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Design and Manufacture of Elastically Tailored Tow Placed Plates

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Abstract

Elastic stiffness tailoring of laminated composite panels by allowing the fibers to curve within the plane of the laminate is a relatively novel design concept that has been demonstrated to be both beneficial and practical. In particular, for structures with highly non-uniform stress states, such as the case of a flat panel with a central hole subjected to in-plane loading, the concept is likely to provide substantial improvements in load carrying capability. The objective of the present study is to determine the effectiveness of stiffness tailoring through the use of curvilinear fibers to reduce stress concentrations around the hole and improve the load carrying capability of panels with holes. The study has two main elements. The first element is the development of software tools for the analysis and design of laminates with curvilinear fibers. Software was created that translates standard finite element models with traditional laminate definitions into ones that possess stacking sequences with curvilinear fiber paths that are directly manufacturable using an advanced tow placement machine. The automated Java software uses fiber path definitions that are described using simple input parameters associated with analytical descriptions used by the designers. Preliminary designs for the manufacturing and testing phase were determined through rudimentary design studies for flat plates without holes under axial compression using ADOPTECH's stacking sequence optimization program OLGA. These candidate designs were then analyzed with STAGS finite element models that accurately reflect the test conditions and geometries in order to decide upon the final designs for manufacture and testing. The second element of the project involved the actual manufacturing of the test panels. The fiber orientation angle variation within the laminates is accomplished by using an advanced tow placement machine VIPER® by Cincinnati Machine. A total of six large panels, measuring three feet by six feet, each of which are used to produce four specimens with or without holes, are fabricated and delivered to NASA for machining and testing.

1.0 Introduction

Traditionally, unidirectional layers of a composite laminate are placed such that orientation of the fibers within each layer are constant throughout a structural component, or only allowed discrete jumps from one section of the component to another. By limiting each ply to a single orientation, the designer is unable to fully utilize the directional material properties offered by advanced composites for structures that possess stress states that vary as a function of location within the laminate. Allowing the fibers to curve within the plane of the laminate does furnish a tailoring possibility to account for a non-uniform stress state, as well as providing other structural advantages such as the alteration of principal load paths. One of the traditional configurations in which stress distribution is highly non-uniform is the case of a flat panel with a central hole subjected to in-plane loading. Therefore, this sample problem will be studied to determine the effectiveness of stiffness tailoring through the use of curvilinear fiber paths to reduce stress concentrations around the hole and perhaps improve the load carrying capability of the structure.

One of the first approaches to improve compressive load carrying capability of composite laminates with an open hole was the experimental work of Yau and Chou[1], who inserted metal pins into woven fabric prior to curing, effectively pushing the fiber tows apart to create a molded hole. The resulting laminates possessed curvilinear fibers around the hole and exhibited improved open-hole strength compared to similar laminates with drilled holes. Hyer and Charette[2] were among the first to investigate the influence of fiber orientation angle around a cutout for a flat plate with a circular hole. They proposed that improved designs could be realized by aligning the fibers with the principal directions of the stress field. Their finite element solution did demonstrate significant improvement with respect to material failure load levels, however their curvilinear fiber designs showed no advantage where buckling was concerned. A follow-up work by Hyer and Lee[3] aimed at improving these buckling loads by using sensitivity analysis and a gradient search method to determine the optimal fiber orientation angles in different regions of the plate modeled by a grid of finite elements. This method produced designs with substantial increases in buckling loads, mostly through the mechanism of transferring the major stresses from the interior region to the edges of the panel. Nagendra et al.[4] also used finite element analysis to develop manufacturable designs, and demonstrated comparable increases for plates with central holes.

Within this time frame, similar research led by Gürdal and Olmedo[5,6] implemented a definition for a variable stiffness ply based on curvilinear fiber paths and formulated closed-form and numerical solutions for simple plates. A follow-up design study by Waldhart et al.[7] again indicated increased buckling performance due to the stiffness variation, which caused re-distribution of the internal loads toward the simply supported panel edges. Additional mechanisms that help improve the buckling load of panels were also identified. This investigation also introduced several methods to construct variable stiffness plies from a small set of parameters. The methods were based on a reference path defined by three angles, with subsequent paths being constructed either "parallel" to the original curved path or by laying down paths identical to the reference curve but "shifted" in the direction perpendicular to the axis of fiber orientation variation. Considerations for the manufacturability of the plies, based on estimates for an advanced tow placement delivery system, were also included to ensure that the designs could be manufactured using these tow-steering methods.

The cumulative effect of these theoretical results prompted a need for experimental validation. Research by the present authors[8] led to the fabrication of two panels using the VIPER® advanced tow placement machine made by Cincinnati Milacron[9]. The panels were based on prototype "shifted" method designs from the study by Waldhart[7], and were built to validate the manufacturability of tow-steering through the application of the curvilinear fiber formats. Photographs of the two panels during manufacture are shown in Figure 1 and Figure 2. The panel shown in Figure 1 used individual tow drops that negated any overlap between successive paths of the ply, while the panel displayed in Figure 2 allowed the tows to overlap to produce a panel with thickness build-ups that act as "integral stiffeners". Subsequent testing by Wu[10,11] confirmed the increased load-carrying capability of the variable stiffness panels, with gains of up to five times the compressive buckling load of a straight fiber panel.

These obvious results illustrated the need for a design tool that could integrate these curvilinear fiber ply formats with standard laminate design methodologies. Thus, the underlying goal of this research is to design, manufacture, and test elastically tailored plates that exhibit improved performance with respect to traditional fiber-reinforced laminates. The test geometry is defined as a rectangular flat panel with a central hole, loaded under axial compression. The elastic tailoring is accomplished through the variation of the fiber orientation angle within each ply, which can be manufactured with the aid of advanced tow placement machines.

The research is conducted in two phases. In the first phase, analysis and design tools for flat panels with holes that utilize these tow-placed ply formats were developed to aid in the design process. Software was created that translates standard finite element models with traditional laminate definitions into ones that possess stacking sequences that change as a function of location due to the presence of the tow placed plies. The software emulates the actual manufacturing process associated with a tow placement machine, and enables detailed analysis of tow placed laminates through simple input parameters associated with each design. Candidate designs for the manufacturing and testing phase were found through rudimentary design studies involving flat plates without holes under axial compression. These candidate designs were then integrated with the finite element models corresponding to the proper test conditions and geometries, and the finite element results were used to decide upon the final designs for future manufacture and testing. The second phase of the project involved the actual manufacturing of the test specimens and any modifications that were required as part of this process. This document summarizes each of the sub-tasks completed as part of this project, and presents the results used to determine the final manufactured designs. Testing will be performed by NASA-Langley personnel and reported elsewhere.

2.0 Analysis of Rectangular Plate with Central Hole

This section introduces the geometry under study and details the specifications for a finite element model that accurately reflects the test conditions. *STAGS* (STructural Analysis of General Shells)[12] is used as the finite element solver, which is a general FEA package developed by Lockheed Martin. Parameters used to define curvilinear ply paths for the tow steered plies are introduced, and several examples are shown to illustrate the design possibilities for stiffness tailoring. Integration of the tow steered concepts with the finite element model is performed through the use of the Laminate Definition Tool software, which was developed during the present study, and the organization and use of the software is explained.

2.1 Test Specimen and Finite Element Model Description

The structure under consideration is a rectangular flat panel with a possible central hole of varying size. The basic geometry and sizing of the test specimen is shown in Figure 3. The top and bottom edges each extend two inches into the potting fixtures, which produces a gage length of twenty inches with fully fixed boundary conditions at each end (all displacements and rotations are assumed to be fixed along the bottom edge and only end-shortening is permitted at the top edge). The loading is introduced through a constant compressive displacement at the top edge, chosen as 0.04 inches. The vertical sides of the specimen are constrained by knife-edge supports, approximately one-third of an inch from the edges. The knife-edge supports constrain the out-of-plane displacement and rotation about the horizontal (x) axis. The panel is assumed to be constructed of a multi-layered laminate using a unidirectional graphite-epoxy composite for each ply. The finite element models and the design study use the material properties given in Table 1, conforming to a typical AS4/9773 system.

Table 1: Material Properties for AS4/9773 Composite System

Longitudinal Modulus, E_1	Transverse Modulus, E_2	Shear Modulus, G_{12}	Poisson's Ratio, ν_{12}	Density, ρ	Ply thickness, t
18.83 Msi	1.34 Msi	0.74 Msi	0.36	0.058 lbs/in^3	0.0075 in.

The preceding information was used to construct three *STAGS* finite element models, one without a hole and the other two with central holes of 1.5-in. and 3-in. diameters, respectively. The mesh density was chosen so as to accurately model the curvilinear fiber paths along with the associated tow drops and overlaps. Typical element sizes were of the order of 1/6 in. on each side, which translates into a rectangular grid of 90×120 quadrilateral shell elements for the model without a hole. The finite element models for the panel with a small hole and a large hole require more intricate meshing around the hole, and are displayed in Figure 4 and Figure 5, respectively.

STAGS finite element code was used to calculate the critical end displacement that would cause buckling in the panel (assuming linear prebuckling response), and resultant forces along the top edge were then summed to determine the panel average stiffness and the force required to cause instability. Standard analyses for these models using traditional straight fiber plies in a twenty ply laminate required several minutes for completion using a typical PC workstation. Sample results indicating the levels of the midplane integrated stress resultant in the direction of the loading (N_y) are shown for all three models in Figure 6 through Figure 8. For these results the laminate stacking sequence is defined as $[\pm45_2/\pm30/\pm45/\pm15]_s$ and the displacement loading is normalized so that each panel is being subjected to a compressive force of 3000 lbs (average stress resultant load of $N_y = 200$ lbs/in). Note that the constraint introduced by the fixed end boundary conditions at the top and bottom slightly alters the expected constant stress field for the model without a central hole (see Figure 6), while the holes present in the other models produce a stress concentration that increases the stress levels by a factor of approximately 2.5. The holes also reduce the buckling resistance of the panel, where the critical load of 9650 lbs for the panel without the central hole drops to 9124 and 8327 lbs, respectively, for the small and large hole models.

2.2 Tow Steered Design Concepts

The first step toward stiffness tailoring through the use of curvilinear fiber formats is to define a manageable set of parameters that can adequately traverse the design space without jeopardizing the efficiency of the optimization algorithms. To achieve this end, a tow steered ply definition that can produce manufacturable designs with a minimum number of parameters was implemented. Here, manufacturable implies that the curvilinear ply paths can be fabricated using existing fiber placement technology, so that designs also depend on some aspects of the machine used. For example, the most important manufacturing constraint for curvilinear fiber paths fabricated on a flat panel is the turning radius of the tow placement head, which delivers as many as 24 individual 1/8 in. wide tows per course. If the turning radius is too small the inner tows tend to wrinkle out-of-plane, which leads to imperfections and degrades the structural load carrying capability of the cured laminate. The tow placement machine manufacturers can provide data on what the critical turning radius is for given specifications (such as the width of the tow head, the number of tows in each course, and/or the material system used). Therefore, the design process must also be able to monitor the minimum turning radius of each design to weed out combinations of the fiber path parameters that produce infeasible designs.

