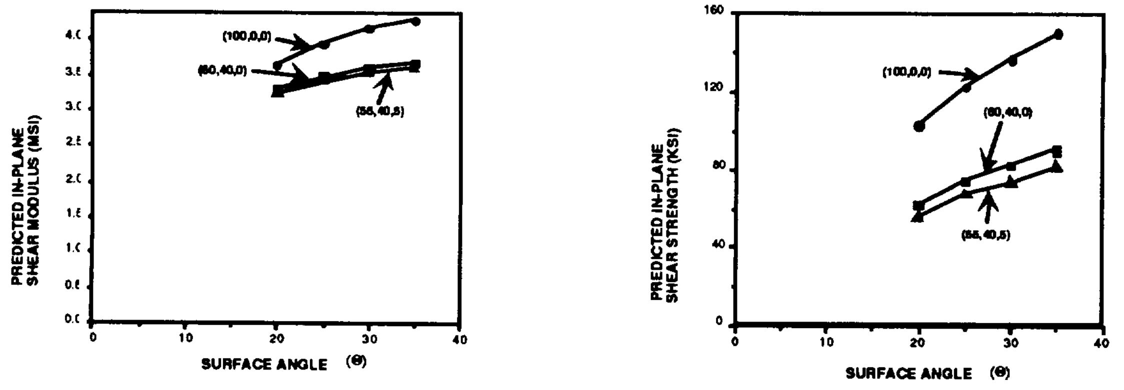
The two fiber architectures contained in the test matrix were determined via a parametric study and the consideration of preform manufacturing constraints at the FMRC at Drexel University. The objective of the parametric study was to find the optimum configuration for two different loading conditions: end loading and shear loading. The parametric study yielded the following configuration for the optimization for end loading: 60% braided yarns at a braiding surface angle of 20° and 40% in-laid longitudinal yarns. The fiber architecture optimized for shear loading was 100% braided yarns at a braiding angle of 35°.

The parametric study was performed using an early version of the analytical model developed during this study. Some results from this parametric study are graphically illustrated in Figure 14 below.



NOTE: NUMBERS IN PARENTHESIS REFER TO: [% BRAIDED, % LONGITUDINAL, % TRANSVERSE]

NOTE: NUMBERS IN PARENTHESIS REFER TO: [% BRAIDED, % LONGITUDINAL, % TRANSVERSE]



NOTE: NUMBERS IN PARENTHESIS REFER TO: [% BRAIDED, % LONGITUDINAL, % TRANSVERSE]

NOTE: NUMBERS IN PARENTHESIS REFER TO: [% BRAIDED, % LONGITUDINAL, % TRANSVERSE]

FIGURE 14.

C-4

the basic tension and compression tests are being conducted using standard specimens. However, specimens had to be designed for the out-of-plane shear test, the out-of-plane tension test, the crippling test, and the bearing test. The out-of-plane shear properties will be obtained using the Iosipescu test [2]. This test method dictated the specimen configuration which is shown in Figure 15a. The out-of-plane tension properties will be determined via a flange bending test; the specimen configuration is shown in Figure 15b. This specimen was designed to produce significant out-of-plane tension stresses (~ 20 ksi) at the bending strength of the material. The specimen designed for the crippling test was a C-section channel, Figure 15c, which was designed for the flanges to buckle first, followed by the web. The final specimen design was the bearing specimen. This configuration, shown in Figure 15d, was chosen because of the two possible failure areas, and the restriction of bending in the test specimen.

