A Designed Experiment in Stitched/RTM Composites

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ABSTRACT

The damage tolerance of composite laminates can be significantly improved by the addition of through-the-thickness fibrous reinforcement such as stitching. However, there are numerous stitching parameters which can be independently varied, and their separate and combined effects on mechanical properties need to be determined. A statistically designed experiment (a 2^{5-1} fractional factorial, also known as a Taguchi L16 test matrix) used to evaluate five important parameters is described. The effects and interactions of stitch thread material, stitch thread strength, stitch row spacing and stitch pitch are examined for both thick (48 ply) and thin (16 ply) carbon/epoxy (AS4/E905L) composites. Tension, compression and compression after impact tests are described. Preliminary results of completed tension testing are discussed. Larger threads decreased tensile strength. Panel thickness was found not to be an important stitching parameter for tensile properties. Tensile modulus was unaffected by stitching.

INTRODUCTION

Advanced polymeric composite materials offer significant potential for weight savings and performance advantages over traditional aircraft materials. Compared to metallic materials, composites offer tailorability of properties along with very high specific strengths and stiffnesses. However, conventional laminated composite structures are presently expensive to manufacture and are less damage tolerant than desired. A major goal of the NASA Advanced Composite Technology (ACT) program is to develop these materials for use in primary structure of commercial aircraft. To meet this goal, the problems of high cost and low damage tolerance must be overcome.

One of the innovative manufacturing concepts being explored under the ACT program is the resin transfer molding (RTM) of dry fabric lamina which have been stitched together. References [1] through [5] discuss the advantages of using modified sewing technology to place fibrous reinforcement through the thickness of a laminated composite preform. The approach offers great potential for lowering manufacturing cost and improving damage tolerance. Aircraft part fabrication using both single needle and multiple needle stitching machines in conjunction with resin transfer molding offers economies in materials handling, automation and reduced part count. In addition, the transverse (thickness direction) reinforcement has been shown to significantly improve the damage tolerance of otherwise brittle composites.

Previous research (references [2]-[5]) has shown that strong threads (e.g., 1000 denier Kevlar®) stitched at a high density (on the order of 30 to 60 stitches per square inch) can significantly improve the compression after impact properties and interlaminar fracture toughness of laminated composites. In fact, sufficient transverse reinforcement can effectively eliminate interlaminar failure modes. However, this improvement in out-of-plane performance comes with a degradation of the in-plane mechanical behavior (e.g., lower tensile and compressive properties) [2]-[5].

Experimental research such as that discussed in references [2]-[5] form the basis for the current state-of-the-art in composite stitching technology. Adequate analytical tools able to accurately predict the mechanical behavior of these 3-D reinforced composites do not exist. Work is being done under the ACT program to develop such tools. Although the data base on stitched composites is growing, it is heavily slanted towards thick laminates. Current stitching work by the aerospace industry has focused on transport point designs, e.g., a thick wing layup. General empirical material design guidelines do not exist for selecting stitching patterns, thread material, thread strength, etc.

With these ideas in mind an experimental study was undertaken to determine the relative significance of important stitching variables. The research examines the trade-offs involved in improvement of damage tolerance combined with the loss of in-plane mechanical performance. The interaction of important variables such as panel thickness and the amount of stitching are also addressed. Experimental design techniques were used to lay out a test matrix with five important stitching variables. This research is well underway, but this study is not yet complete. Results available to date are presented in this paper. The results gained from the completion of the test matrix will be used to build regression models with the overall objective of providing stitching guidelines for aircraft material design.

MATERIALS

Constituent Materials

The materials manufactured for this study were flat panels of stitched carbon/epoxy. The in-plane lamina were AS4 3k uniweave fabric produced by Textile Technologies Inc. A uniweave fabric is a loosely woven fabric where roughly 98% of the fiber (3k carbon warp tows, 18 tows per inch,150 g/m^2 of graphite) lies in one direction. The 2% fill fiber is a fine denier E-glass yarn (Owens/Corning ECD 450 1/0 1.0Z 620-1, 9 yarns per inch) which serves only to hold the carbon together as a fabric. All fibers were purchased with an epoxy compatible sizing.