With these thoughts in mind, the design parameters used here are based on earlier work led by Gürdal[5-8], who defined a general reference path based on a linear variation of the fiber orientation angle in a specified direction. Several construction methods were also defined that were able to construct an entire tow steered ply from the reference path while monitoring the turning radius constraint. For the construction methods used here, the necessary parameters for the reference path are:

(x_0, y_0) → coordinates of the origin of the reference path
T_0 → fiber orientation angle of the reference path at the origin
ϕ → angle representing the major direction of variation
d → characteristic length in ϕ-direction
T_1 → fiber orientation angle of the reference path at d

These six parameters provide a general description of a reference path (referred to as a *linear angle* variation) that satisfies the equation

$$\theta(r) = \begin{cases} \phi + (T_1 - T_0)r/d + T_0 & \text{for } 0 < r < d \\ \phi + (T_0 - T_1)(r - d)/d + T_1 & \text{for } d < r < 2d, \end{cases}$$

where r is the coordinate in the ϕ-direction. For the remaining domain, the fiber orientation angle repeats indefinitely with period $2d$ so that $\theta(r)$ is periodic and continuous. Thus the variation of the fiber orientation angle follows a continuous saw-tooth pattern with limits T_0 and T_1. Furthermore, the radius of curvature for such a reference curve can be found analytically, so that once the parameters are chosen the determination of the minimum turning radius is easily calculated. An example ply course using this reference path is shown in Figure 9, where the dotted line is the reference path (at the center of the course) and the solid curves represent the outer edges of one course of the fiber placement head.

To construct an entire ply from this reference curve, additional courses are laid down at a certain distance perpendicular to the ϕ-direction. This distance is defined as the shift parameter, and is calculated so that no gaps exist between adjacent courses. Due to the curvature of the reference curve and the shifted construction method used for additional courses, overlaps may exist between tows of adjacent courses (as shown in Figure 10, in which the light gray area represents the overlap region). Two techniques are employed to handle this overlap. The first, referred to as the "tow drop" method, instructs the fiber placement machine to cut/drop individual tows within each pass so that no thickness build-up occurs in the regions of overlapping paths. This results in constant thickness panels that contain small wedge-like areas that contain no fibers due to the dropping of the individual tows. An example of this type of construction method is shown in Figure 11, where the alternately shaded regions denote successive courses using a head width of 3 in. and 24 tows per course. The small wedges are the white regions between successive courses, and are more easily seen in the close-up displayed in Figure 12. These small fiber-free areas are likely to create resin-rich regions during cure, and occur because the tows are cut straight across at 90°. However, since each course possesses similar angle orientation with respect to each other at the tow drop location, the shallow angle of the wedge shape tends to minimize the area that contains no fibers (as illustrated in Figure 12). The partial panel layup shown in Figure 1 shows numerous white streaks between successive passes of the tow placement head, which are the result of the empty wedge regions. The second construction method is called the "overlap" method and allows for full overlap between adjacent paths, which leads to considerable thickness build-ups for some areas of the panel (as is evident in Figure 2). Numerical algorithms were developed to generate course data for a given ply path definition and to visualize the resulting fiber paths. Examples for both types of construction methods using the test geometry dimensions, assuming a head width of 3 in. and 24 tows per course, are shown in Figure 11 and Figure 13. Numerical methods are also developed to extract the fiber orientation angles that exist for a given point within a panel, including the possibility of overlaps and gaps between courses.

The general designation for a tow steered ply using this construction method is written as $\phi\langle T_0|\ T_1\rangle$, where the origin is assumed to be at the center of the plate and d corresponds to half the panel dimension in the ϕ-direction. For design purposes, the two fiber orientation angles T_0 and T_1 are the major design variables, while ϕ is usually stipulated as 0 or 90 degrees for a rectangular panel. The origin and characteristic length are generally set at their default values, as mentioned above, unless multiple panels are being constructed simultaneously. Additionally, when the overlap method is used an *overlap* parameter is also defined, which allows for the overlap between adjacent courses to be increased or decreased. For most cases, this parameter is set to unity to guarantee the minimum overlap without any gaps between courses (the "no gap" configuration). When the overlap parameter is set to zero, the shift parameter is calculated such that the adjacent courses touch only at their closest point, which produces plies with no overlaps but with considerable gaps between neighboring courses ("no overlap"). Values between zero and one lead to shift values that vary linearly from the "no overlap" solution to the "no gap" configuration. Note that for a straight fiber definition, these configurations will be identical, since the shift parameter for a straight path produces adjacent courses with neither gaps or overlaps. Values of the overlap parameter that are greater than one are used to increase the amount of overlap between adjacent paths. For these cases, the linear variation of the shift parameter is based on a percentage of the head width. Thus a value of 1.1 will increase the shift by 10% of the head width. This method can be used for both straight and curvilinear ply definitions.

The parameters described above allow a wide variation of tow steered configurations and can easily be assessed for manufacturability, thus providing a thorough basis to explore the effectiveness of stiffness tailoring through curvilinear fiber construction.

2.3 Laminate Definition Tool for Tow Steered Designs

The finite element models analyzed in section 2.1 were originally constructed using identical layups, each element corresponding to a traditional straight fiber layup. That is, each element entry in the model definition pointed to the same shell property entry that specified the stacking sequence of the composite laminate. For tow steered laminates that have curvilinear fiber paths, it is necessary to define a specific stacking sequence for each individual element due to the variation of the fiber orientation angle within the tow steered ply. Using the parameters introduced in the previous section, the local stacking sequence can be calculated for an arbitrary point in the panel. Thus, a generic finite element model can be transformed into a tow steered design merely by re-defining the layups for each element's property entry. This process has been automated through the development of a Java-based software tool designed to re-define a flat laminate with the desired tow steered layup. This section summarizes the operation of the software tool using the tow steered design parameters introduced in the previous section.

A screen shot of the software tool, referred to as *LDT* (Laminate Definition Tool), that was developed for this purpose is shown in Figure 14. To define a tow steered configuration using the laminate definition tool, the first parameter required is the total number of plies in the laminate. If the laminate is symmetric, the appropriate box is checked, which reduces the number of required ply definitions by a factor of two. A table of ply definitions is automatically constructed, and the appropriate parameters for each ply can be entered. For example, the layup shown in Figure 14 corresponds to a $[\pm 45/0\pm\langle 45|60\rangle_2]_s$ laminate that has a group of ±45 straight fiber plies on both outer surfaces of the laminate. The selection of whether to use a straight or curvilinear layup is made by choosing from a drop-down menu under the "Method" heading of the "Ply Definitions" section of the *LDT.* In addition to the "constant" and "shifted w/ overlap" entries shown in the figure, the drop-down menu also has "parallel" and "shifted w/ tow drops" options. Depending on the construction method selected, the numeric fields under the various headings become active for entry of additional parameters that are required to completely define the ply. For the example shown in Figure 14, the laminate uses the overlap ply construction technique that requires all the parameters discussed in the previous section. The last step within the operation of the *LDT* consists of selecting an existing finite element model and the file name for the transformed model. Execution involves reading in the original model, finding the specific stacking sequence at the centroid of each element, and writing a new model that correlates each element with its local stacking sequence. The rest of the finite element model (including node numbering, boundary conditions, loading, and output specifications) is left unchanged. Analysis using the finite element package can then be performed.

The development of this software tool was instrumental for determining the prototype designs for this research. With it, detailed finite element models using the general tow steering definitions could easily be produced and analyzed to estimate and compare the response characteristics of the tow steered panels considered in the present study. However, this technique is still not suitable for full scale optimization (which will require an iterative re-definition of the layup parameters) due to the computational time needed to calculate the local layups and write the new *STAGS* input files. For the finite element models shown in Figure 4, approximately five minutes were needed to re-define and write around 10,800 elements with layups using tow steered plies. Therefore, other methods were required for the initial stages of the design process, which are detailed in the next section.

3.0 Design Study Results and Prototype Candidates

Since the finite element model definition and analysis for tow steered laminates are computationally expensive, stacking sequence design optimization that utilizes a discrete mathematical programming approach is not suitable due to the large number of analysis runs required. Therefore, this section introduces a laminate analysis/design tool, which can be used in the preliminary design phase, that uses a simplified numerical scheme for the analysis of tow steered panels. The first section describes the capabilities and limitations of this design software. Design studies for both straight and curvilinear fiber formats are performed, and several candidate laminate designs are chosen. Next, the candidate designs are transformed into viable finite element models using *LDT* and evaluated with the finite element analysis techniques. The results of the finite element analyses are then used to determine the final prototype designs destined for manufacture and testing.

3.1 *OLGA* Design Software

The preliminary design study was carried out using a software package called *OLGA* (Optimization of Laminates using Genetic Algorithms), which was developed by ADOPTECH to optimize the stacking sequence of laminates subjected to in-plane loads. The laminate optimization feature of *OLGA* is based on a specialized Genetic Algorithm (GA), which is known to provide a practical means to account for the discrete nature of stacking sequence optimization[13]. In addition to specialized operators developed specifically for composite laminate design, the software has several advanced features pertaining to laminated structures, such as automatic blending of multiple connected laminates (monolithic or sandwich) for manufacturing improvements. An example screen shot demonstrating the multiple panel capabilities and analysis options of OLGA is shown in Figure 15. For the present work, modifications to this in-house laminate design tool were performed to allow tow-steered plies as another option to the laminate make-up.

Traditionally, the design variables for a stacking sequence optimization problem are the fiber orientation angles of each layer. The GA chooses angles from a predetermined set to make up a unique layup, and then a performance criterion is calculated according to the desired type of analysis. For example, if the permissible fiber orientation angles are constrained within a set of angles in 15° increments, a possible (symmetric) layup generated by the GA may be $[-15/+45/-60/0/90/0]_s$. Note that the number of layers is determined by the GA, and there are twelve possible choices for the angle in each layer. Each layup (termed a member of a population) generated by the GA must then be analyzed and assigned a fitness value based on some performance criterion. New designs are created by genetic operators, which mix different parts of superior members (parents) in an effort to increase the fitness of an offspring design. Other issues, such as balancing and ply adding/dropping, are also taken care of by the GA optimizer. Details of the implementation of these techniques for stacking sequence optimization within *OLGA* can be found in reference 14.

To implement tow-steered designs, the main modification needed is to include the possible choices for the tow-steering parameters of a given ply definition. Of course, a minimum number of parameters are desired so that the number of combination for the angle choices does not become too large (this leads to more efficient optimization). The dialog window for the laminate fabrication method within the *OLGA* software is displayed in Figure 16, which depicts the choices and parameters that are required to define a tow-steered lamina. As indicated in the dialog window, design may be performed using traditional (straight) plies only, or several definitions for tow steered configurations can also be selected which include the straight angle configurations by default (as will be discussed shortly). The first choice when using steered fiber designs is the ply construction type, which will be limited here to the tow drop method. The overlap method is not an option within this software, since the thickness build-up tends to require more terms in the analysis (described later) for sufficient accuracy, which makes computations prohibitively expensive. However, both the overlap and tow drop method generate similar variations in stiffness, so that the tow drop results should indicate relative increases for the overlap technique. The origin (x_0, y_0) of the coordinate axis for the fiber orientation variation, variation direction ϕ, and characteristic distance d are determined by the next two choices in the dialog. First, ϕ is restricted to be either 0° or 90° by using the **Horizontal/Vertical** selection buttons. The **Centered** check box is used to locate the origin and to determine the characteristic distance. If checked, the origin is at the panel center and the distance d is set to one-half the panel dimension in the ϕ-direction. Conversely, a non-centered specification locates the origin at the more negative edge (left or bottom edge, depending on the variation direction), while the distance d is now exactly equal to the relevant dimension. This last choice allows for designs that do not need to be symmetric about the center of the panel. Lastly, the head width and allowable radius of the tow placement machine (provided by the tow placement machine manufacturer) are supplied to calculate the minimum radius of curvature for a given design.