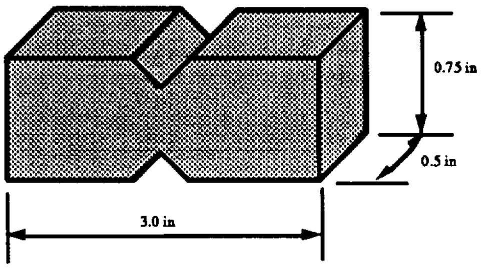


**FIGURE 15a**

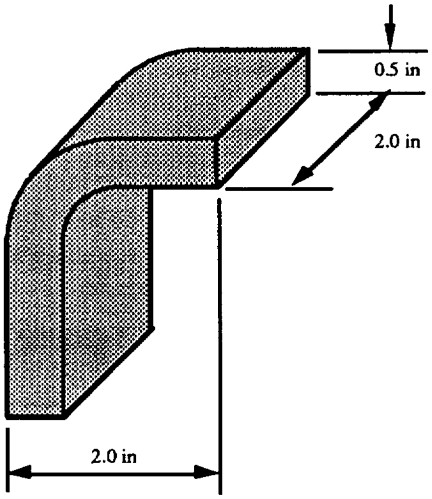


**FIGURE 15b**

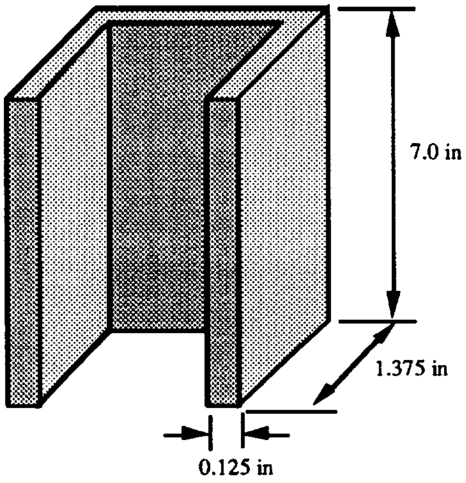


**FIGURE 15c**

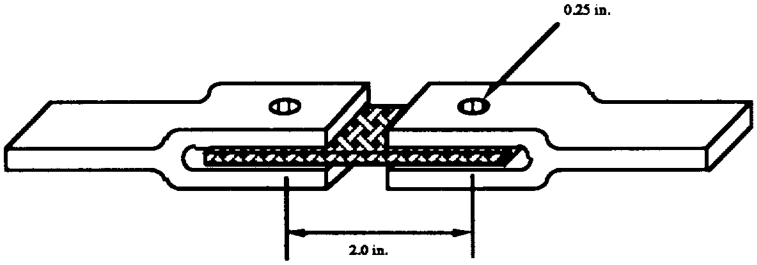


**FIGURE 15d**

The overall analysis goal of the braiding ATCAS study is to develop analytical models which accurately predict the mechanical behavior of braided composite structures. The schematic of the approach followed to achieve this goal is shown in Figure 16.

The first step to the approach was to acquire an understanding of the existing analytical models that predict the stiffnessses and strengths of braided