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DEVELOPMENT OF STITCHING REINFORCEMENT FOR TRANSPORT WING PANELS

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INTRODUCTION

The NASA Advanced Composites Technology (ACT) Program has the objective of providing the technology required to obtain the full benefit of weight savings and performance improvements offered by composite primary aircraft structures. Achieving the objective is dependent upon developing composite materials and structures which are damage tolerant and economical to manufacture. Researchers at Douglas Aircraft Company and NASA Langley Research Center are investigating stitching reinforcement combined with resin transfer molding to produce materials meeting the ACT Program objective. The Douglas work is being done under a contract entitled Innovative Composites Aircraft Primary Structures (ICAPS).

The Douglas research is aimed at materials, processes and structural concepts for application in both transport wings and fuselages, but the emphasis to date has been on wing panels. Empirical guidelines are being established for stitching reinforcement in structures designed for heavy loads. Results are presented from evaluation tests investigating stitching types, threads and density (penetrations per square inch). Tension strength, compression strength and compression strength after impact data are reported.

New composite material and manufacturing concepts are required to overcome the cost and performance barriers that now limit the application of composites in aircraft primary structures. As shown in figure 1, the approach adopted by Douglas Aircraft Company for achieving affordable and durable composites involves three steps: first, stacking layers of dry carbon fabric in the desired structural orientation, second, stitching the layers of carbon fabric for through-the-thickness reinforcement, and third, resin vacuum impregnation molding of the woven/stitched preform and curing to complete the fabrication. Douglas has developed a patented method for stitching reinforcement and a patented resin transfer molding (RTM) process they call vacuum impregnation molding (VIM). The process uses low viscosity thermosetting resins to fabricate composite laminates.

Breakthrough technology for transport composites using this approach is an important objective of the NASA ACT Program. Certain toughened matrix resins and thermoplastic materials provide the required damage tolerance and structural efficiency. However, these materials cost $100/pound or more and are considered too expensive at this time for widespread application in transport aircraft. Automated manufacturing processes are being explored, but costly, labor intensive manufacturing processes still predominate.

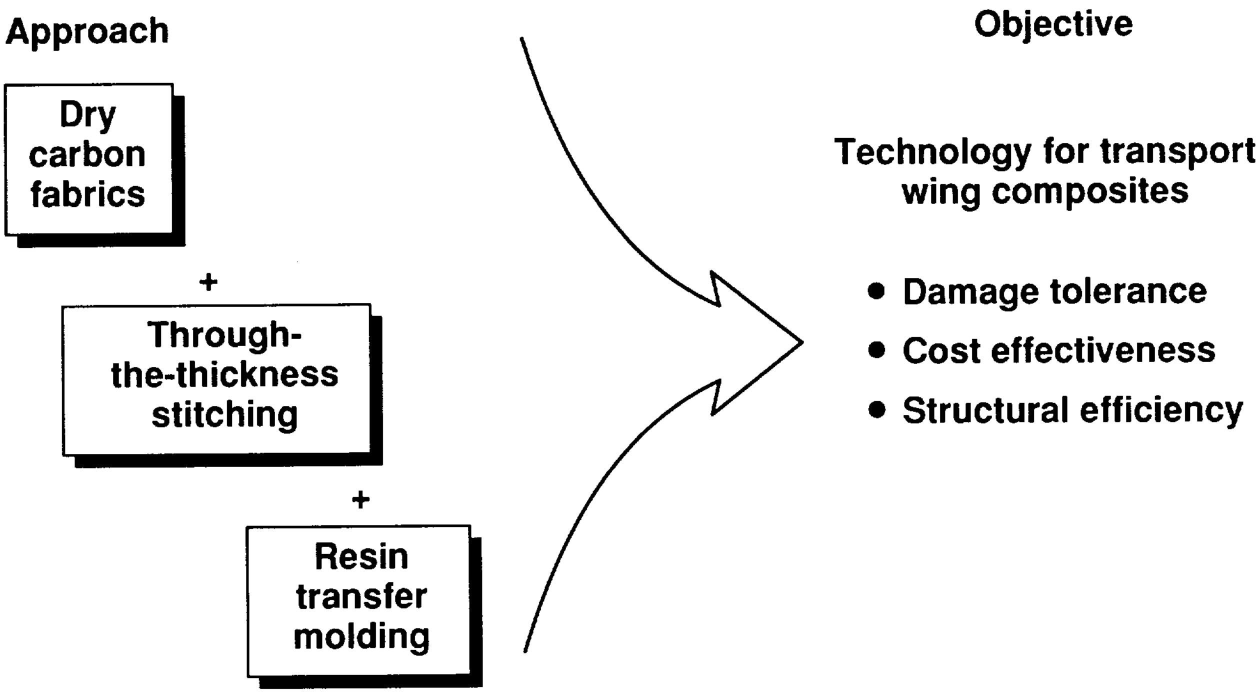


Figure 1

The first step in making stitched laminates is to stack layers of dry carbon fabric in desired orientations. All the laminates discussed in this paper were stacked with $[45°/0°/-45°/90°]_{6s}$ orientation to produce a symmetric quasi-isotropic layup 48-plies thick. Next, the layers of dry fabric are stitched in the thickness direction as shown in figure 2. Figure 2 depicts an array of lock stitching, but chain stitching is an alternate method; these stitch types are described later in the paper. The stitching is done at a specified stitch pitch (penetrations per inch) and stitching rows are spaced at specified distances. Stitching density, a term used later in the paper, is defined as the number of stitching penetrations per square inch. Finally, the stitched dry preform is filled with epoxy resin by vacuum impregnation molding, a type of resin transfer molding (RTM) described in reference 1.