The preceding specifications limit the number of design variables that are needed to define a tow-steered ply to two, namely the angles T_0 and T_1. The selection of T_0 and T_1 is done from a database of laminate angles that is a standard part of the *OLGA* software. Note that each ply angle selection in the database applies to both T_0 and T_1. Thus, if the set of ply angles {15°, 30°, 45°} is selected in the database, then T_0 and T_1 may take on any value in the set. A straight fiber layer is assumed if $T_0 = T_1$. In accordance with our earlier example, T_0 and T_1 would then be allowed a maximum of twelve unique possibilities (using 15° increments), which would bring the total number of choices for each ply to 144. To incorporate the tow-steered ply definitions into the genetic algorithm, each ply angle combination is represented by an integer value from 1 to 144. A transformation table is then defined to convert each integer value into a $\{T_0, T_1\}$ ply definition. This implementation was used because it required very little change to the genetic algorithm procedure. However, this implementation may also lead to many infeasible designs, for when T_0 and T_1 differ by a large amount the radius of curvature tends to be below the allowable limit imposed by the tow-placement hardware. To alleviate this problem, minimum radius calculations (based on user-defined panel dimensions) are performed before the optimization begins and infeasible $\{T_0, T_1\}$ combinations are discarded from the set. This method guarantees that the final designs will be feasible and greatly reduces the number of design choices, which improves the efficiency of the optimization algorithm.

Once the design choices are determined, the panel is analyzed using a numerical Rayleigh-Ritz solution for a rectangular plate with variable stiffness properties under in-plane loading. This solution was developed by ADOPTECH specifically for the purpose of large scale optimization, and is therefore relatively efficient (three to four second computation times for a variable stiffness panel) and accurate. Material failure and linear bifurcation loads can be calculated; however the analysis is currently limited to flat panels with simple support boundary conditions. Therefore, the design considerations lack the detail of the actual test geometry and boundary conditions as well as the central hole. However, earlier design studies using curvilinear fiber formats[7] have indicated that the main mechanism to increase the load-carrying capability of flat panels is to transfer the loads away from the center and toward the edges of the panel, which should also prove useful for plates with central holes. Therefore, the initial design studies will employ the idealistic plate geometry, and after several candidate designs are found the more realistic finite element models will be used to judge the designs.

3.1.1 Straight Fiber Laminate Design Study

The first design study considered only straight fiber plies, to serve as a baseline for the tow-steered panels. A 15 in. × 20 in. rectangular panel was defined within *OLGA*, subject to a 1 lb/in compressive load in the vertical direction. Critical loads corresponding to buckling and material failure were calculated, where material failure was based on a first-ply-failure estimation using the Tsai-Hill criterion and was calculated at a grid of points within the structure. The laminate was further restricted to be symmetric and constructed of twenty plies. The design variables were based on the fiber orientation angles within each layer and were allowed to vary in 15° increments. Two-ply stacks of plus/minus orientations were also used to ensure the laminate was balanced and to effectively reduce the size of the design space.

The five best candidate designs are shown in Table 2 along with their critical compressive load, which was due to buckling for all cases.

Table 2: Straight Fiber Design Study Results for Rectangular Panel

Design	Stacking sequence	Buckling load (lbs)
1	$[\pm45_2/\pm30/\pm45/\pm30]_s$	7918
2	$[\pm45_2/\pm30/\pm45_2]_s$	7916
3	$[\pm45_2/\pm30/\pm45/\pm60]_s$	7903
4	$[\pm45_2/\pm30/\pm45/\pm15]_s$	7903
5	$[\pm45_2/\pm30/\pm45/0_2]_s$	7897

All five layups are quite similar and possess nearly equal bifurcation levels. It should also be noted that the magnitude of the buckling load for design 4 differs from one with an identical layup reported in

Section 2.1 due to the different boundary conditions (simply supported ends are used in the design study, while the STAGS results approximate clamped end conditions).

3.1.2 Tow Steered Laminate Design Study

The second design study allowed for steered fiber plies that used the tow drop method. The angle ϕ was fixed to be 0°, since experience has shown that stiffness variation in the direction perpendicular to the loading provides the greatest load-carrying improvement. The parameter d was specified to be one-half the width of the panel, and the reference path origin was chosen as the center of the panel. Therefore, the only remaining design variables are T_0 and T_1. These variables were allowed to vary in increments of 15°, and each resulting configuration was checked against a minimum radius of curvature constraint to ensure that the ply was manufacturable by the tow placement machine. Tow-steered ply definitions with a minimum radius of curvature less than 25 in. (the reported limit of the Viper tow placement machine) were not incorporated in the design study. Furthermore, the two outer plies in the symmetric layup were constrained to be straight fiber plies. This restriction is to ensure that the gaps and overlaps that arise due to the curvilinear ply definitions do not exist on the exterior of the laminate. The results for the best five designs are shown in Table 3.

Table 3: Tow Drop Design Study Results for Rectangular Panel

Design	Stacking sequence	Buckling load (lbs)
1	$[\pm 45/0\pm\langle 45\vert 60\rangle_2/0\pm\langle 45\vert 30\rangle/0\pm\langle 30\vert 15\rangle]_s$	9313
2	$[\pm 45/0\pm\langle 45\vert 60\rangle/0\pm\langle 30\vert 15\rangle/0\pm\langle 45\vert 60\rangle_2]_s$	9244
3	$[\pm 45_2/0\pm\langle 45\vert 60\rangle/0\pm\langle 30\vert 15\rangle/0\pm\langle 45\vert 60\rangle]_s$	9225
4	$[\pm 45/0\pm\langle 45\vert 60\rangle_2/0\pm\langle 30\vert 15\rangle/0\pm\langle 45\vert 60\rangle]_s$	9211
5	$[\pm 45/0\pm\langle 30\vert 45\rangle/0\pm\langle 45\vert 60\rangle_2/0\pm\langle 30\vert 15\rangle]_s$	9186

The best tow steered ply designs (using the tow drop method) improved the load-carrying capability of the structure by almost 18% compared to the best straight fiber design and without any increase in weight. Even greater gains are to be expected when the overlap method is used.

3.2 *STAGS* Analysis and Final Design Determination

The candidate designs reported in the previous section were used to define new finite element models for *STAGS* analysis. Fifteen different layups were investigated: five constant stiffness designs from Table 2; and ten steered fiber designs, five each using the tow drop and overlap methods from the set of five tow steered designs given in Table 3. For each layup, three finite element models were re-defined from the existing *STAGS* models of plates with different hole sizes. For the straight fiber laminates, re-definition of the stacking sequence merely involved altering the single stacking sequence entry that was present in the input deck. For the tow steered laminates, the Laminate Definition Tool (discussed in Section 2.3) was required to define the local stacking sequences on an element-by-element basis. Buckling loads were calculated for these forty-five models, and the results are summarized in Figure 17. Within this bar graph, the buckling loads for the no hole, small hole, and large hole models are normalized with respect to the failure level for constant stiffness design 4 without a central hole (see Table 2). This particular layup was arbitrarily selected as the baseline design (and used for the results shown in Figure 6-Figure 8). Additionally, the lightest gray bar (labeled "stiffness") shows the relative global stiffness (load per displacement in the direction of the loading) of the designs without holes. Particular attention should be focused on the fourth design of each steered fiber group, since that is the design that showed the most promise and will be used as the prototype design.

Several conclusions can be immediately drawn from the results. First, the straight fiber designs for the "no hole" configuration demonstrated increased scatter for the buckling loads as compared to the design study results generated by the simplified analysis. This is mainly due to the different boundary conditions at the potted ends of the panel, which generates shear stresses that alters the distribution of the loading. Secondly, the degradation due to the presence of the holes was fairly uniform for the straight fiber designs (~5.5% decrease for the small hole and ~13.5% for the large hole for each design). For the tow steered designs, buckling loads were increased by around 20% and 60% for the tow drop and overlap methods, respectively, and both methods also exhibited relatively small degradation when holes were introduced. The reason for the increased buckling loads is that the stiffness variations produced by the curvilinear fiber paths (as well as the thickness build-up for the overlap method) tend to steer the loads toward the edges of the panel. This unloads the center of the panel where buckling is most likely to occur. Additionally, this feature helps minimize the effect of the central holes since the center region does not carry as much load.

Example results from the finite element models confirm these conclusions. Shown in Figure 18 and Figure 19 are two contour plots (for the small and large hole models, respectively) representing the in-plane stress resultant for panels that use the tow drop method for tow steered plies (tow drop design 4 from Table 3). The panels are loaded with a compressive force of 3000 lbs for direct comparison to the straight fiber results (Figure 7 and Figure 8). Note how the variation within the tow steered laminate results in lower stress levels in the center of the plate, leading to a 14% higher buckling load than the straight fiber laminate.

Results for the overlap method are even more dramatic. To illustrate the mechanism behind the large increase in load carrying capability for the overlap method, a plot of the thickness variation within the finite element models due to the overlap method for design 4 is displayed in Figure 20. Each element is shaded according to the number of layers in the stacking sequence. The darker regions represent thickness build-up due to the overlaps, while the lighter areas signify layups that are comprised of the standard twenty plies. Also shown in the figure are two circles representing the small and large size holes used for this study. Note how the overlaps tend to generate stiffeners-like features, which will carry a larger percentage of the load and effectively unload the thinner regions of the laminate. This feature is expected to be one of the predominant mechanisms, along with increased bending stiffness due to the extra thick regions, that will increase the buckling load and minimize the effect of the central holes. The contours for the stress resultant N_y under a 3000 lb compressive force are shown in Figure 21 for overlap design 4, with a $[\pm45/0\pm<45|60>_2/0\pm<30|15>/0\pm<45|60>]_s$ layup. Note how the thickness variation from the $0\pm<45|60>$ ply groups tends to dictate the load paths for the structure. However, the drastic thickness changes exhibited here may prove to be detrimental during the manufacturing phase. An effective solution to this thickness problem is discussed in Section 4.1.

Relevant results for the final designs are displayed in Table 4. The calculated weight W, critical buckling load F_{cr}, effective stiffness k_{eff} (force per unit displacement) and relative increase to the second buckling eigenvalue (λ_2/λ_1) is supplied for each panel. This last parameter represents the ratio between the first and second eigenvalues, where for all cases the first mode consisted of one half-wave in both directions and the second mode possessed one half-wave in the x-direction and two half-waves in the y-direction, and is included to indicate the possibility of secondary mode buckling for an imperfect panel or a change in mode shape in the postbuckling range of loading. Note that the buckling load levels are much higher than expected from the design studies (reported in Table 2 and Table 3). This is due to the fixed end conditions within the finite element models (simple support conditions were assumed for the design study).