composites. After reviewing existing models, a simple 3-D stress analysis model was developed to act as a base model which would be expanded. The next step was to expand the base model to improve physical representation of the unit cell and to add hygrothermal effects, stiffness modifications, and an advanced failure criterion in order to improve predicted results. With the aid of experimental test results, the analysis will be refined in order to produce a model which accurately predicts the behavior of braided structures under any loading condition.

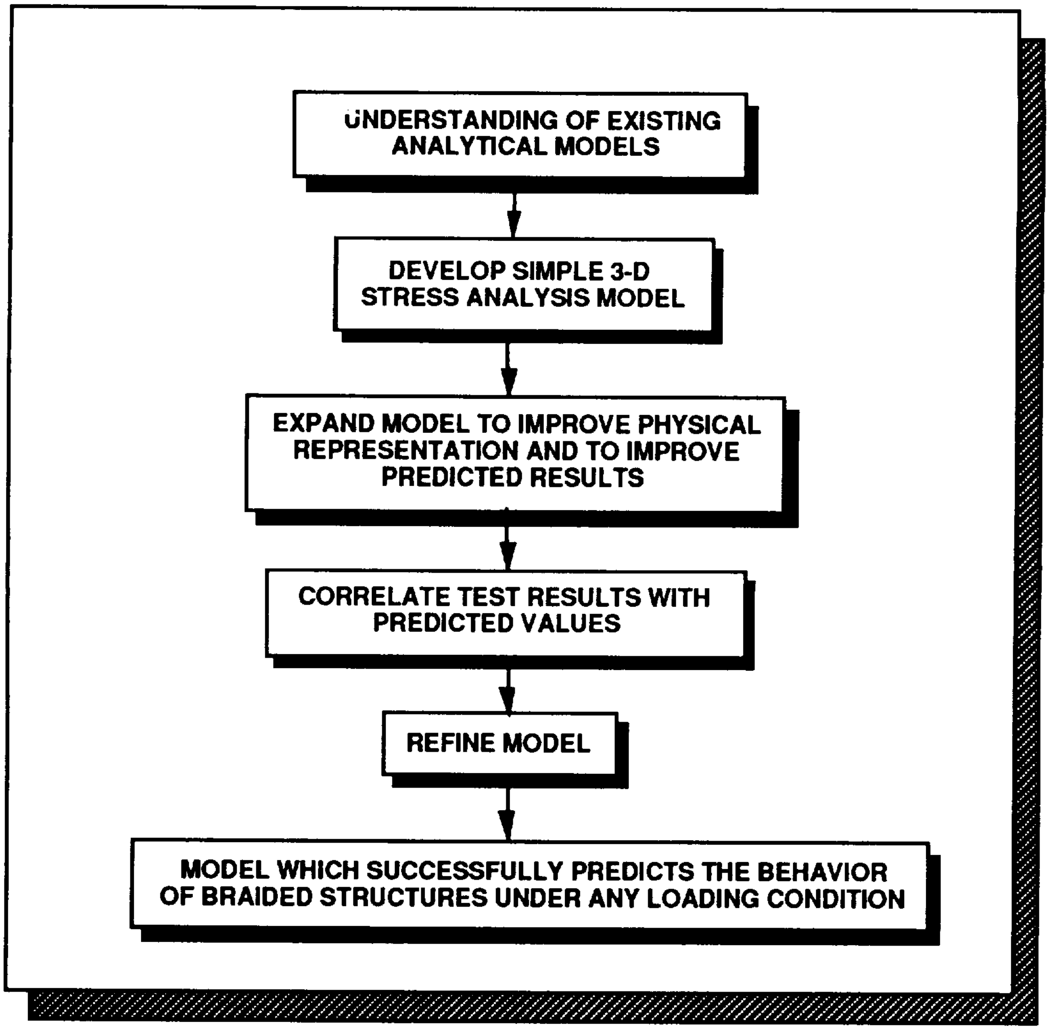
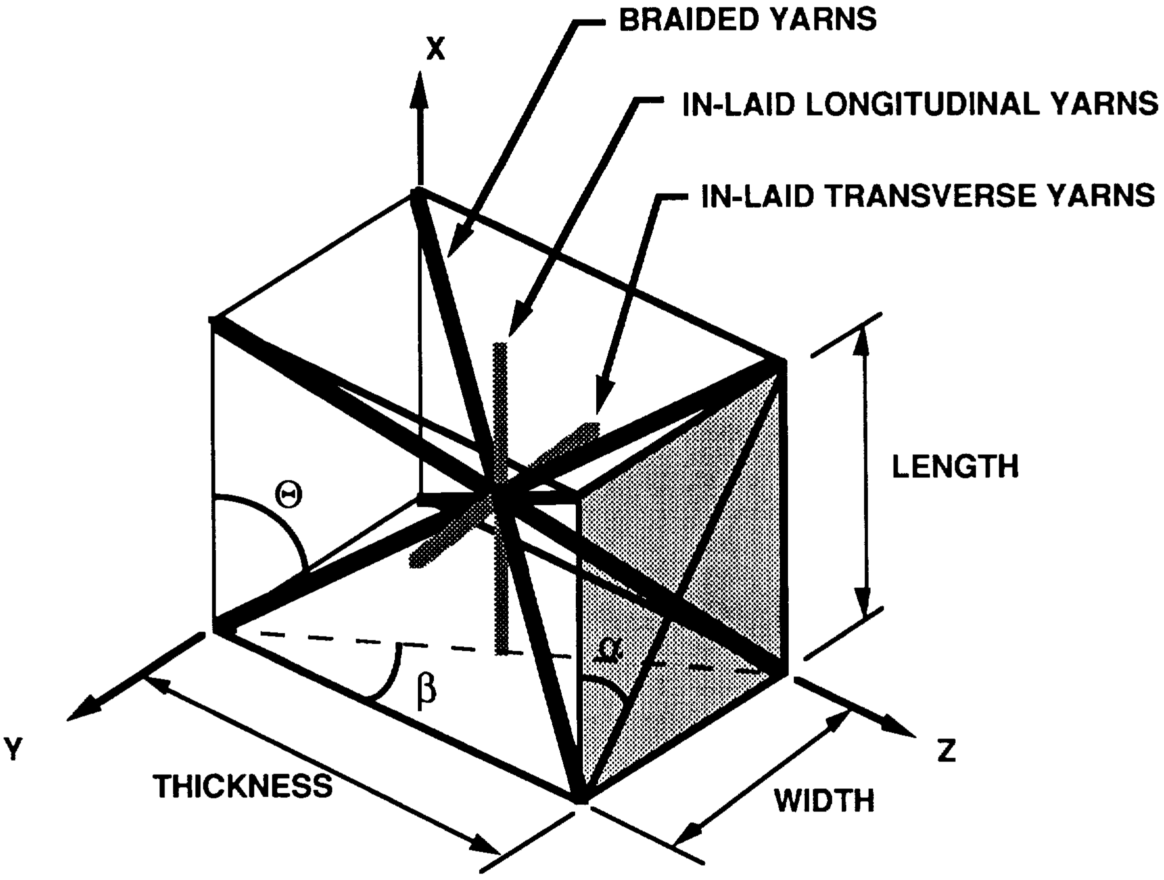