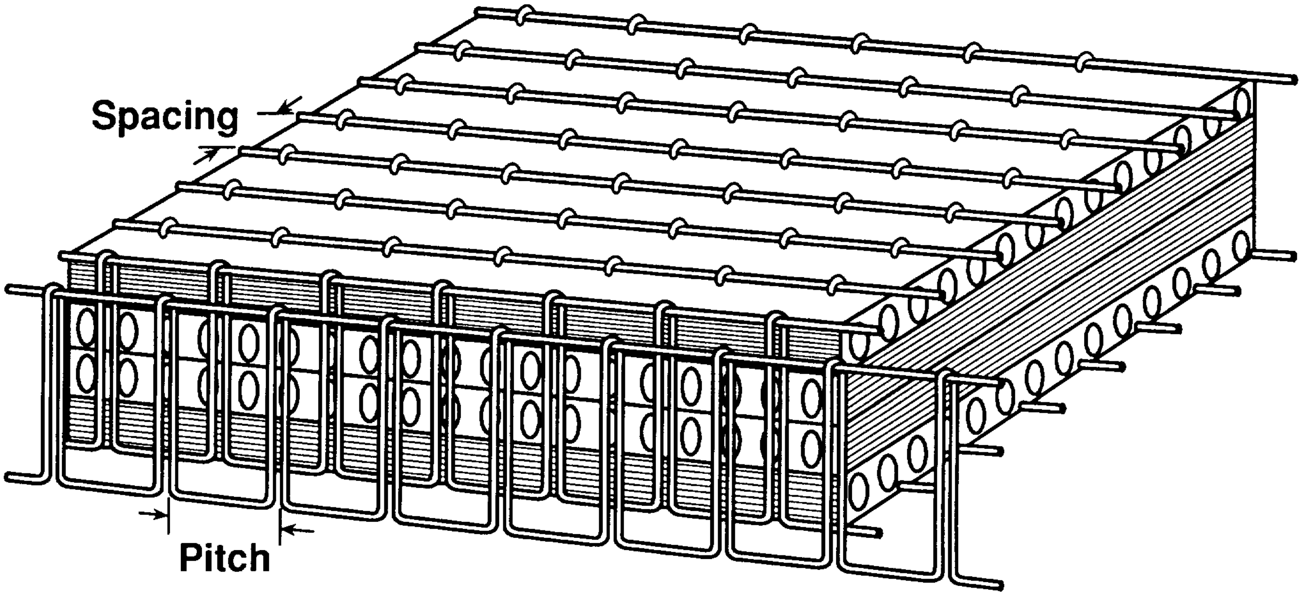
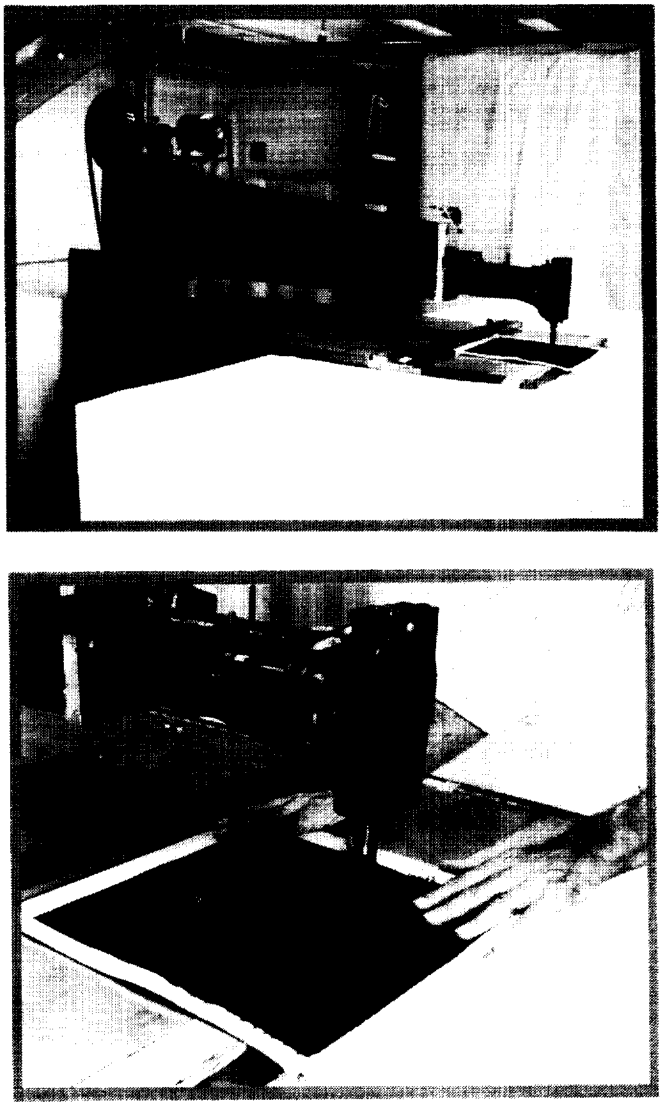


Figure 2

SINGLE NEEDLE LOCK STITCHING MACHINE

Figure 3a shows a single needle lock stitching machine which was used to stitch laminates for the present development. The manually controlled machine has an arm length of five feet and it can stitch through a 0.5 in. thick stack of dry carbon fabric. The stitching speed is variable but the usual speed is 120 penetrations per minute. Figure 3b shows a closeup of the machine stitching with carbon thread into layers of carbon fabric. In this instance, the lock stitches are spaced 1/8 in. apart in parallel rows. A simple guide, which is reset after each pass, is used to maintain the desired spacing.