Two types of stitching thread were selected, Kevlar® 29 and S2 glass, with two threads of each type. The four stitching threads are listed in table I along with the other constituent materials. The threads were selected such that one Kevlar® and one glass would have a breaking load of about 60 lbs. The other two threads were chosen to have breaking loads of about 10 lbs. A fifth thread, a 200 denier two-end-twisted Kevlar®, was used as a needle thread in all panels. Stitching details will be discussed in detail in the next section

The matrix resin was British Petroleum's E905L two part epoxy. E905L was developed as an aerospace grade RTM resin and is one of the RTM resins being evaluated under the ACT program.

Preform Details and Stitching Variables

The preform details are shown in figure 1. The uniweave fabric layers were stacked in a quasi-isotropic layup, $[+45/0/-45/90]_{ns}$. These preforms were then stitched by Ketema, Textile Products Division. The stitching was done in parallel rows in the 0° direction using a modified lock stitch. It has been shown that stitching in only one direction provides adequate damage tolerance [3]. The modified lock stitch shown in figure 1 may be referred to as a "modified lock stitch up." In this case, the needle and needle thread punctures through the fabric stack and pulls the bobbin thread and stitching knot back up through the preform. The bobbin thread is thus the "stitching" thread since it acts as the through the thickness reinforcement. The knot and the smaller needle thread lie on the top surface. Actual photos of panel surfaces showing the stitch threads are displayed in figure 2.

In the future, economies of production may warrant using the larger thread as a needle thread, thus creating a "modified lock stitch down." The bobbin has a limited thread supply while the needle thread supply is much larger. Hence, if the larger thread is used with the larger supply, the bobbin would not need to be refilled as often. In the case of the modified lock stitch down, the needle thread acts as the through the thickness fiber. The needle thread follows a path down through the preform and the stitching knot and bobbin thread lie on the bottom surface. This resulting structure is a mirror image of the modified lock stitch up. The effect on mechanical properties of such variations in the stitching process remain to be explored.

The important stitching variables selected for consideration in this work are shown in figure 1. These parameters are stitch pitch (stitches per inch in each row), stitch row spacing, stitch thread material, and stitch thread strength or size (diameter) and panel thickness (no. of plies). Panel thickness, while not exactly a stitching variable, may play a significant role in the material behavior. Reference [6] suggests that the loop on the surface formed by the heavy stitching thread has a detrimental effect on mechanical performance due to the crimping of the in-plane load carrying fibers. This fact suggests that there could be a strong interaction between thickness and stitching. Given the same amount of stitching, a thinner composite may suffer a greater loss than a thick composite since the loops of large stitching thread on the surface could crimp a higher percentage of in-plane fibers.

Resin Transfer Molding

The dry stitched preforms were resin transfer molded (RTM) by Boeing Aerospace. A schematic of the RTM process is shown in figure 3. The two part liquid resin (E905L) was mixed and pumped into the picture frame mold containing the preform. The entire mold assembly was placed in a hot press. The mold was closed to a preset thickness controlled by a shim or caul plate (see figure 3). To avoid as much variation as possible, the same shim was used to make all panels of the same thickness. Based on fabric areal density, a panel thickness was calculated to result in a nominal in-plane fiber volume fraction (i.e., volume fraction of the carbon fiber only) of 0.60. All panels were manufactured to within ± 0.005 in. of their targeted thickness.

DESIGN OF THE EXPERIMENT

There are a large number of potentially important variables associated with stitched composites. In addition, many interactions among the variables may be as much or more important than individual variables themselves. A large number of variables and their interactions can be studied with a relatively small number of tests with the proper use of experimental design techniques. This cannot be done with the traditional "change one factor at a time" approach. For these reasons, experimental design techniques were employed for this research. Discussion of such techniques may be found in many textbooks including reference [7].

Two key elements of the experimental design techniques used in this work are a balanced orthogonal test matrix and factor transformation. A balanced orthogonal test matrix enables the different variables (factors) and their interactions to be evaluated simultaneously and independently of each other. In effect, the test matrix (i.e., different combinations of levels of the assorted factors) is laid out in such a way that the responses of the variables and variable interactions do not overlap at all or overlap in a known manner.

Factor transformation is another key element of experimental design. It would be difficult to statistically analyze a discrete variable such as stitch thread material which is measured in increments of "Kevlar®" and "glass." To enable variables measured in different units to be compared equally, the factor's values are transformed into a common domain. In a two level experiment (variables evaluated at two levels, a high and a low value), the values are transformed into a -1 and +1. Thus Kevlar® and glass become -1 and +1, respectively, and can be evaluated equally along with the other variables, all having transformed ranges from -1 to +1. A well designed experiment using transformed factors in a balanced and orthogonal test matrix will enable tools such as multiple regression to be used to develop a predictive capability based on both important variables *and* their interactions.