FIGURE 16.

The analysis of a 3-D textile composite structure requires the knowledge of the internal fiber architecture of the structure. The main concept presented here is that one can assume that the fiber architecture can be represented by a series of repeating building blocks called unit cells [3]. The unit cell, shown in Figure 17, is composed of six elemental component tows: four braided components which are the diagonals of the cell, a longitudinal component, and a transverse component. The orientation of the braided components are represented by the through-the-thickness angle $\Theta$. Each component is assumed to be continuous throughout the structure, have a circular cross-section, and be embedded in a matrix. The geometry of the unit cell (length, width, height, and interior angles) is dependent on the braiding ratio (ratio of track to column movement) and braiding surface angle $\alpha$ shown below on the surface of the unit cell.



$\alpha$ = BRAIDED SURFACE ANGLE

FIGURE 17.

The first phase of development of the model was to incorporate 3-D stress analysis on the unit cell. The maximum stress failure criterion was applied to predict the strength of the unit cell under an applied loading condition. The second phase incorporated the unit cell methodology to shear deformable plate theory. The application to plate theory relates the unit cell to a structure with finite dimensions and provides the stiffness and strength properties for the analysis of plates with a wide variety of loading conditions including hygrothermal effects. The flow chart for the model described above is shown in Figure 18.

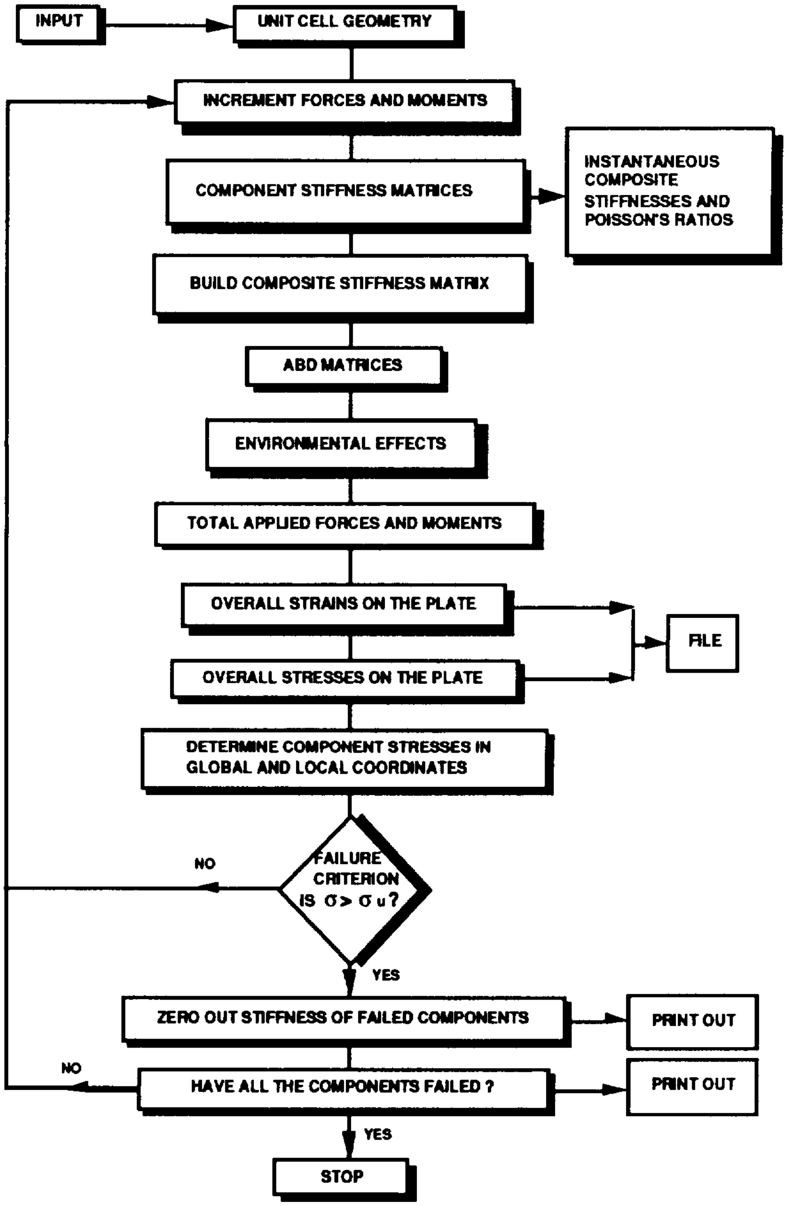
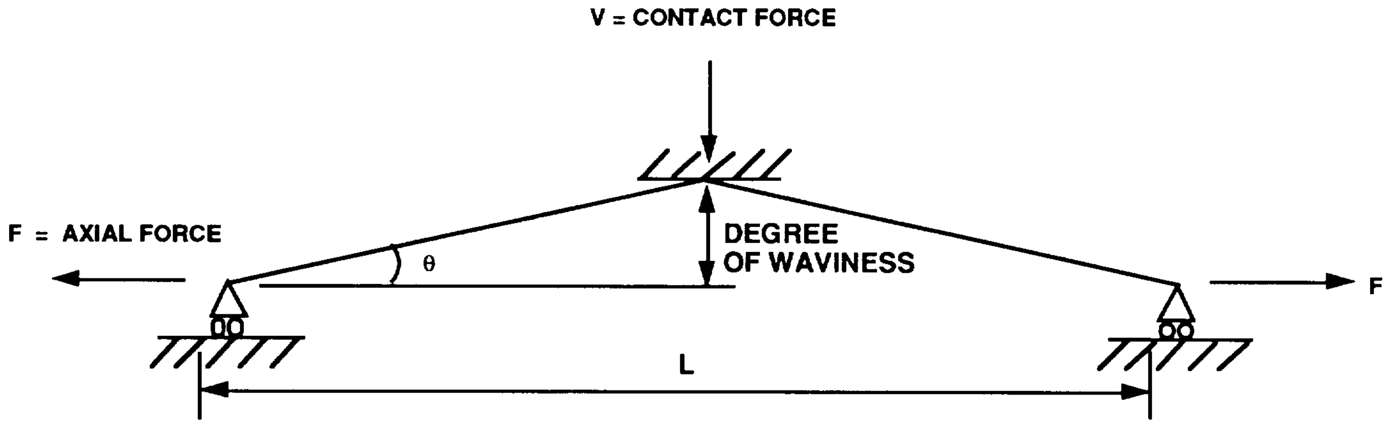


FIGURE 18.

# INTRODUCTION OF STIFFNESS MODIFICATIONS

Stiffness modifications were introduced into the model to account for fiber bending because the unit cell assumes that the elemental tow components are continuous and remain straight throughout the preform. Stiffness modifications are needed to reduce the component stiffnesses since a tow experiences waviness around areas of interlacing and turn-around points as it transverses through a preform. The stiffnesses were modified by an elastic strain-energy approach [4]. This approach, which uses beam elements to represent the bending behavior of a braided tow, is shown in Figure 19. The stiffnesses of the beam element assembly are determined via the total strain energy of the system. The total strain energy includes the strain energy due to bending, extension, and compression in the matrix over the region of contact and is dependent on the length of the fiber in the unit cell "L", the material properties of the tow, and the degree of waviness of the fiber, which itself depends on the fiber architecture and the braiding ratio of the preform.