Single needle machines of the type depicted are satisfactory for the stitching involved in concept evaluations. Obviously, such machines lack the speed and size required in the practical application of stitched aircraft structures. Under the ICAPS contract, Douglas will use stitching machines with considerably greater output to stitch preforms for large wing panels. These machines are described in reference 2.


(a)

(b)

Figure 3

Previous studies (ref. 3) of the compression after impact (CAI) strengths of quasi-isotropic laminates of AS4/3501-6, with and without stitching are shown in figure 4. The left-hand figure shows data obtained on laminates without stitching (solid symbols) and laminates stitched in various patterns with 200 denier Kevlar 29 thread. Denier (d), a textile measure, is defined as weight in grams for a 9000 meter length of thread. The figure shows the dramatic loss in compression strength resulting from impact damage on unstitched laminates. Stitching improved the CAI strength, but the values were considerably below the 50 ksi target value.

The right-hand figure shows data from tests of laminates stitched with 1500 denier Kevlar 29 thread. Laminates stitched with closely spaced rows at 8 penetrations per inch showed outstanding CAI strength. In these initial evaluations, the stitching with heavy thread produced considerable fiber damage as evidenced by the drop in compression strength from over 80 ksi to about 65 ksi in tests without impact damage. Nonetheless, these data showed the potential of stitching and RTM to produce damage tolerant and cost effective structures.

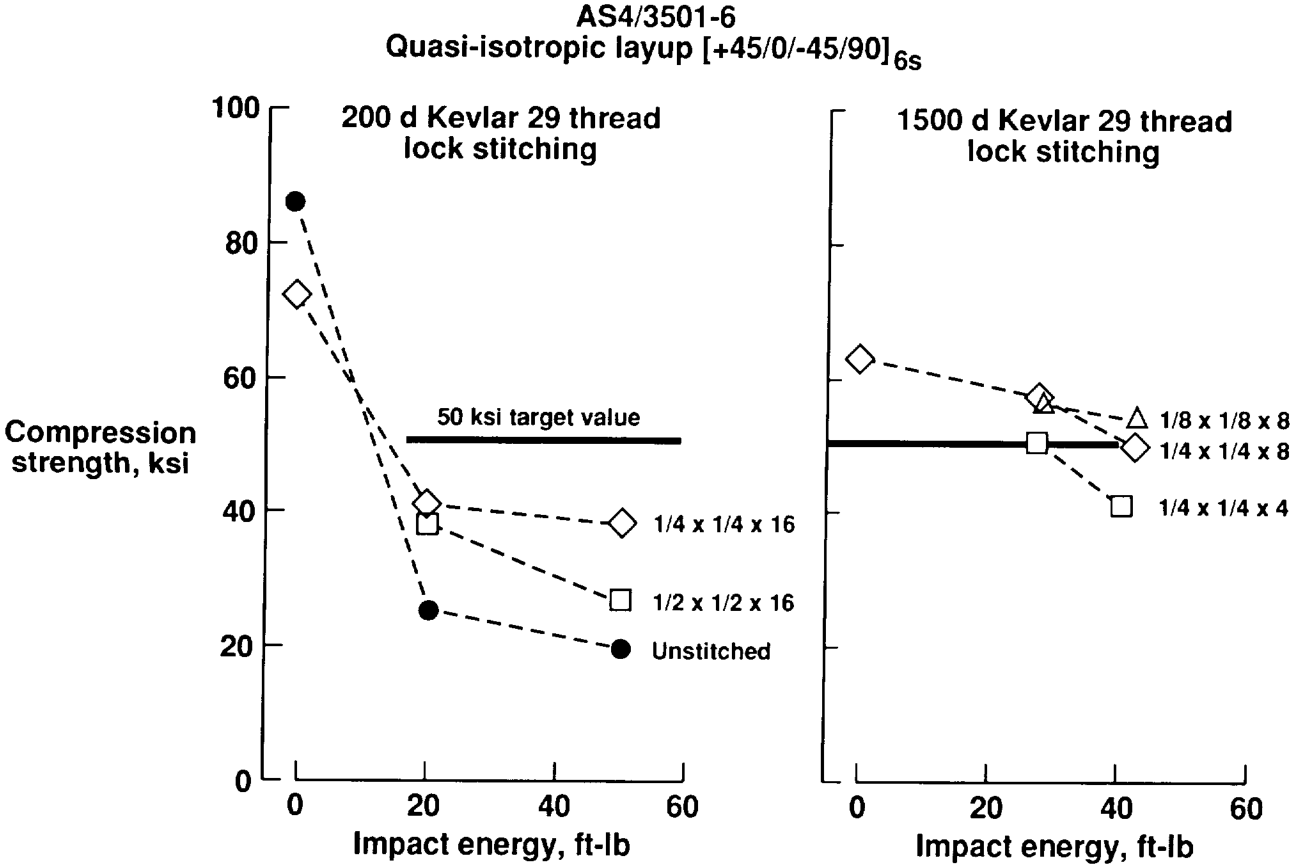


Figure 4

KEY FINDINGS FROM PREVIOUS STITCHING TESTS

During the period from 1986–88, Douglas Aircraft Company, working under a small NASA contract, made a series of stitched/VIM laminates which were tested by NASA Langley. Test results are reported in reference 4. The key findings are summarized in figure 5.