A 2^{5-1} fractional factorial experiment was selected to study the five variables described in the previous section. The 2 refers to a two level experiment where each variable was evaluated at two different levels. In all, 32 different combinations of five factors at two levels are possible. A 2^{5-1} is a resolution V design (reference [7]), allowing all five variables and their two-way interactions to be evaluated independently with only 16 different combinations (tests or runs). This experimental design is equivalent to a Taguchi L16 test matrix [7].

A stitched composite panel was made for each of the 16 different combinations of stitching variables. Two unstitched panels were also manufactured for comparative purposes. The test matrix is shown in table II. Panel thickness was evaluated at 16 plies (thin, 0.09 in.) and 48 plies (thick, 0.27 in.). These thicknesses approach practical applications in an aircraft fuselage (thin) skin and a wing (thick) skin. The values of stitch thread material, stitch thread strength, stitch row spacing and stitch pitch were selected based on the findings of references [2]-[5]. Heavy Kevlar®, glass and carbon threads were found to be equally effective in improving damage tolerance in [2] and [3]. Kevlar® and glass threads were selected over carbon stitching thread based on cost, availability and ease of stitching. The thread strengths (breaking loads) of 10 and 60 lbs were selected to give an adequate range which might apply to both thick and thin panels. The high and low values of row spacing and pitch were chosen to be 4 and 8. These values resulted in stitching densities (stitches per square inch) ranging from 16 to 64, a range similar to those studied in [2]-[5].

Efforts were made to reduce process variations to only those described above for the five variables. These efforts included using the same manufacturers, equipment and operators (where possible) to make all panels. To insure resin consistency, all panels were made from the same batch of E905L resin. To keep thickness constant, the same shim was used to make all panels of the same thickness.

MECHANICAL TESTING

Tension, compression and compression after impact (CAI) testing was planned to evaluate the effects of the stitching process. The test specimen configurations are shown in figure 4. To date only the tension testing has been completed for the full test matrix. Hence, the remainder of this paper will focus on some of the preliminary results from the tensile testing.

Three tensile specimens were cut and tested from each panel. The testing was performed in the 0° direction, parallel to the rows of stitching. The specimens were instrumented with 350 ohm back-to-back strain gages as shown in figure 4. Data were gathered with a 16 bit resolution A/D micro-computer-based data acquisition system. The tension tests were performed at a constant stroke of 0.05 in./min in a 50 kip electro-hydraulic test machine equipped with hydraulic grips. The specimens were un-tabbed, but each end had a coarse grit paper and lexan film between the knurled grips and specimen.

RESULTS AND DISCUSSION

Tensile properties for both the stitched and unstitched panels are listed in table III. The values listed are the averages of three tests. The coefficients of variation for the strength and ultimate strain were typically less than 5% and were 10% or less in all cases.

The modulus had much less variation with coefficients of variation being 3% or less.

Figure 5 compares the strengths and moduli for the thick and thin unstitched materials. The error bars in the graphs represent the entire range of the three repeat tests. While there was no difference between the moduli of the thick (48 ply) and the thin (16 ply) materials, figure 5 shows a slight difference in strength. The average strength of the thin panels was 100 ksi while the average strength of the thick panels was 95.9 ksi. The respective data ranges overlapped slightly and the difference in strength was not large enough to be considered significant. It should be noted that the thin unstitched specimens were inadvertently cut in the 90° direction. Several short (5.75 in.) tension specimens were cut in the proper direction from scrap material and then tested. As expected for a quasi-isotropic layup, the strengths, moduli and failure strain results for these additional tests suggested that there was no significant difference between 0° and 90° properties.

The tensile strengths for the stitched materials are shown in figure 6. The strength is shown as a fraction of the unstitched material strength, i.e., a ratio of thick stitched strength over thick unstitched strength or thin stitched strength over thin unstitched strength. This fraction of unstitched strength has been plotted in the form of a marginal means plot. Each data point in the plot (X) represents the average of the strengths of all panels made at the value of the corresponding variable on the abscissa. For example, the first X , shown above the thread strength of 10, is the average of the strengths of all panels stitched with a thread breaking load of 10 lbs. There were 16 stitched panels with 8 panels manufactured at the high value of each variable and 8 panels at the low value. Therefore each X represents 24 tension tests (8 panels, 3 tension coupons each). This type analysis allows the variables to be independently considered and compared with each other. The slope of the line connecting the X's for the high and low values of each variable is a measure of the significance of that variable. A steep slope indicates that variable has a large effect on tensile strength. The variables have been listed on the abscissa in the order of decreasing significance (decreasing absolute value of slope).