Table 4: *STAGS* results for Final Designs

	$[\pm45_2/\pm30/\pm45/\pm15]_s$ Straight Fiber	$[\pm45/0\pm<45\vert 60>_2/0\pm<30\vert 15>/0\pm<45\vert 60>]_s$	
		Tow Drop Method	Overlap Method
No hole model	W = 2.610 lbs F_{cr} = -9575 lbs k_{eff} = 359.1 kips/in λ_2/λ_1 = 1.065	W = 2.610 lbs F_{cr} = -10589 lbs k_{eff} = 547.9 kips/in λ_2/λ_1 = 1.181	W = 2.911 lbs F_{cr} = -14738 lbs k_{eff} = 630.1 kips/in λ_2/λ_1 = 1.177
Small hole model	W = 2.595 lbs F_{cr} = -9213 lbs k_{eff} = 353.2 kips/in λ_2/λ_1 = 1.132	W = 2.595 lbs F_{cr} = -10288 lbs k_{eff} = 541.2 kips/in λ_2/λ_1 = 1.239	W = 2.898 lbs F_{cr} = -14528 lbs k_{eff} = 624.1 kips/in λ_2/λ_1 = 1.227
Large hole model	W = 2.549 lbs F_{cr} = -8478 lbs k_{eff} = 335.6 kips/in λ_2/λ_1 = 1.266	W = 2.549 lbs F_{cr} = -9589 lbs k_{eff} = 520.3 kips/in λ_2/λ_1 = 1.351	W = 2.848 lbs F_{cr} = -13878 lbs k_{eff} = 602.0 kips/in λ_2/λ_1 = 1.314

4.0 Manufacturing Phase

This final section discusses the details of turning the prototype designs into manufactured panels. Additional fabrication aspects not previously investigated, such as multi-panel construction and optimizing the head width of the tow placement machine, are explored and used to aid in the fabrication process. The algorithm to translate the idealized designs into manufacturing code is outlined, along with slight adjustments that were required for unforeseen problems that arose during manufacture. Lastly, models are constructed to conform to the manufactured parts with these final details in mind, and numerical estimates of buckling loads and stiffness levels are performed for all parts.

4.1 Multi-Panel Construction

To minimize the cost of manufacture, four test panels of each type (straight fiber, tow drop and overlap methods) are fabricated as one large sheet and then machined after cure to separate into individual specimens. The formulation used to define the curvilinear fiber courses is conducive in defining the layup for the large sheet, since the definition repeats with period $2d$ (which is equal to the individual panel width by design). Simultaneous fabrication reduces overall machine time and eliminates scrap, as well as producing test specimens that are manufactured and cured in the same environment. The layout design of four test specimens from one sheet is displayed in Figure 22 for the overlap method, where the darker regions indicate the increased thickness build-up due to the three 0±<45|60> ply groups (the darkest regions) and the 0±<30|15> ply group (the lighter and shallower curves). Note how the overlap regions are symmetric about each panel center due to the cyclic nature of the tow steering definition, yet the intersections of oppositely oriented overlap regions are not regularly spaced across the sheet. This is due to the fact that the locations of the intersections do not depend merely on d, the characteristic distance of the fiber orientation definition, but also on the direction of the fiber course and the width of the tow placement head. For example, if the general direction of the overlap regions are aligned at positive and negative forty-five degrees, the intersections will occur much more frequently than if the direction is at fifteen degrees. Therefore, when overlaps are used the four specimens are not exactly identical due to the non-regular spacing of the intersection points.

To alleviate this problem, interweaving of the identical 0±<45|60> ply groups was performed by re-defining the origin of the variation axes for the second and third 0±<45|60> group. By translating these plies vertically, the drastic thickness build-up was more evenly distributed along the length of the panel and the non-similarity of the test panels was diminished. The distribution of the number of plies in each element for this interwoven technique is displayed in Figure 23, and the stress contours for the resulting models are shown in Figure 24 and Figure 25 for the small and large hole models, respectively. Although the interweaving reduced the variation in thickness, the buckling load showed no appreciable decrease. Furthermore, when a tow drop design is used, the interweaving technique provides an added bonus of distributing the gaps that result from dropping tows more evenly within the structure. Therefore this technique of interweaving ply groups is recommended whenever identical ply groups are present in a tow steered design.

Additionally, in light of the result that the overlap panels depend on the width of the tow placement head, an investigation was conducted to determine the best head width to use for the tow steered designs. The default value assumes 24 tows that are 1/8 inch wide (3.03 inches total, allowing for a 1% space between tows). Models were constructed and analyzed using 12 to 36 tows to determine if the different head widths demonstrated greater improvement and/or increased resistance to the central holes due to the different location of the overlap intersections. However, the results showed little difference between designs with different head widths (less then 2% over the total range). Therefore the designs will use the default value of 24 tows, which is the maximum number of tows in the actual tow placement machine and should minimize fabrication time.

Also shown in Figure 22 are the locations of the central holes for testing, which will be machined in when the specimens are processed. For the tow steered sheets (manufactured using the tow drop and overlap methods), it was decided to produce two test specimens each for the two different hole sizes. For the straight fiber sheet, a baseline panel with no hole will be produced, as well as two with the smaller central hole and one with the larger. The test specimens are labeled and differentiated by construction method (A = straight fiber; B = tow drop; C = overlap) and position on the large sheet (1-4, numbered from left to right). Table 5 on page 13 summarizes the test specimen characteristics. Note that the weight is based on theoretical calculations from the finite element analysis, not the measured weight of the panel.

4.2 Fabrication Details

The prototype parts are fabricated using *VIPER®*, an advanced tow placement machine manufactured by Cincinnati Machine. First however, the final configurations of the prototype designs, including the interweaving technique, multi-panel fabrication method, and head width determination, must be translated into suitable data that can be read by the computer-controlled tow placement machine. This is accomplished through the use of Cincinnati Machine's *ACRAPLACE* software, which is the main interface that supplies the computer-driven commands to the tow placement machine. The general capabilities of *ACRAPLACE* enable the user to implement a variety of options for layup of arbitrary surfaces and parts, and also check feasibility and estimate manufacture time before the actual part is constructed.

For our purposes, the curvilinear fiber paths on a flat panel were translated into *ACRAPLACE* course information on a ply by ply basis using programs written by ADOPTECH personnel, which enabled near exact replication of the idealized designs. This helped to insure the integrity of the finite element models and completed a vital link between design and manufacture. Course information included the coordinates of the path centerline and outer edges, as well as a binary string designating which tows were present. This last feature provided complete control of the tow drops to the designer, so that the cut-off points using the tow drop method could be designed and analyzed before construction to ensure maximum coverage. For example, it was discovered before production that some of the tow drop paths violated a minimum cut length parameter. This parameter is based on the distance from the tow cutter to the application roller on the tow placement head, and each tow path that is started and then cut must exceed this minimum requirement (5 in. for the *VIPER®* machine) otherwise the fiber tow would be cut before the leading end reaches the application head and is compacted to the panel surface. This new constraint was subsequently integrated within the design software and the course data was re-calculated to ensure that unnecessary gaps did not occur in the tow drop panel due to this constraint.

Fabrication of the three sheets was completed in June, 2001 at the Cincinnati Machine facilities in Cincinnati, OH. One final re-adjustment was material selection. The original designs assumed the material properties supplied in Table 1, however that material was not available at time of production. Instead, a 977-2/G40-800 material system was chosen due to its availability, cost, and similarity to the design properties. One major difference, however, was that the slit tape was 0.0054 in. thick as opposed to the design thickness of 0.0075 in. Though this drastically altered the buckling load levels of the panels, it should not significantly affect the relative difference between construction techniques and designs.

Several rough photographs of the panels during production are shown in Figure 26 and Figure 27. Production was hampered by the lack of tackiness of the material, which resulted in numerous restarts of the courses when material would not separate easily from the applicator spools. Due to this problem, production of the three panels required five days when three were originally scheduled. A second set of panels using freshly manufactured material was fabricated in September, 2001 as a follow-up task. During this time frame, tow placement of the fiber tape proceeded without problems and indicated the requirement for quality material during the manufacturing phase. This follow-up task resulted in an extra sheet available for testing for each construction method, and plans for alternate testing of these panels is underway.

4.3 Prototype Part Results

Table 5 supplies some of the final characteristics of the fabricated panels. The weight calculation is based on the finite element models and includes the absence of material in the holes. Analysis data is based on finite element results for models conforming as closely as possible to the actual manufactured panels. Slight variations between panels with identical geometry and layup are due to the differences in orientation angles resulting from the multi-panel construction method, which is accounted for in the finite element models. Also note that the buckling load values are decreased from earlier estimations due to the smaller thickness used in fabrication. A sample shot of a test specimen with a hole that has been machined from the four-specimen panel is displayed in Figure 28.

Table 5: Final Predictions for Fabricated Test Specimens

Specimen designation	Construction method	Central hole	Weight W (lbs)	Stiffness k_{eff} (kips/in)	Buckling load F_{cr} (lbs)	Eigenvalue ratio, λ_2/λ_1
A1	Straight fiber	None	1.879	258.5	-3574	1.065
A2, A3	Straight fiber	1.5″ D	1.868	254.3	-3439	1.132
A4	Straight fiber	3.0″ D	1.835	241.6	-3164	1.266
B1	Tow Drop	1.5″ D	1.868	389.6	-3840	1.239
B2	Tow Drop	1.5″ D	1.868	389.6	-3842	1.239
B3	Tow Drop	3.0″ D	1.835	374.6	-3581	1.351
B4	Tow Drop	3.0″ D	1.835	374.6	-3580	1.351
C1	Overlap	1.5″ D	2.087	449.7	-5425	1.226
C2	Overlap	1.5″ D	2.086	449.3	-5423	1.223
C3	Overlap	3.0″ D	2.052	433.9	-5176	1.317
C4	Overlap	3.0″ D	2.052	433.9	-5183	1.315

The predictions in Table 5 will later be compared with their experimental counterparts. Testing of the panels was completed during the final stages of this publication. The raw test data will be reduced and the results will be reported elsewhere.

5.0 Concluding Remarks

The development of the software tools for the analysis and design of tow steered laminates constitutes a significant step toward fully exploring the usefulness of curvilinear fiber concepts. In particular, the ability to parameterize a tow steered ply with a small number of variables provides the designer with a viable design space for rigorous optimization. Furthermore, integration of the tow steered ply definitions with state-of-the-art finite element programs allows for detailed analysis of the laminates under general loading and boundary conditions. All of these tools should contribute greatly toward the advancement of tow steered concepts for elastic tailoring of composite laminates.

The systematic procedure from design to fabrication employed in this project produced an excellent method for incorporating manufacturing constraints within the design process. By limiting the design choices to feasible configurations, the optimized designs could be directly translated to machine language to provide exact agreement with the prototype parts. The results presented here indicate that significant increases in load-carrying capability compared to traditional straight fiber laminates can be realized, and demonstrate that elastic tailoring is a useful technique for improving the performance of composite laminates.