Based on these findings, the following guidelines were set for the present stitching development:

1. AS4 carbon fabric and 3501-6 resin would be the baseline materials.
2. Evaluation tests would be performed using 48-ply laminates in a quasi-isotropic layup.
3. For stitching reinforcement, closely spaced stitches with strong thread would be used, predominately with glass threads.
4. Dry carbon fabric preforms would be stitched in one direction only, parallel to the 0° carbon tows.

- **Strong threads and dense stitching produce good damage tolerance in otherwise brittle composites.**
- **Kevlar, fiberglass and carbon stitching threads are effective for damage tolerance.**
- **Stitching laminates in one direction (parallel to major load path) provides adequate damage tolerance.**
- **Stitching dry fiber preforms followed by RTM processing, holds attractive potential for transport wing structure.**

Figure 5

ACT STITCHING EVALUATION PROGRAM

The scope of the present stitching evaluation study is summarized in figure 6. Data are presented in this paper from the stitching parameter tests and from hot, wet compression tests of stitched laminates with and without impact damage. Results are shown from reference 5 for compression fatigue tests of stitched laminates with impact damage. Elements and panels will be tested to investigate the structural performance of stitched composites. Evaluation tests will be made on laminates incorporating alternate matrix resins selected for their potential to simplify the RTM process or to reduce material costs. Under a separate NASA contract, these matrix resins will be tested following exposure to typical aircraft fluids and fuel. New equipment, capable of rapidly stitching structural preforms, will be acquired and used to make the carbon fabric preforms for the 4 ft by 6 ft panels.

Data available:

- Stitching parameter tests
  - Lock vs chain stitching
  - Stitching thread weight
  - Stitching density
- Hot, wet compression tests with and without damage
- Fatigue tests after impact damage

Fabrication and testing in progress:

- Stiffener pull-off tests
- Performance tests of alternate matrix resins
- Compression tests of blade-stiffened panels (2 ft x 2 ft)
- Installation and checkout of new stitching equipment

Fabrication pending:

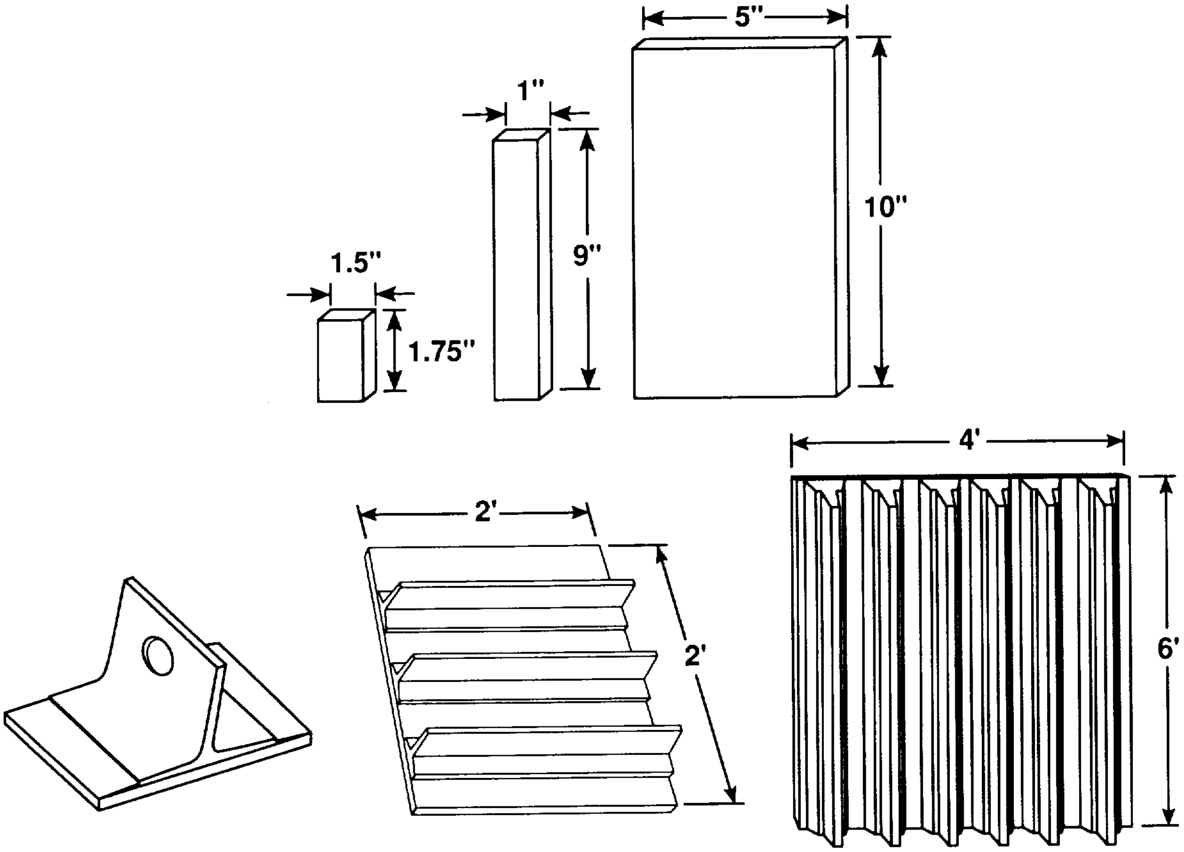
- Large stiffened panels (4 ft x 6 ft)