$U_B$ = STRAIN ENERGY DUE TO BENDING

$U_E$ = STRAIN ENERGY DUE TO EXTENSION

$U_C$ = STRAIN ENERGY DUE TO COMPRESSION OVER THE REGION OF CONTACT

$$U_B = \frac{M^2}{2B} \qquad U_E = \frac{T^2}{2\lambda} \qquad U_C = \frac{V^2 D}{2\mu}$$

$$U_{TOTAL} = U_B + U_E + U_C$$

FIGURE 19.

# AVERAGE STRESS FAILURE CRITERION

The next phase in the development of the analytical model involved the incorporation of a more advanced failure criterion. An average stress failure criterion was substituted for the maximum stress failure criterion, allowing the strength predictions to be formulated on a constituent fiber and matrix level. The yarn bundle stresses were broken down into constituent fiber and matrix stresses using an average stress procedure. The allowables for the fiber and matrix strengths were used to compute failure ratios for the fiber and matrix for tensile, compressive and shear failure modes. The strength approach was then extended into a sequential failure analysis mode wherein matrix dominated failures were not considered catastrophic. If the first failure was a matrix failure, the matrix properties for the appropriate yarn bundle were reduced and the analysis was continued until fiber failure occurred. Ultimate strength was characterized by fiber axial failure or sudden increases in strain levels due to stiffness reductions as a result of large numbers of transverse and shear failures. The average stress failure criterion was also used to observe the effects of residual and hygrothermal stresses on composite failure. A flow chart which illustrates how this failure criterion fits into the overall analytical model is shown in Figure 20.

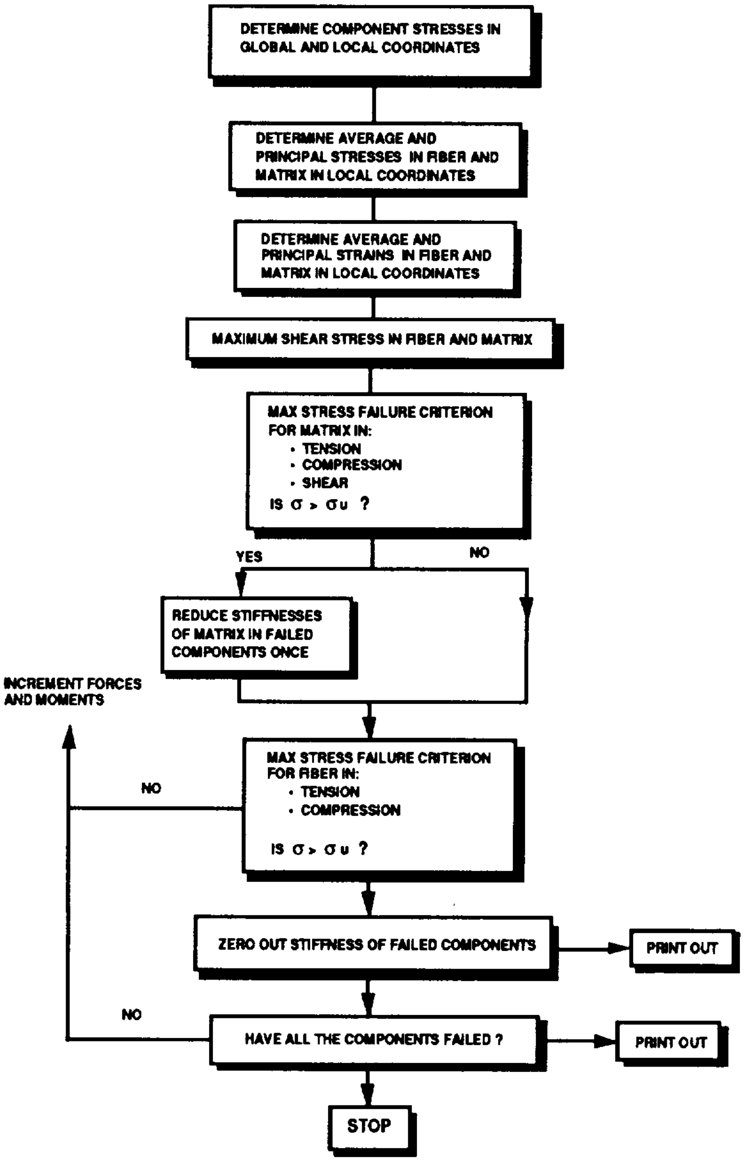


FIGURE 20.

## INCORPORATING A COMBINATION OF FAILURE CRITERIA

A problem with the average stress failure criterion used in the model was unveiled after the completion of a preliminary parametric study. It was observed that the values of the predicted failure stresses and strains were too high because the average stress failure criterion only tested the fiber for tension and compression failure. Since any off-axis fiber fails in shear (before tension and compression), the correct failure mode of the fibers was not being checked. To correct this shortcoming, the failure criterion was modified to operate in the following manner: the average stress failure criterion is first used to detect matrix cracking in a component, the matrix stiffness is then reduced proportionally in the failed component, finally a maximum stress failure criterion is then used to check the component strength in each of the possible failure modes including shear. It was concluded that the average stress failure criterion cannot alone predict the strength of braided composites as first thought. The flow chart of this combined failure criterion is illustrated in Figure 21.