Figures

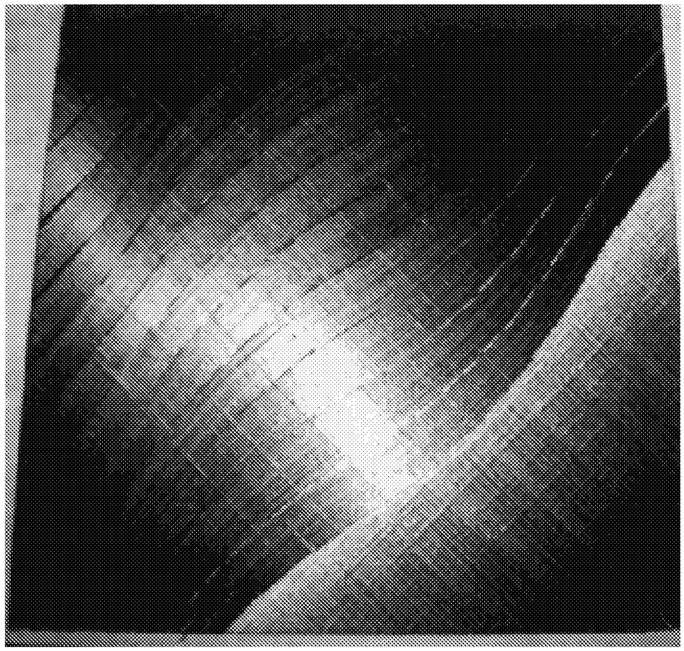

Figure 1: Fabricated Panel using Tow Drop Method

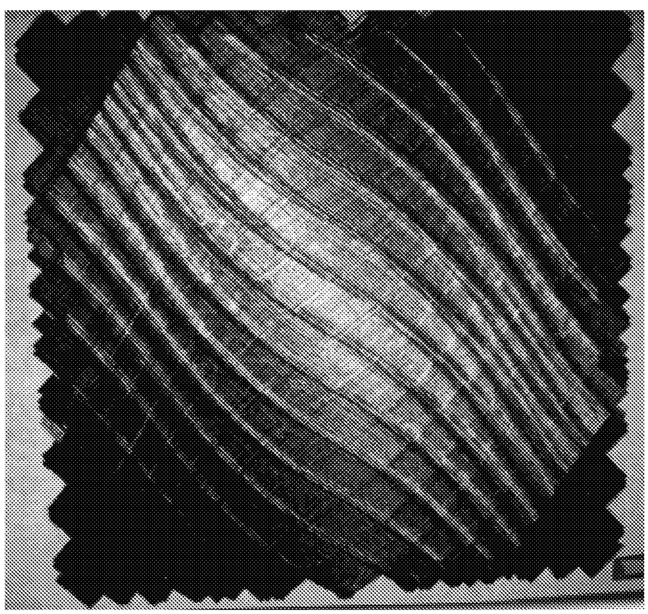

Figure 2: Fabricated Panel using Overlap Method

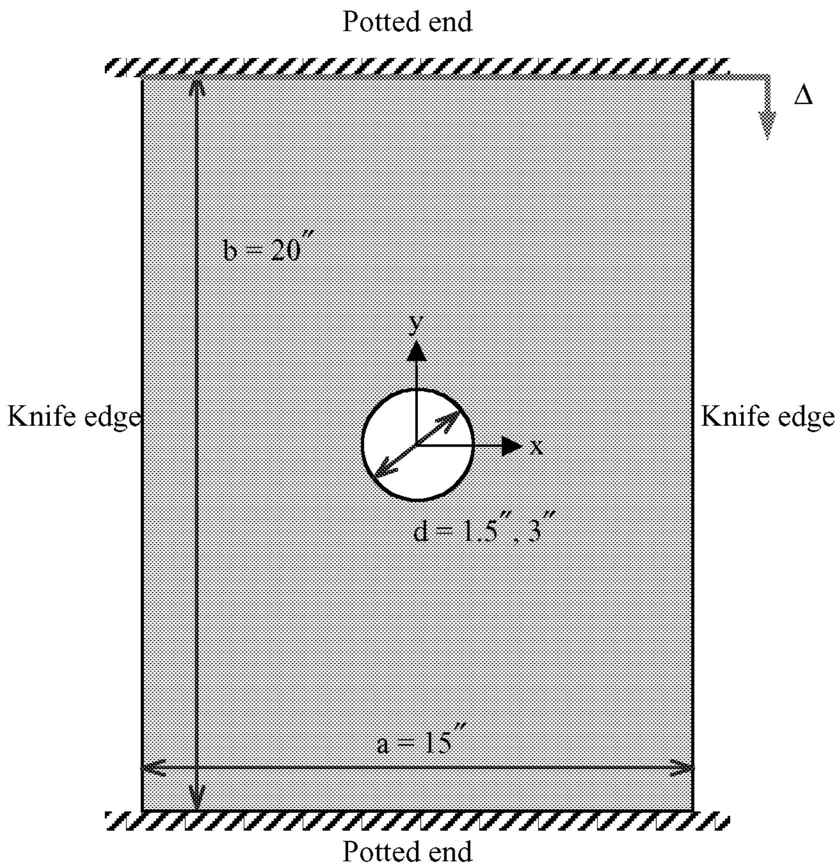

Figure 3: Test Specimen Geometry

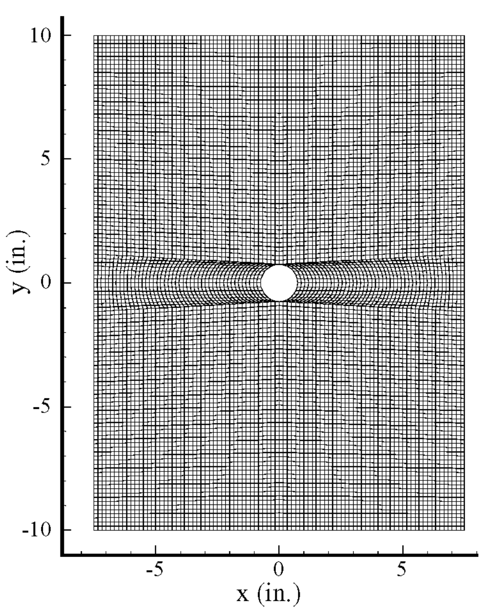

Figure 4 : Small Hole (1.5 in. diameter) Finite Element Mesh for STAGS Analysis

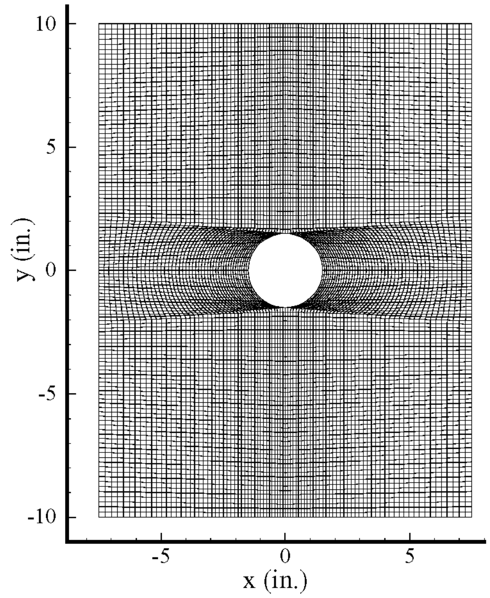

Figure 5: Large Hole (3 in. diameter) Finite Element Mesh for STAGS Analysis

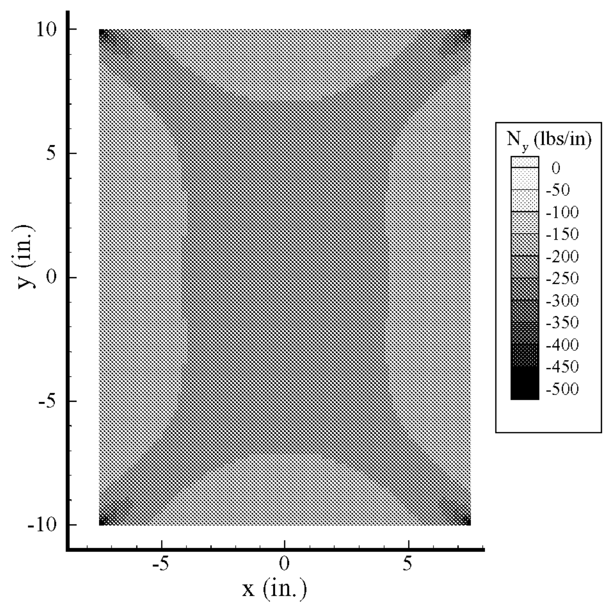

Figure 6: Stress Resultant for [±45$_2$/±30/±45/±15]$_s$ Panel without Hole

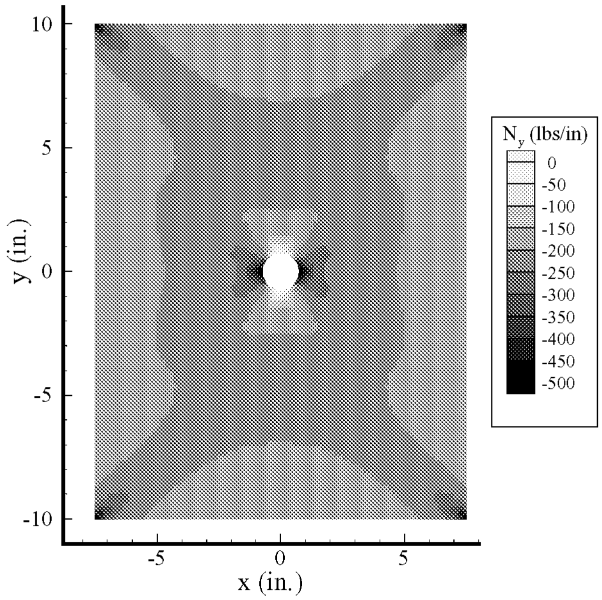

Figure 7: Stress Resultant for $[\pm45_2/\pm30/\pm45/\pm15]_s$ Panel with Small Hole

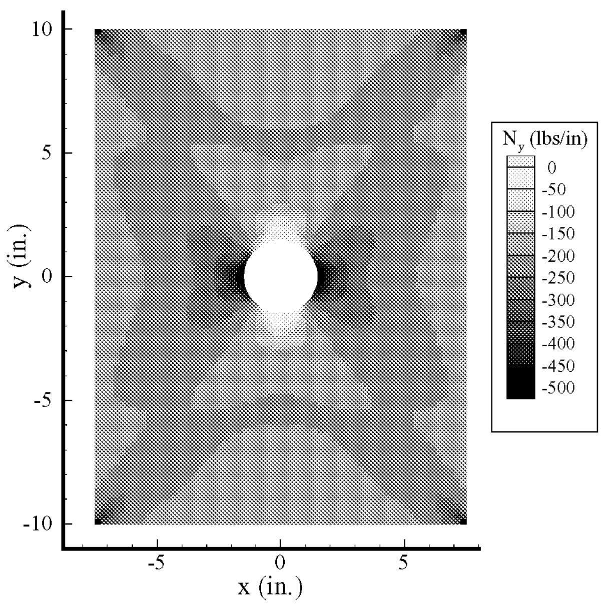

Figure 8: Stress Resultant for $[\pm45_2/\pm30/\pm45/\pm15]_s$ Panel with Large Hole