As shown in figure 6, increasing the thread breaking load from 10 to 60 lbs decreases the tensile strength. This decrease in tensile strength may be attributed to the larger diameter of the larger threads. A larger diameter thread will cause more crimping and curvature of the in-plane carbon fiber, and hence, a larger reduction of unstitched strength. The effect of the stitch thread diameter may also be seen in the effect of the thread type. The glass threads reduced the tensile strength more than the Kevlar® threads. Of the two larger threads, the glass thread had a significantly larger diameter than the Kevlar® (see table I).

The effects of changing the stitching density (penetrations per unit area) can also be seen in figure 6. Increasing the number of stitching rows per inch decreased the tensile strength. Similar results were reported in [2]-[5] where increased stitching lowered the in-plane properties. The increase in tensile strength gained by increasing the pitch from 4 to 8 cannot be explained at this time. A similar finding can be seen in the data of [2]; however, thickness was not kept constant in reference [2] and a strong trend is not identifiable . In the current work, an analysis of variation has yet to be completed. More analysis is underway to establish the level of noise or random variation, and thus gain a better measure of the significance of the effects of changing theses variables.

Even without considering the level of noise, the effect thickness (number of plies) on tensile strength is negligible. As discussed earlier, reference [6] reported that the unavoidable surface loop associated with stitching reduced compression strength. However no tensile testing was performed in [6]. Thickness may play a more significant role in the subsequent compression and CAI testing yet to be completed.

The effects on strength caused by changing the variables as discussed above are plainly evident in figure 6. However, these same variables had no significant effect on modulus (see table III). Over the ranges of the parameters studied, stitching did not cause meaningful changes in tensile modulus.

CONCLUDING REMARKS

A research project investigating the effects of five stitching variables on the mechanical properties of stitched carbon/epoxy composites has been outlined. The effects of panel thickness, stitching thread material, stitch thread strength, stitch row spacing and stitch pitch on tension, compression and compression after impact properties were included. The tension testing has been completed and preliminary analysis has revealed that tensile modulus remained unaffected by stitching. Larger stitching threads were found to have a detrimental effect on the tensile strength. The loss of tensile strength due to stitching was found to be the same in both the thick (48 plies) and thin (16 plies) panels. In fact, the data suggested that an interaction between thickness and stitching did not occur. However, these findings apply only over the specific parameter ranges covered in this study, and are true only for tension properties. Since fiber waviness or crimp plays a more significant role in compression than in tension, the effects of the variables on the compressive and CAI properties may be expected to be different.

The described compression and CAI testing is in progress. Some testing 90° to the stitched direction is also planned. Experimental design analysis techniques will continue to be employed. The future work will include a detailed look at the random variation within the experiment. Once the unimportant variables are eliminated (e.g., thickness in the case of tension), regression models will be developed to describe the behavior of these materials. These models, along with knowledge gained from the experiment, will be used to generate general stitching guidelines for the design of stitched composite materials.

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Table I. Constituent Materials

Uniweave fabric	AS4 3k carbon fiber	
Matrix resin	E905L epoxy	
Stitching threads	breaking load (lb)	cross sectional area ($in.^2$)
• Kevlar 29 1500 denier	60	1.79
• Kevlar 29 400 denier	10	0.48
• S2 1250 449AA glass	60	2.52
• S2CG 150 493 glass	10	0.41

Table II. Test Matrix

PANEL #	# OF PLIES	THREAD TYPE	THREAD STR. (lbs)	ROW SPACING (rows/in.)	PITCH (stitches/in.)	THICKNESS (in.)
1	16	KEVLAR	10	4	8	0.09
2	16	KEVLAR	10	8	4	0.09
3	16	KEVLAR	60	4	4	0.09
4	16	KEVLAR	60	8	8	0.09
5	16	GLASS	10	4	4	0.09
6	16	GLASS	10	8	8	0.09
7	16	GLASS	60	4	8	0.09
8	16	GLASS	60	8	4	0.09
9	48	KEVLAR	10	4	4	0.27
10	48	KEVLAR	10	8	8	0.27
11	48	KEVLAR	60	4	8	0.27
12	48	KEVLAR	60	8	4	0.27
13	48	GLASS	10	4	8	0.27
14	48	GLASS	10	8	4	0.27
15	48	GLASS	60	4	4	0.27
16	48	GLASS	60	8	8	0.27
17	16	Unstitched	-	-	-	0.09
18	48	Unstitched	-	-	-	0.27