Figure 6

ELEMENTS AND SUBCOMPONENTS

Figure 7 shows the various elements and subcomponents that have been or will be fabricated and tested in the development of stitched/RTM transport wing structures. To evaluate various stitching parameters, small specimens have been tested and the results are presented in this paper. The configurations of these specimens, which were machined from flat laminates, are shown in the top part of figure 7. The 1.75 in. by 1.5 in. (short block) compression specimen is a NASA Langley configuration suitable for tests of angle ply laminates. For tension tests, the 9 in. by 1 in. specimen was used; for compression after impact tests, the 10 in. by 5 in. specimen was used, as recommended in reference 6.

Other elements and subcomponents are in various stages of completion. The stiffener pull off tests are intended to investigate the effectiveness of stitching in maintaining the structural integrity of stiffened panels. The small (2 ft by 2 ft) three-stiffener element panels and the large (4 ft by 6 ft) six-stiffener subcomponent panels will be tested in compression with and without induced damage.



Wing element panel

Wing subcomponent panel

Figure 7

MATERIALS IN STITCHING EVALUATION

The carbon fiber, epoxy resin and stitching threads used in test laminates are listed in figure 8. Vacuum impregnation molding and curing of the test laminates were performed by Douglas Aircraft Company. Specimen testing was done by the NASA Langley Research Center. The AS4 fibers and 3501-6 epoxy resin were the baseline materials used in every evaluation specimen. From a cost standpoint, AS4/3501-6 at about $40/pound (tape prepreg) is an attractive choice. To facilitate stitching, the dry carbon fibers in 3K tows were woven with fiberglass fill tows to form a fabric called uniweave. Initial laminates were made with a fabric containing 95 percent 0° warp carbon and 5 percent 90° fill fiberglass by weight. To reduce crimp in the carbon tows and thereby increase stiffness properties, a second uniweave fabric with 97.5 percent carbon and 2.5 percent glass was obtained and used. Individual layers of 0° fabric were cut and stacked in a $[45^\circ/0^\circ/-45^\circ/90^\circ]_{6s}$ sequence as the preform for a quasi-isotropic laminate. These dry fabric preforms were mostly lock stitched with glass threads of various strengths and weights. A few specimens were lock stitched with Kevlar threads, and one series of specimens was chain stitched with glass thread. To reduce material scrappage, Douglas has recently started using 0°, 45° and 90° fabrics.

Carbon fibers

- 3 K AS4

Dry fabric No. 1

- AS4 uni-weave fabric with fiberglass fill yarn
- 95% carbon-5% glass by weight
- Areal weight carbon: 145 gm/sq m

Stitching thread materials

- Kevlar 29
- S-2 glass

Epoxy matrix resin

- 3501-6

Dry fabric No. 2

- AS4 uni-weave fabric with fiberglass fill yarn
- 97.5% carbon-2.5% glass by weight
- Areal weight carbon: 145 gm/sq m

Stitching

- Lock stitching
- Chain stitching

Stitching thread specifications

	Yd/lb	Breaking strength, lb
S-2 glass-CG-150 8/0	1875	39
S-2 glass-CG-150 10/0	1500	49
S-2 glass-449-1250 untwisted	1250	59
S-2 glass-449-750 untwisted	750	98
Kevlar 29 200d 2 end twisted	11162	12
Kevlar 29 1000d untwisted	4470	36

Figure 8

DRY FABRIC STITCH TYPES

Figure 9 shows the prominent features of the lock and chain stitching used to sew reinforcing threads perpendicular to the layers of dry carbon fabric. Lock stitching employs a bobbin and needle thread and requires access to both surfaces of the layers being sewed. In standard lock stitching, the knots formed by the needle and bobbin threads are located within the layers. However, in the present study, to minimize carbon fiber damage, thread tensions were adjusted to provide a modified lock stitch which positioned the knots on the outer surface of the stacked fabrics. Also, in this instance, the bobbin threads were considerably heavier and stronger than the 200 denier Kevlar needle thread. Chain stitching uses a single thread and requires access to only one surface. Because this feature might provide significant cost savings in production applications, a limited evaluation was performed. Unfortunately, however, most chain stitching machines use a needle motion to move the material being stitched, and current machines cannot be used to stitch fabric preforms of the size required for aircraft structures.