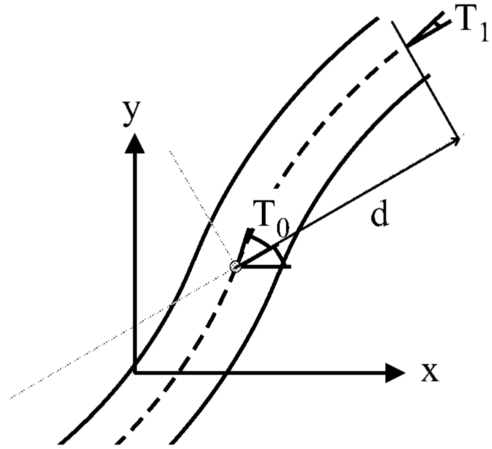

Figure 9: Geometry for Linear Angle Reference Path

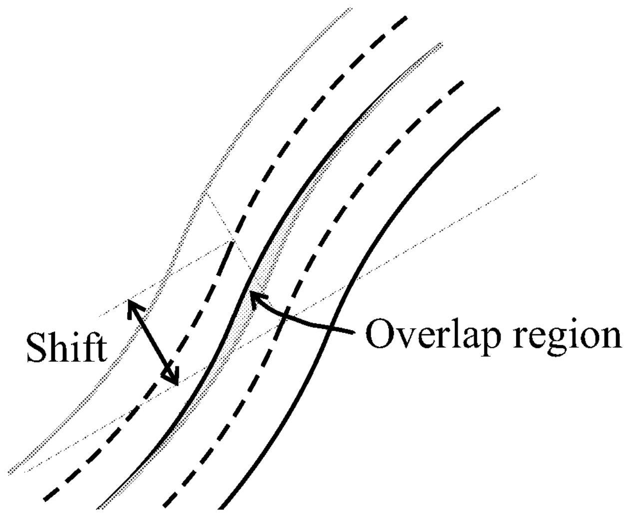

Figure 10: Geometry for Shifted Course Construction

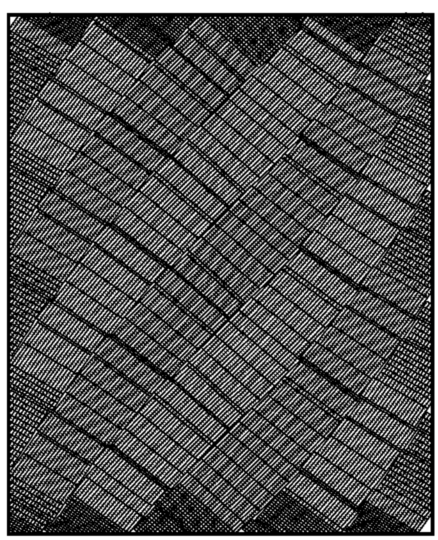

Figure 11: Ply Courses for 0<45|60> Configuration using the Tow Drop Method

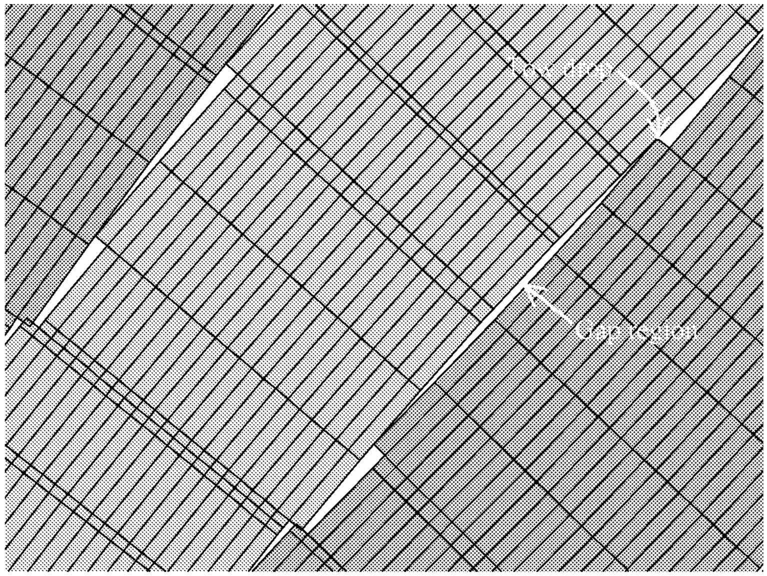

Figure 12: Close-up of Successive Courses for Tow Drop Construction Method

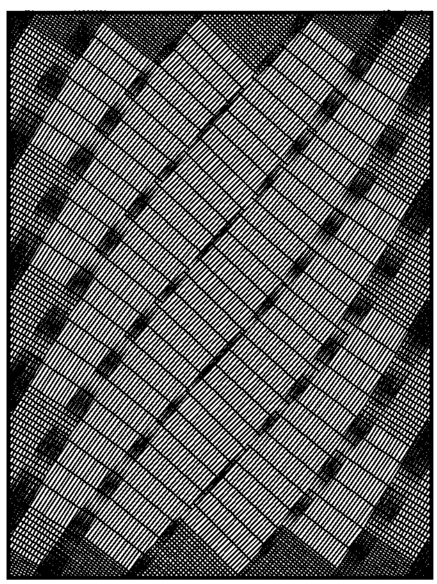

Figure 13: Ply Courses for 0<45|60> Configuration using the Overlap Method

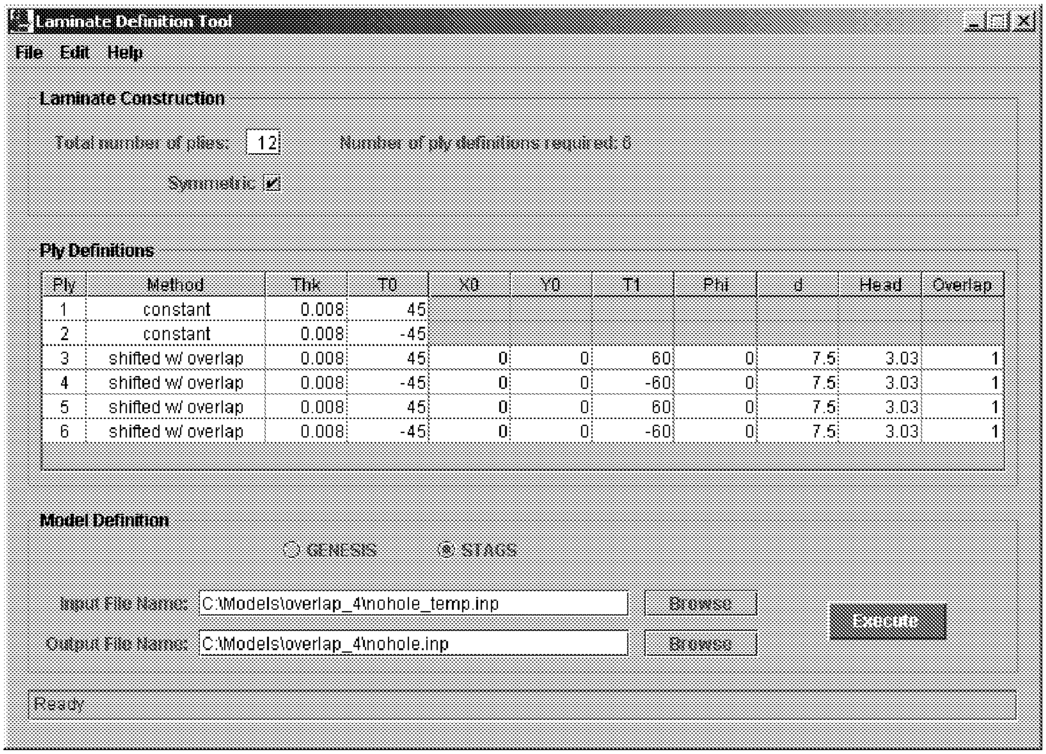

Figure 14: Screenshot of Laminate Definition Tool (*LDT*)