Table III. Tensile Properties of Stitched and Unstitched Quasi-isotropic Laminates

PANEL ID	STRENGTH (KSI)	Strength fraction of unstitched	ULTIMATE STRAIN (%)	Ult. strain fraction of unstitched	MODULUS (MSI)	Modulus fraction of unstitched
1	91.1	0.91	1.27	0.91	7.44	1.02
2	96.3	0.96	1.31	0.94	7.68	1.05
3	92.7	0.93	1.22	0.87	7.81	1.07
4	89.1	0.89	1.26	0.89	7.48	1.02
5	89.6	0.90	1.26	0.90	7.36	1.01
6	95.6	0.96	1.31	0.94	7.67	1.05
7	93.5	0.93	1.30	0.92	7.71	1.05
8	80.7	0.81	1.17	0.83	7.18	0.98
9	91.5	0.95	1.25	0.93	7.53	1.03
10	90.4	0.94	1.28	0.95	7.30	1.00
11	87.9	0.92	1.24	0.92	7.22	0.99
12	84.5	0.88	1.18	0.87	7.35	1.00
13	92.9	0.97	1.29	0.95	7.42	1.01
14	81.3	0.85	1.14	0.85	7.34	1.00
15	82.3	0.86	1.18	0.87	7.37	1.01
16	82.8	0.86	1.22	0.91	6.93	0.95
17	100.0	1.00	1.40	1.00	7.31	1.00
18	95.9	1.00	1.35	1.00	7.33	1.00

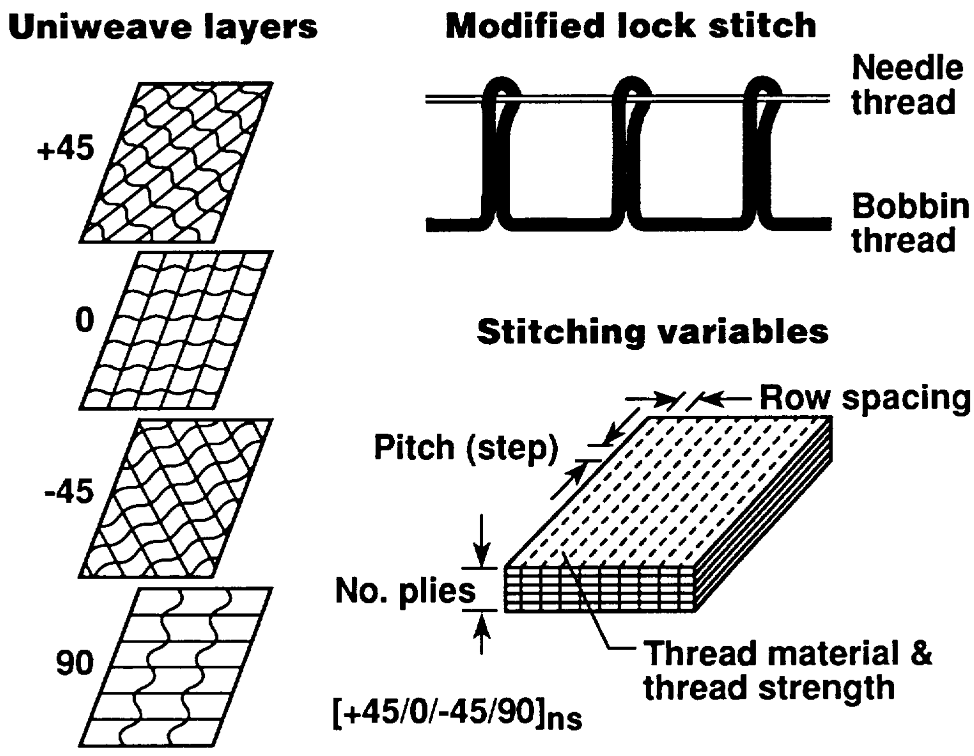

Figure 1. Preform stacking sequence and stitching parameters.