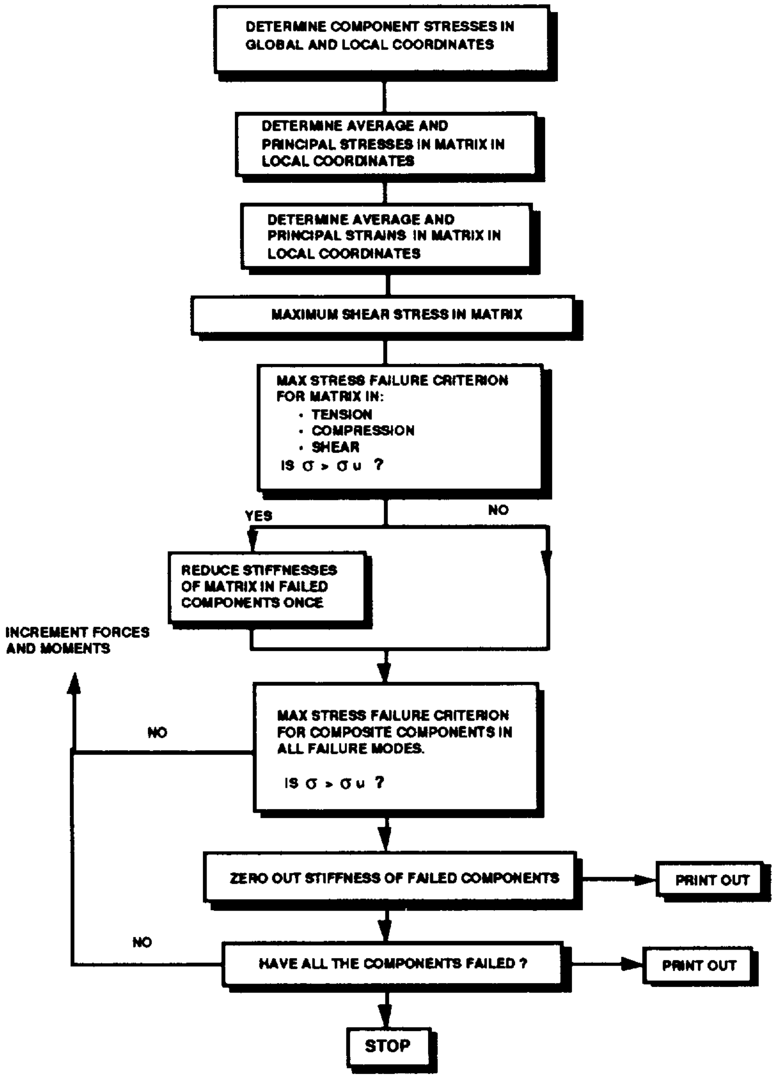


FIGURE 21.

# PARAMETRIC STUDY

A preliminary parametric study investigating the mechanical behavior of 3-D braided composite plates was initiated following the addition of the combined failure criterion to the model. The purpose of this study was to provide some insight to the problem of determining the precise amount of through-the-thickness fiber reinforcement required in a preform to improve such properties as damage resistance and out-of-plane strength without excessively degrading in-plane properties.

The preliminary parametric study examined the effect of various fiber architectures on composite stiffnesses and strengths. Figure 22a through Figure 22c illustrates the relationships between fiber architecture and braided composite stiffnesses . Figure 22d illustrates the effect of braiding ratio on the preform fiber angles. Figure 22e shows the relationship between longitudinal strength and surface braiding angle, and finally, Figure 22f shows the longitudinal strength and out-of-plane shear strength for different braiding surface angles. These figures demonstrate the capabilities and the variety of studies that can be performed using the developed model.

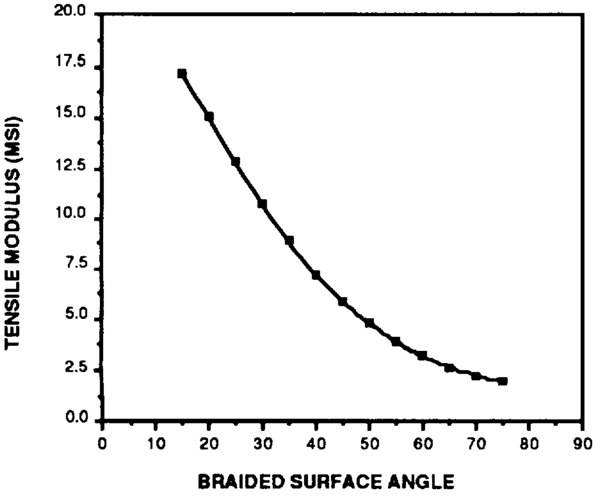


FIGURE 22a.