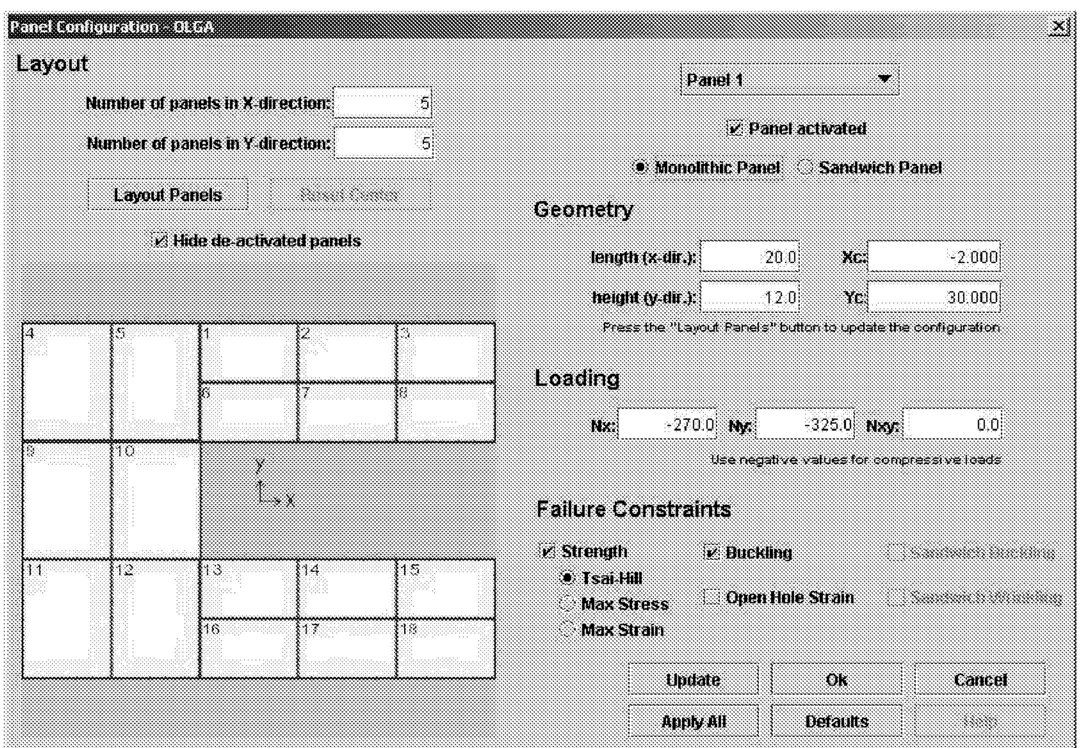

Figure 15: Screenshot of *OLGA* Design Software – Panel Configuration

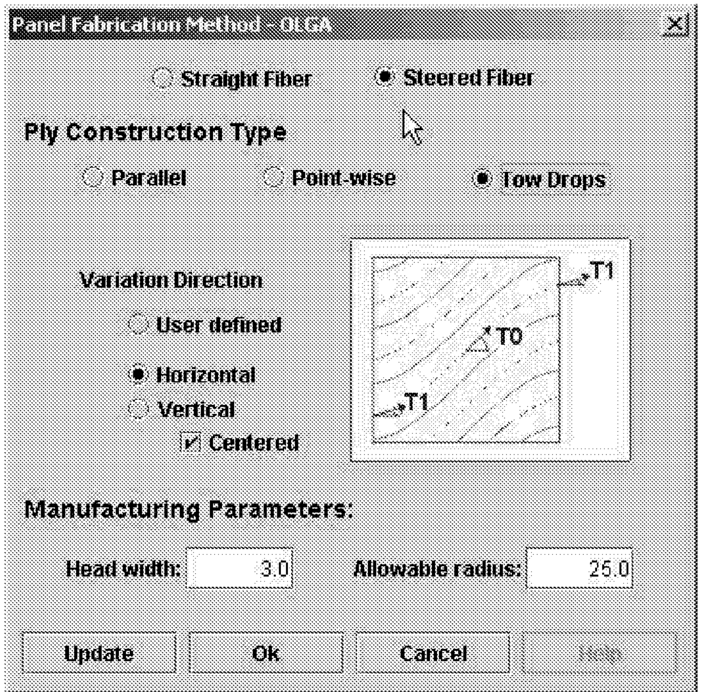

Figure 16: Screenshot of OLGA Design Software – Panel Fabrication Method

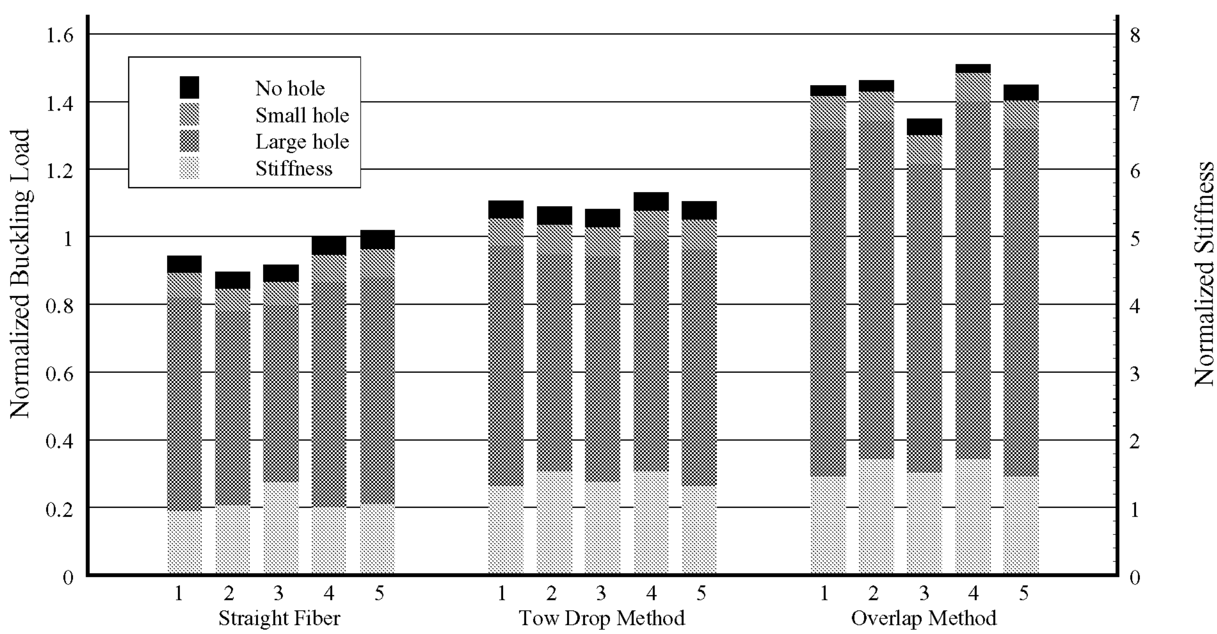

Figure 17: Finite Element Results for Candidate Designs

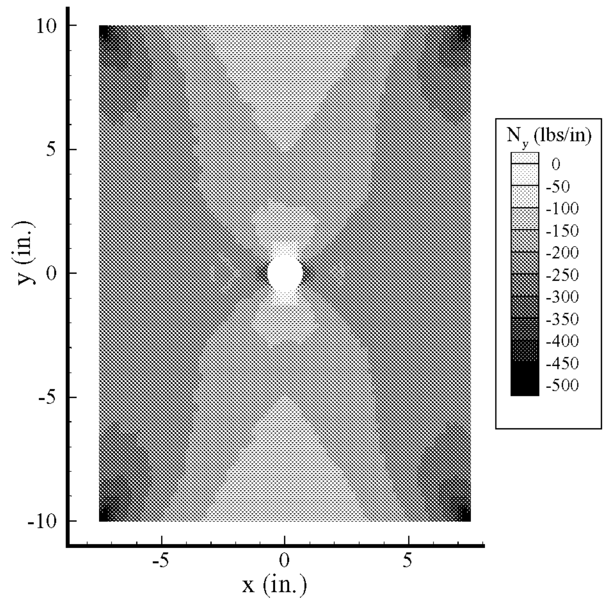

Figure 18: Stress Resultant Plots for [±45/0±<45|60>$_2$/0±<30|15>/0±<45|60>]$_s$ Tow Drop Panel (Small Hole Model)

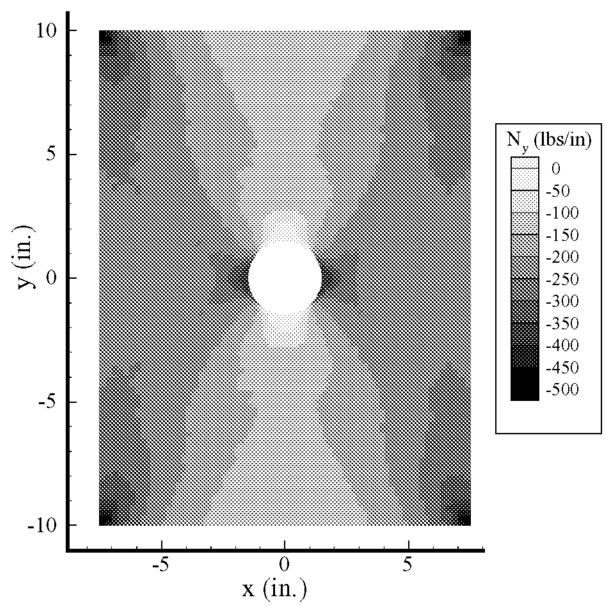

Figure 19: Stress Resultant Plots for [±45/0±<45|60>2/0±<30|15>/0±<45|60>]$_s$ Tow Drop Panel (Large Hole Model)

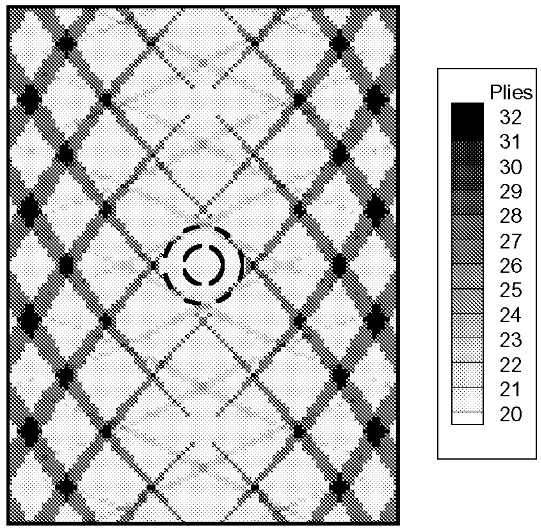

Figure 20: Thickness Distribution for Overlap Method, [±45/0±<45|60>$_2$/0±<30|15>/0±<45|60>]$_s$

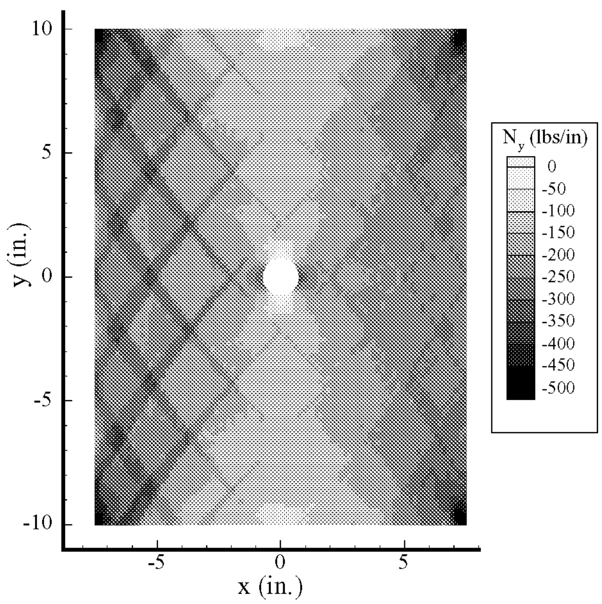

Figure 21: Stress Resultant Contours for Overlap Method, [±45/0±<45|60>2/0±<30|15>/0±<45|60>]$_s$

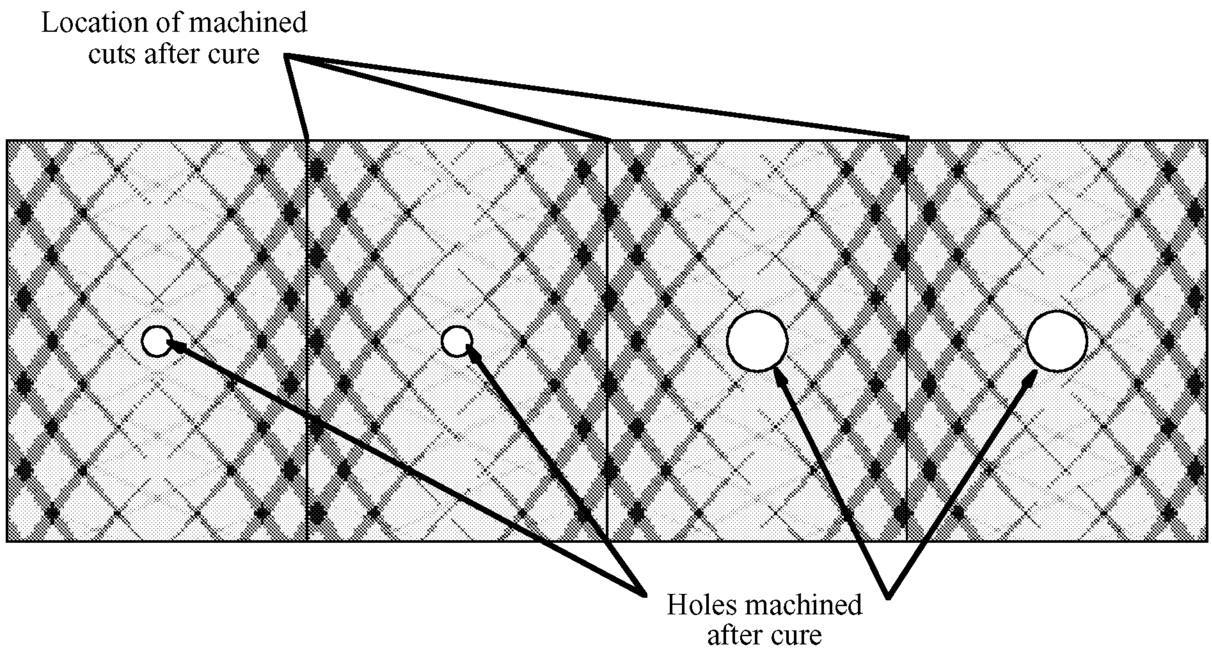

Figure 22: Thickness Distribution of Multi-Panel Layout for Overlap Design (use legend below for contour levels)