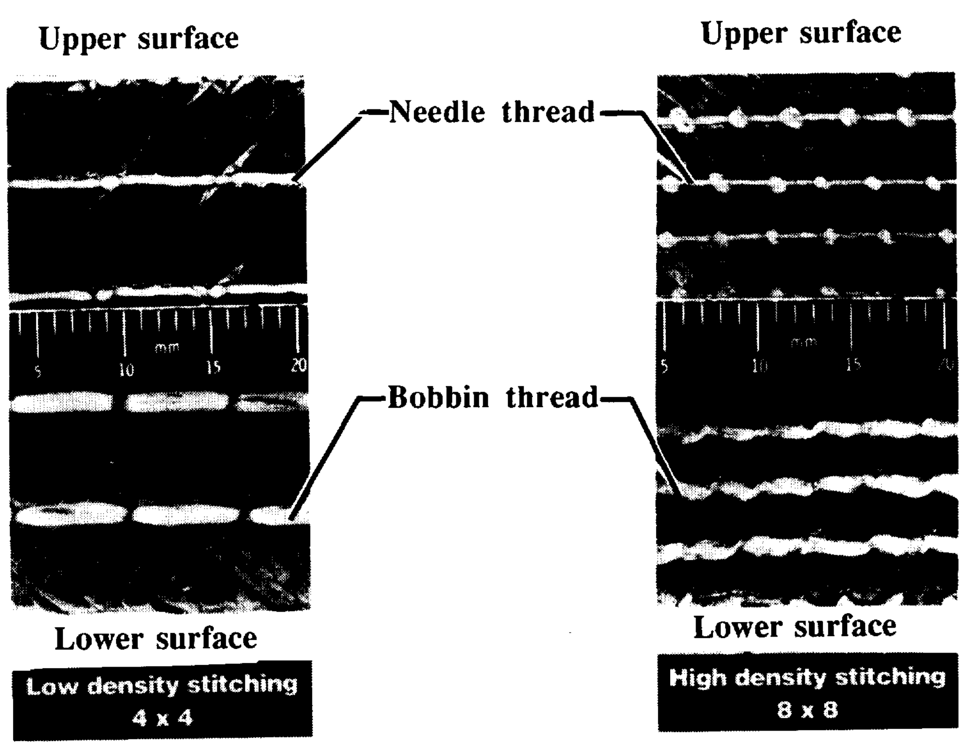

Figure 2. Surfaces of stitched panels.

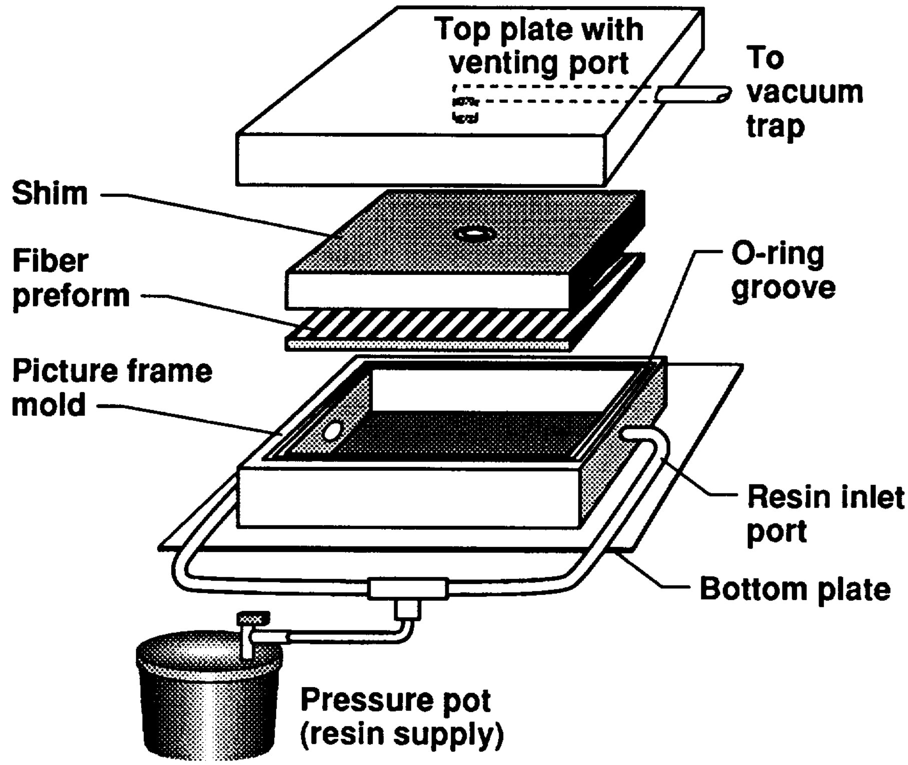

Figure 3. RTM process schematic.