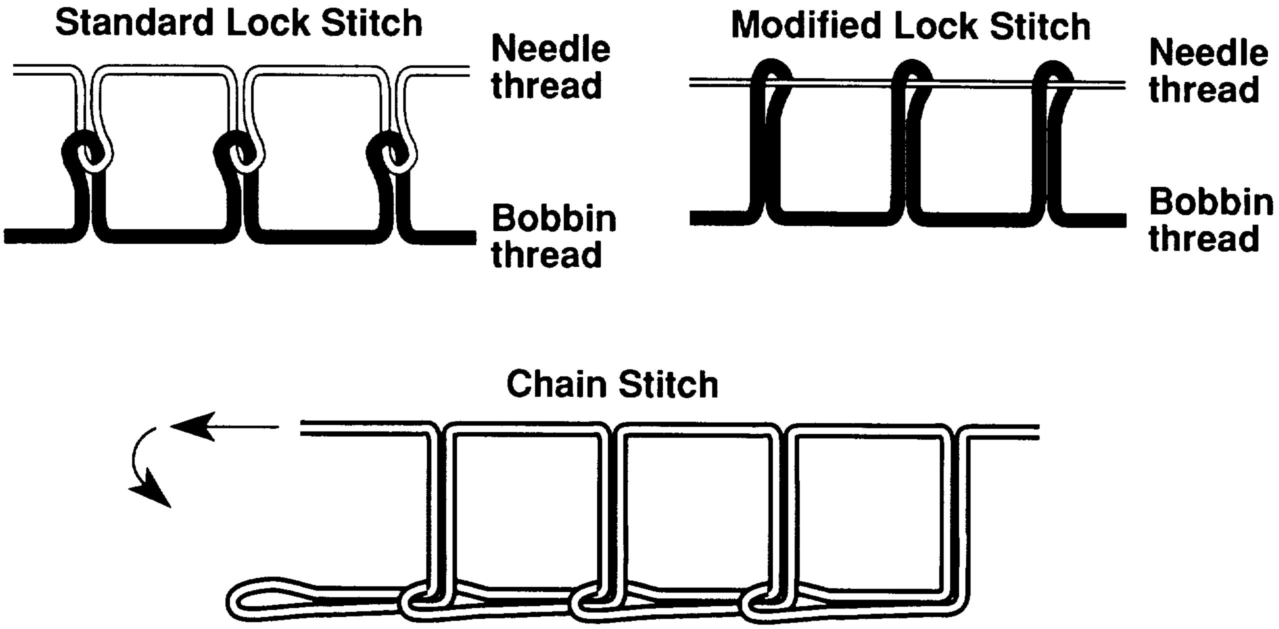


Figure 9

DROP WEIGHT IMPACT APPARATUS

Impact damage was induced in the various test laminates with a drop weight apparatus, which is shown in figure 10. The free-fall distance of the drop weight was adjusted to produce the desired impact energy. The 48-ply laminates were impacted at impact energies up to 70 ft-lb using a 0.5 in. hemispherical steel tip attached to a 10-pound drop weight. Impacts at 100 ft-lb were performed with a 1 in. hemispherical steel tip attached to a 20-pound weight. Post impact testing was performed using a NASA fixture (ref. 6) to support the specimen.