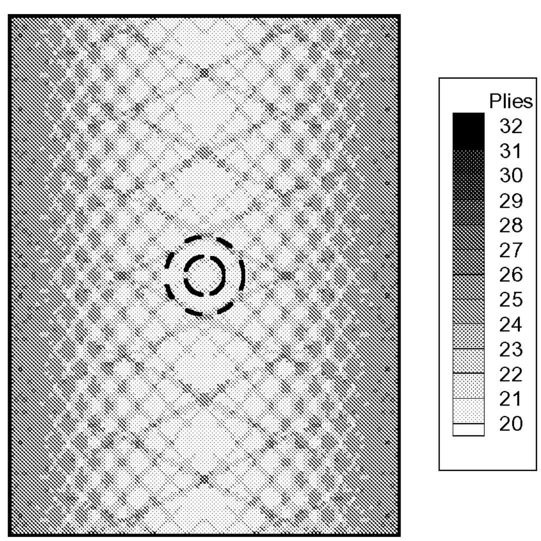

Figure 23: Thickness Distribution for Overlap Design 4 using Interwoven Technique

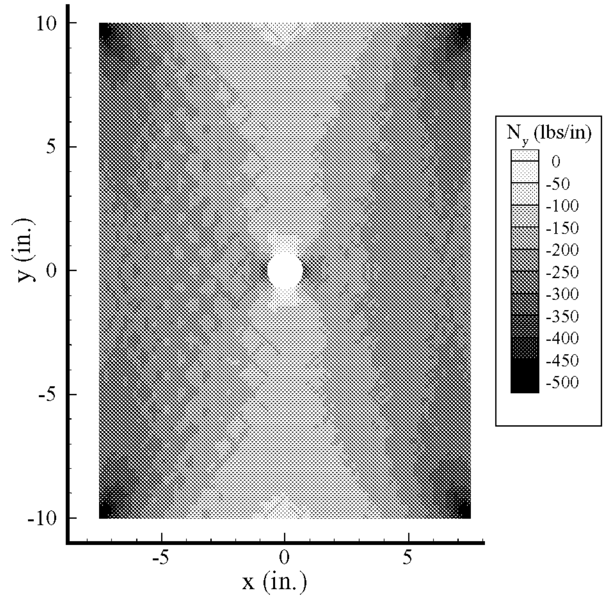

Figure 24: Stress Resultant Plots for [±45/0±<45|60>$_2$/0±<30|15>/0±<45|60>]$_s$ Overlap Panel using Interwoven Technique (Small Hole Model)

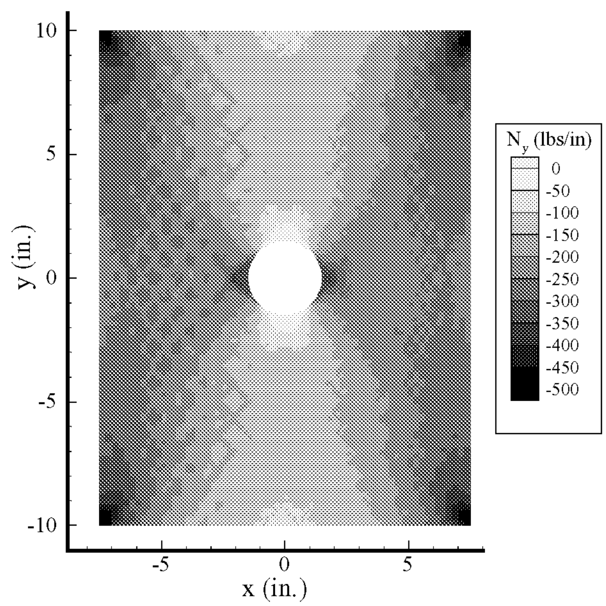

Figure 25: Stress Resultant Plots for [±45/0±<45|60>2/0±<30|15>/0±<45|60>]$_s$ Overlap Panel using Interwoven Technique (Large Hole Model)

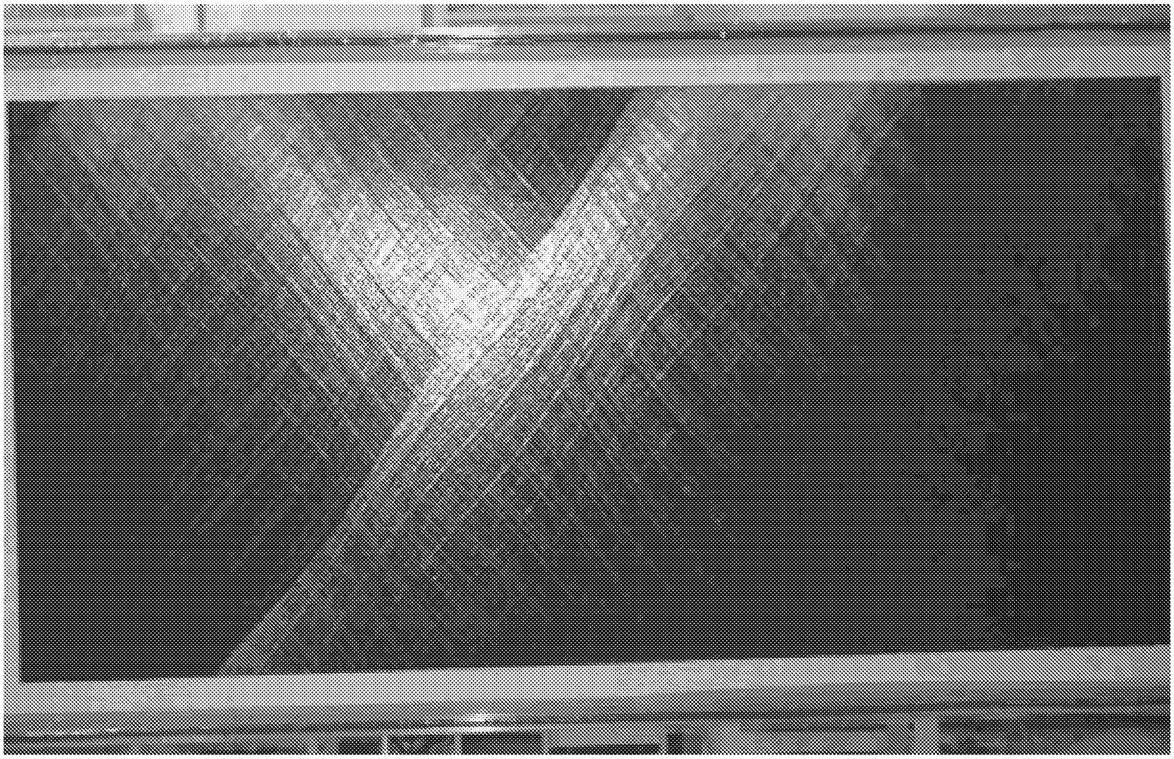

Figure 26: Multi-Panel Sheet for Overlap Construction

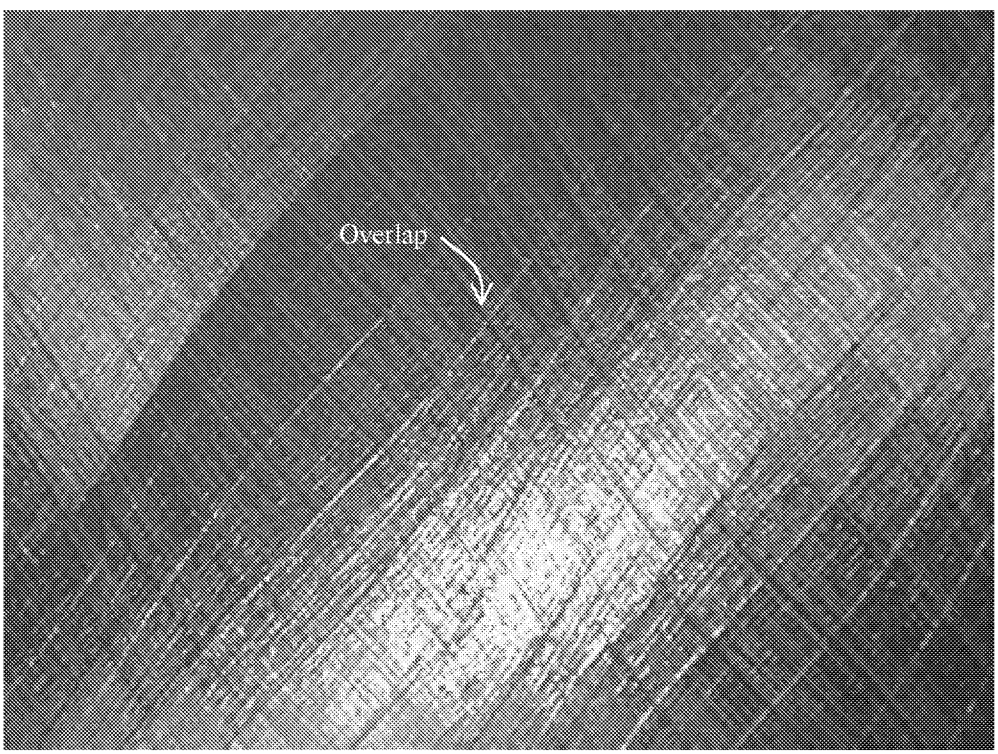

Figure 27: Close-up (2×) of Overlap Panel Sheet Fabrication

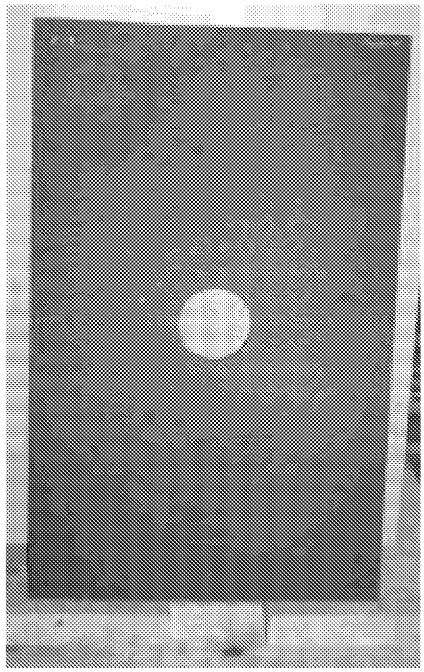

Figure 28: Test Specimen after Machining (Panel C1)
(dimensions 15 in. × 20 in.)

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13. ABSTRACT *(Maximum 200 words)*
Elastic stiffness tailoring of laminated composite panels by allowing the fibers to curve within the plane of the laminate is a relatively novel design concept that has been demonstrated to be both beneficial and practical. In particular, for structures with highly non-uniform stress states, such as the case of a flat panel with a central hole subjected to in-plane loading, the concept is likely to provide substantial improvements in load carrying capability. The objective of the present study is to determine the effectiveness of stiffness tailoring through the use of curvilinear fibers to reduce stress concentrations around the hole and improve the load carrying capability of panels with holes. In this study software was created that translates standard finite element models with traditional laminate definitions into ones that possess stacking sequences with curvilinear fiber paths that are directly manufacturable using an advanced tow placement machine. Preliminary designs for the manufacturing and testing phase were determined through rudimentary design studies for flat plates without holes under axial compression. These candidate designs were then analyzed using finite element models that accurately reflect the test conditions and geometries in order select final designs for testing. A total of six large panels, measuring three feet by six feet, each of which are used to produce four specimens with or without holes, were fabricated and delivered to NASA for machining and testing.

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