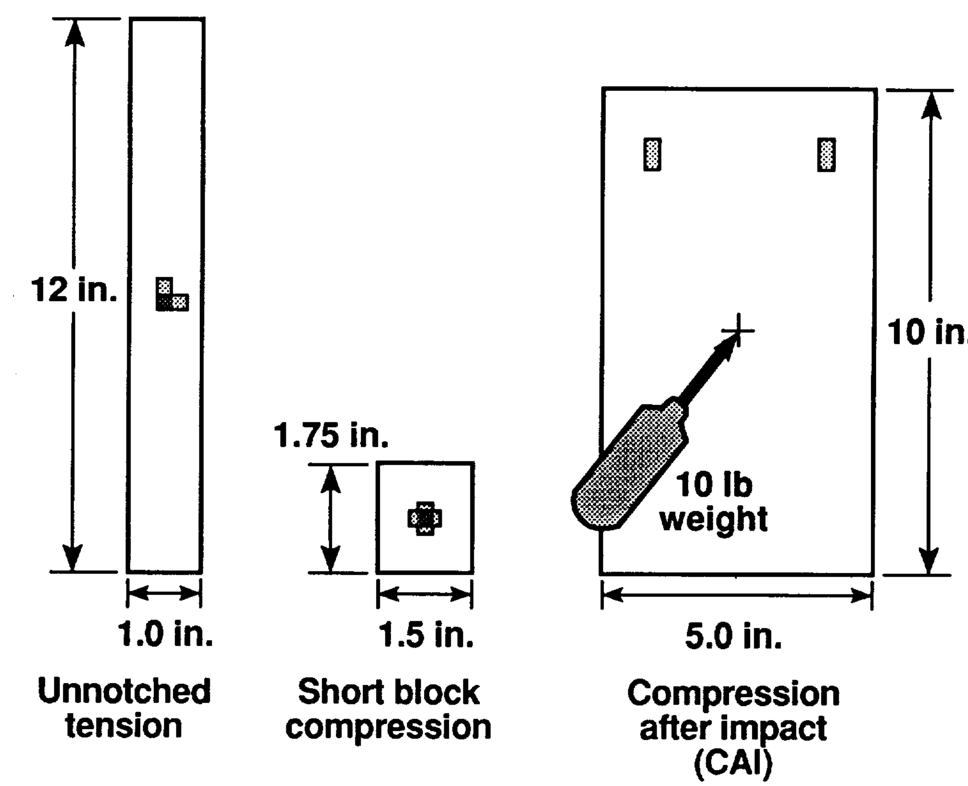

Figure 4. Test specimen configurations.