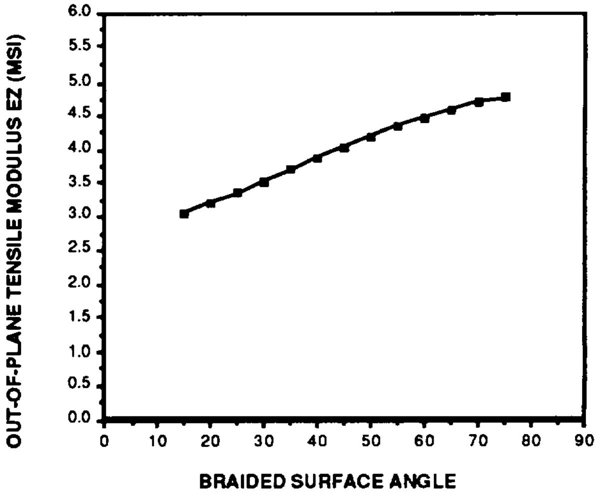


FIGURE 22b.

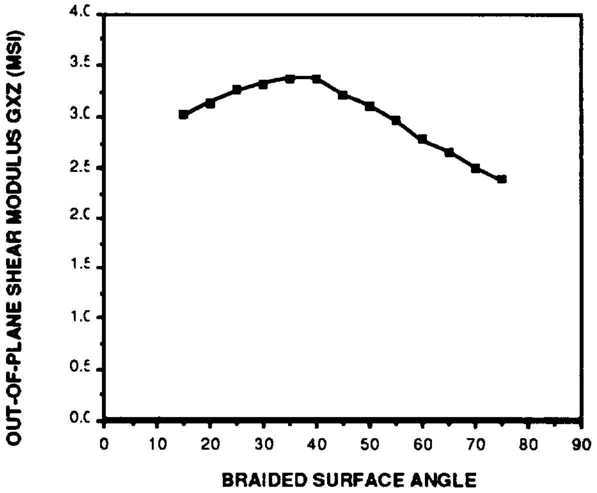


FIGURE 22c.

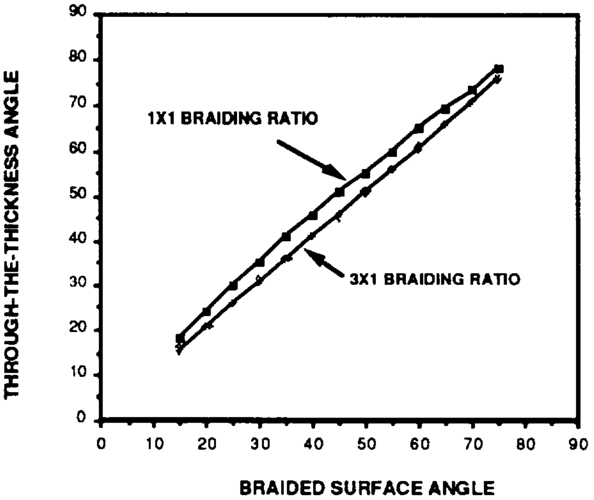


FIGURE 22d.

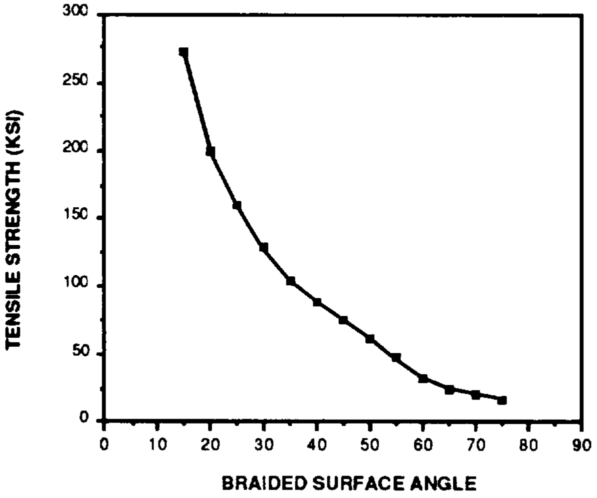


FIGURE 22e.

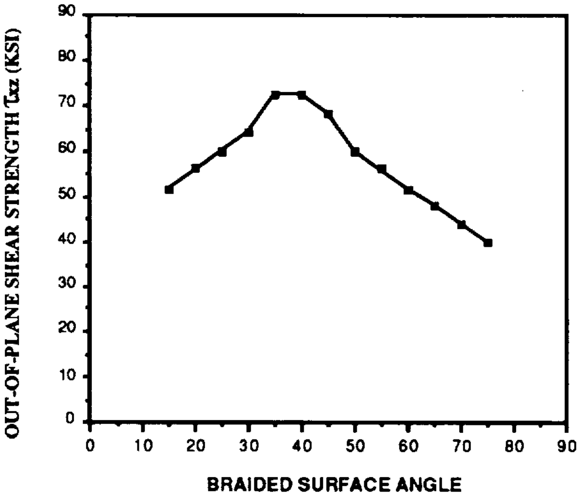


FIGURE 22f.

The analytical model developed in this study can be used as a tool for creating material cards for finite element models of braided structures. One example of this application is the modelling of the Iosipescu test specimen, illustrated in Figure 23, which will be used to determine the out-of-plane shear properties of braided composites in this study. This capability of the model will be used in the future to produce material cards for complicated braided structures such as full circumferential braided frames.