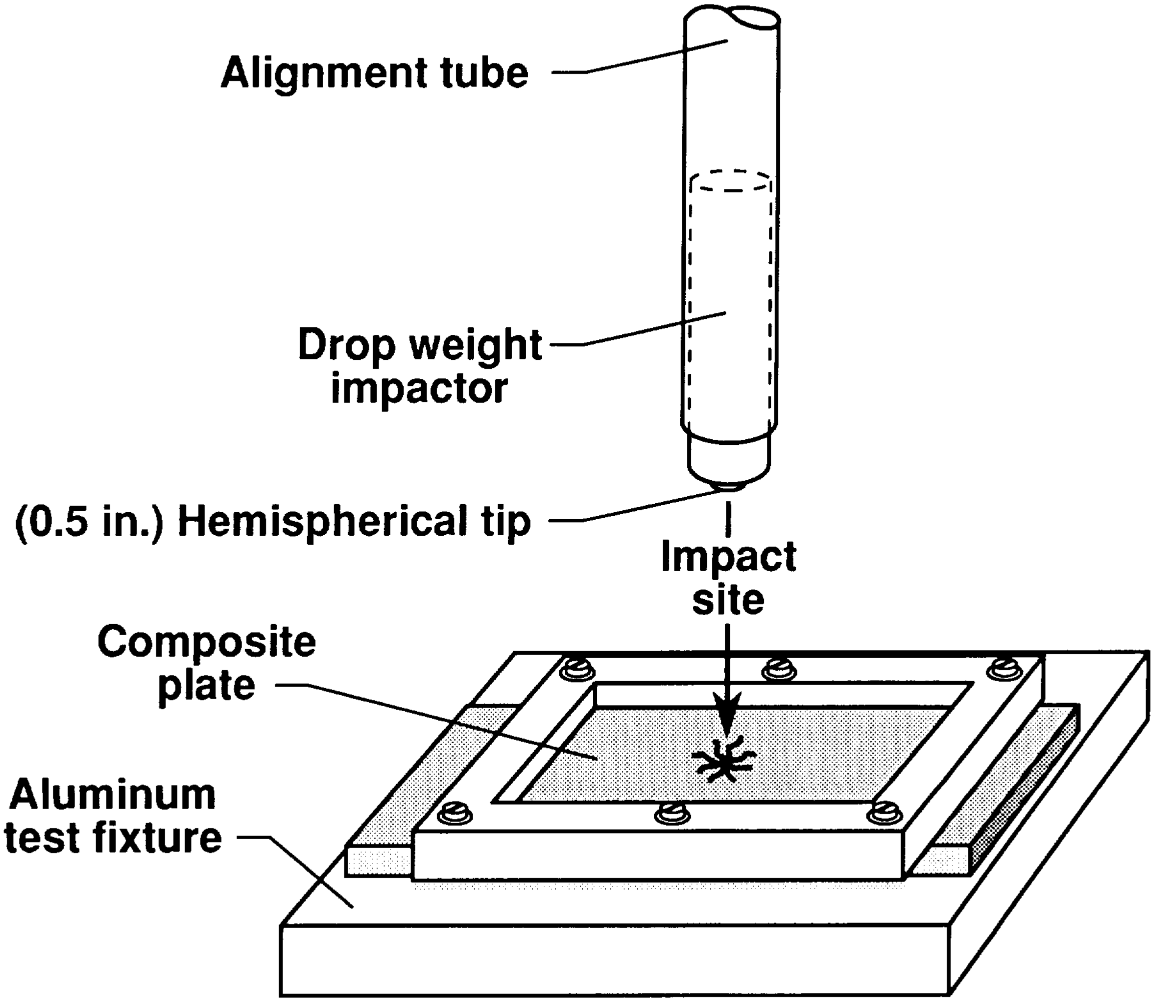


Figure 10

IMPACT PENETRATION OF A STITCHED PLATE

An example of the ability of stitched laminates to limit impact damage is shown in figure 11. In this instance, the panel (lock stitched with glass thread at 1250 yd/lb) was impacted with a 0.5 in. hemispherical impactor at an energy of 100 ft-lb. As shown, the impactor punched through the 48-ply laminate (see back view) and stopped embedded in a tangled mass of laminate fragments and stitching threads (see side view). The panel was subsequently C-scanned (damage area 3.2 sq in.) and tested in compression to failure at 33 ksi. To eliminate penetration, a 1 inch hemispherical impactor was used thereafter for 100 ft-lb impacts.