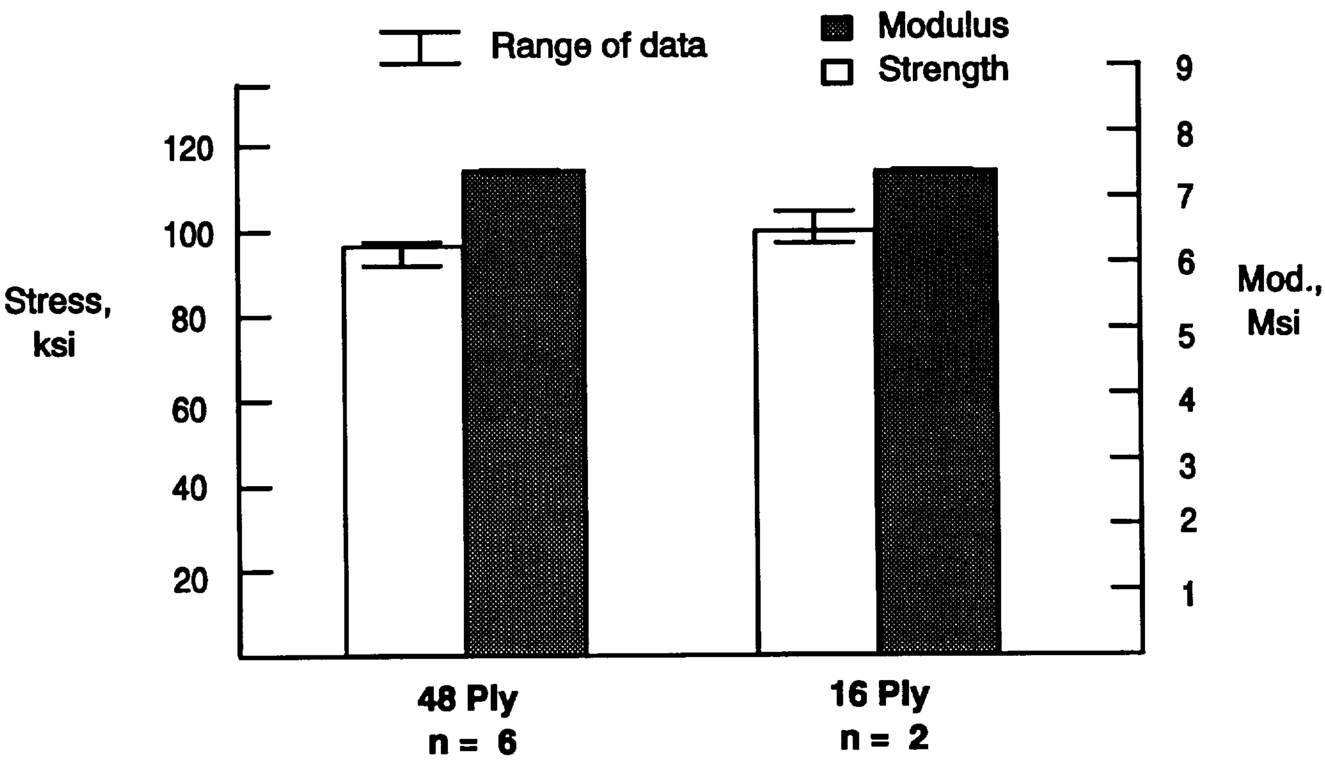

Figure 5. Unstitched tensile properties of quasi-isotropic panels.

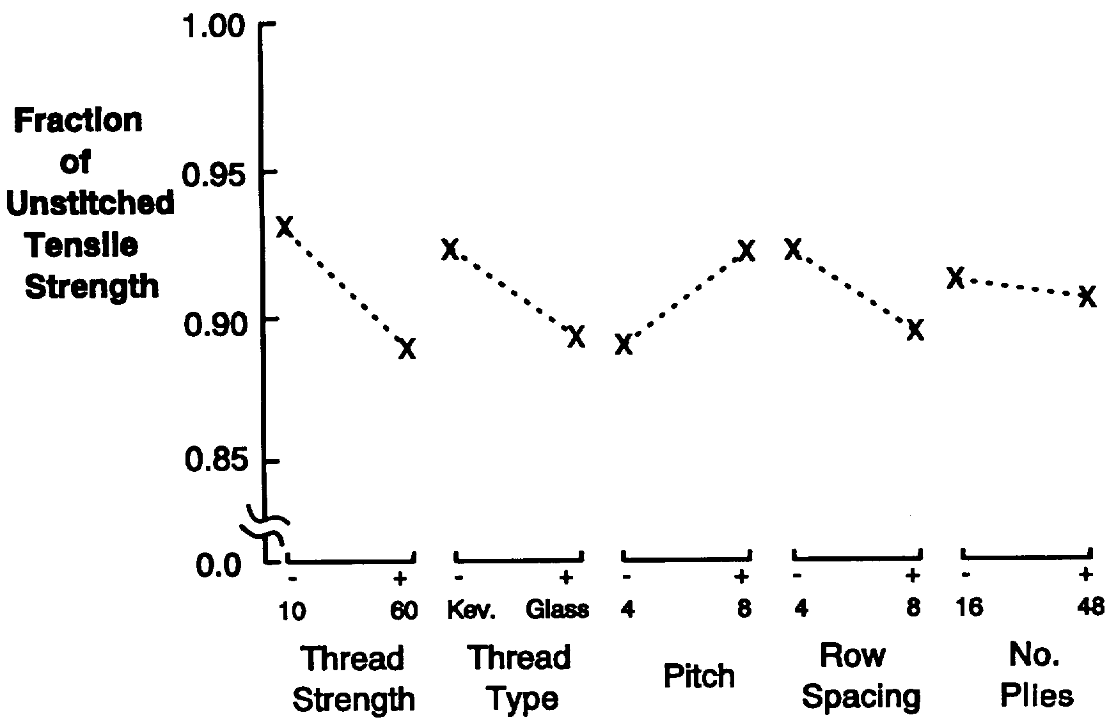

Figure 6. Tensile strengths of stitched quasi-isotropic panels.