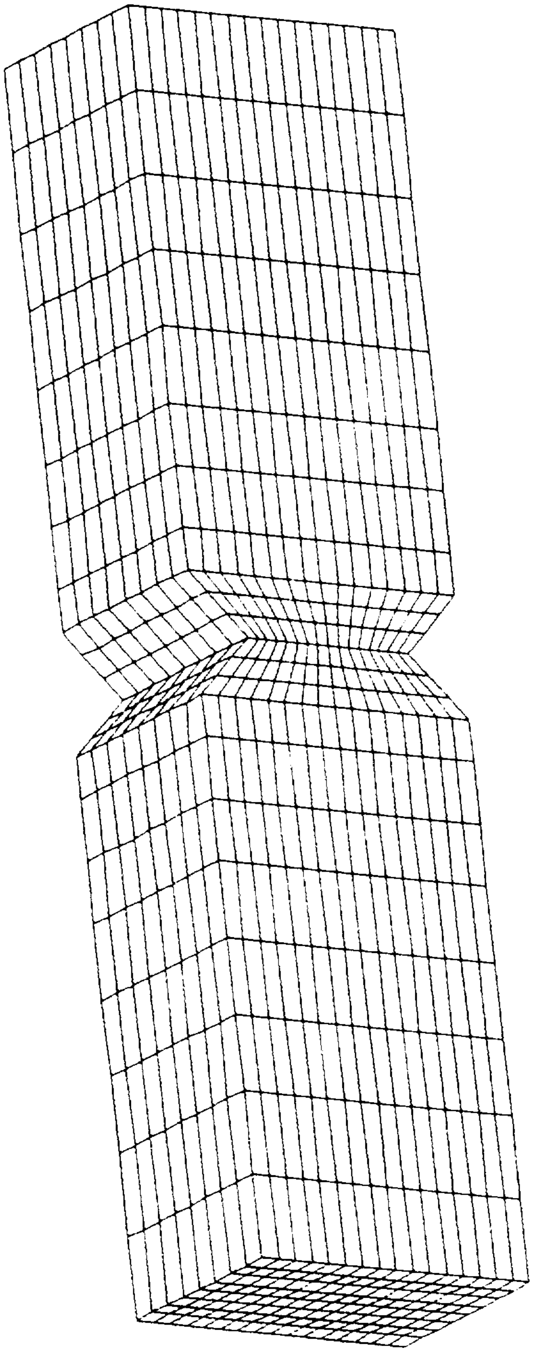


FIGURE 23.

## SUMMARY OF ANALYTICAL MODEL CAPABILITIES

The analytical model developed in the ATCAS braiding program predicts stiffnesses and strengths for both 2-D and 3-D braided composite plates under a variety of loading conditions. Features of the model capabilities are summarized in Figure 24 below.

- UNIT CELL GEOMETRY (APPLICABLE TO 3-D ONLY)
    - dimensions of unit cell
    - interior fiber angles of unit cell
    - fiber lengths within unit cell
    - number of unit cells in a composite plate
- WIDE VARIETY OF LOADING CONDITIONS
    - in-plane tension and compression
    - in-plane shear
    - transverse shear
    - bending
    - twisting
    - hygrothermal loading
- PREDICTION OF COMPOSITE MODULI AND POISSON'S RATIOS
    - $E, G, \upsilon$
    - stiffness modifications to account for fiber bending
- PRODUCE MATERIAL CARDS FOR FINITE ELEMENT MODELS
- STRENGTH PREDICTION
    - predicts stress state when matrix cracks in each component
    - predicts stress and strain state when a component fails
    - predicts stress and strain state at subsequent composite failure

**FIGURE 24.**

## CONCLUSIONS AND FUTURE WORK

The primary objective of this study was to evaluate braided composite technology for applications to a commercial transport fuselage. This objective was accomplished through the investigation of four areas: 1) Design and Forming of 2-D and 3-D Braided Fabrics with Advanced Composites, 2) Manufacturing Braided Composite Parts, 3) Mechanical Testing of Braided Composites, and 4) Analysis of Braided Composite Structures.

The feasibility of braiding near net shape structural components was demonstrated by the fabrication of the simple and complex shaped preforms required by the ATCAS braiding program test matrix. The fabrication of both 2-D and 3-D braided preforms consisting of several fiber architectures and two different material tows was demonstrated.

The successful manufacturing of these preforms into composite components was demonstrated using both thermoplastic and thermosetting resins. The critical parameters inherent to the processing techniques (thermoplastic consolidation and resin transfer molding) used to manufacture the composite test specimens were identified and optimized through quality assessment testing.

A test matrix was developed to evaluate the structural performance of braided composites. The test methods that will be performed to achieve this goal include: tension, notched tension, compression, CAI, rail shear, Iosipescu shear, flange bending, bearing, and C-channel crippling.

An analytical model was developed to predict the behavior of 2-D and 3-D braided composites. The model is based on the concept of a fundamental unit cell to represent the fiber architecture. It is then expanded to provide stiffness and strength properties for analyzing structures based on shear deformable plate theory. Hygrothermal effects, stiffness modifications, and an advanced failure criterion are also incorporated to improve predicted results. The results obtained from this model will be correlated with experimental test data when it becomes available. Future work in this area will build upon the existing model by including the effects of nonlinear material properties and a progressive failure model of the matrix which will more closely represent the physical behavior of the matrix.

The study discussed in this paper will be completed by the end of 1990, at which time the ATCAS braiding program will progress from an evaluation stage to a practical application stage for commercial transport fuselage.

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