PENETRATION OF STITCHED PLATE BY 100 FT/LB IMPACT

AS4/3501-6 $[45/0/-45/90]_{6s}$

S-2 Glass stitching thread 0.5 in. Hemispherical impactor

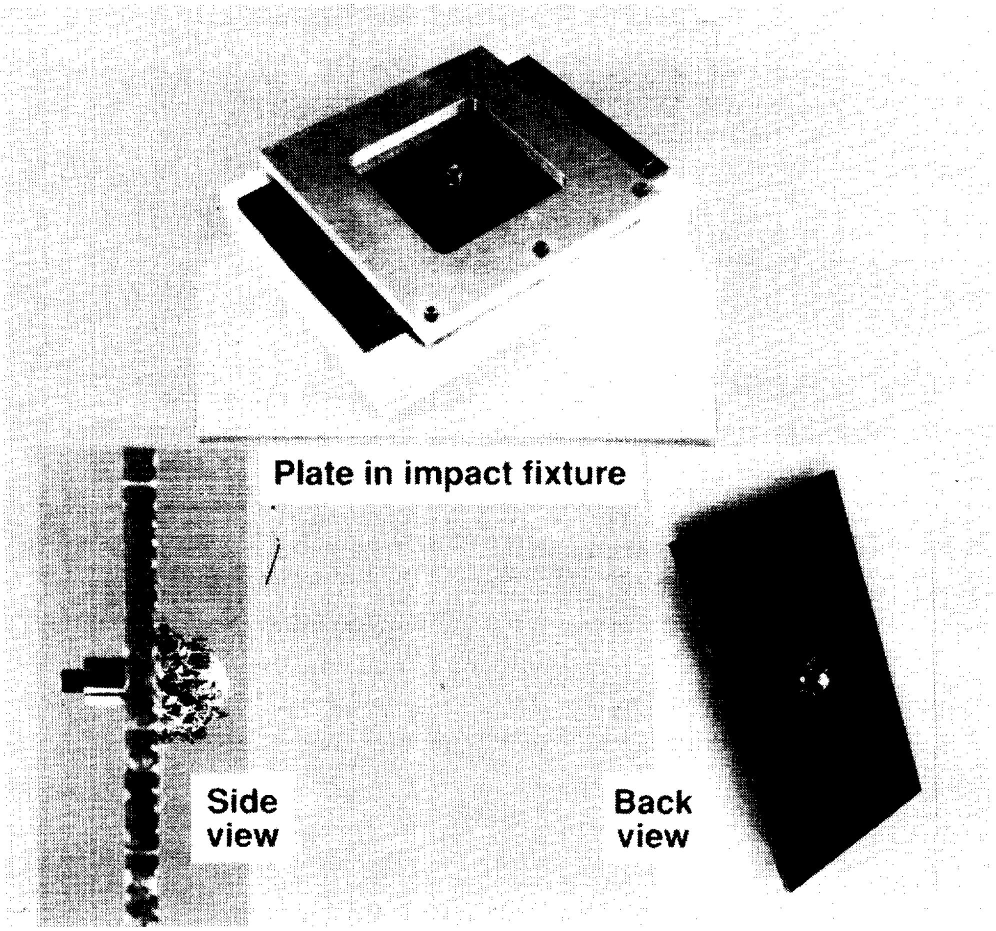
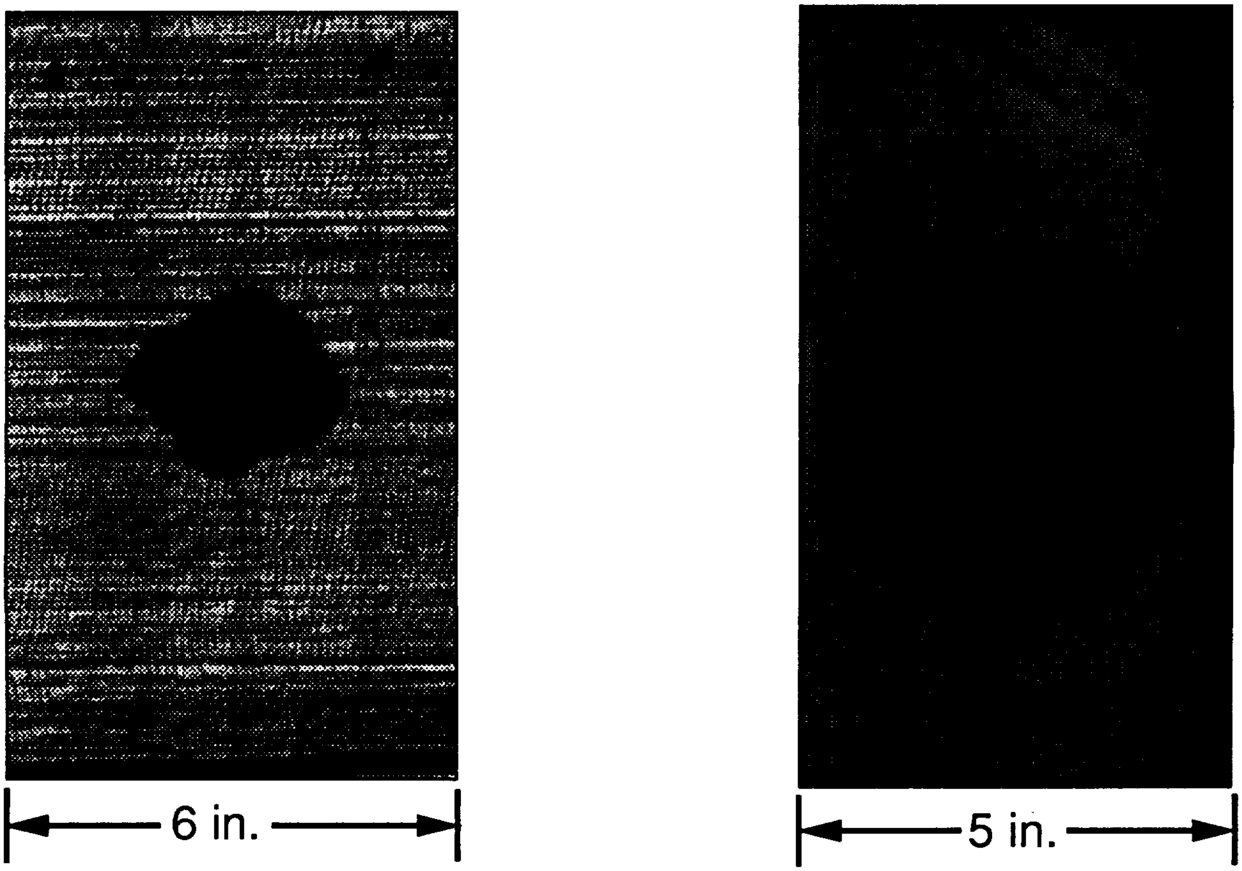


Figure 11

IMPACT-INDUCED DAMAGE OF STITCHED AND UNSTITCHED COMPOSITE PANELS

The capability of through-the-thickness stitching to limit impact damage is shown in figure 12, which presents C-scan images of specimens with and without stitching. Both panels contained 48 plies of AS4 fabric and were resin transfer molded using 3501-6 resin. Prior to the molding, the panel on the left was chain stitched with glass thread (1250 yd/lb) at a density of 64 stitches per square inch. Both panels were impacted at 100 ft-lb in the drop weight apparatus. The damaged area in the unstitched panel (19.6 sq in.) was three times greater than that in the stitched panel (6.4 sq in.). Because of the extensive damage, the unstitched panel was not tested. The stitched panel was tested in compression to failure at 44 ksi.

100 Ft-lb Impact



Stitched
AS4/3501-6
$(45/0/-45/90)_{6s}$

Unstitched
AS4/3501-6
$(45/0/-45/90)_{6s}$

Figure 12

Tension, compression, and compression after impact (CAI) tests were made on 48-ply laminates made using chain stitched and lock stitched fabric preforms. In each instance, identical layers of uniweave fabric no. 1 were stacked in quasi-isotropic layups which were stitched with identical S-2 glass stitching thread at 8 stitches per inch in rows spaced at 1/8 in. Chain stitching was done by Puritan, Inc., while Ketema performed the lock stitching. Vacuum impregnation molding with 3501-6 resin and autoclave curing were performed by Douglas. Test results are shown in figure 13. Neither type of stitching showed a marked advantage in strength or damage tolerance but the best values were obtained with chain stitching. Under severe impact conditions of 40 and 70 ft-lb, both types of stitched laminates demonstrated excellent damage tolerance.

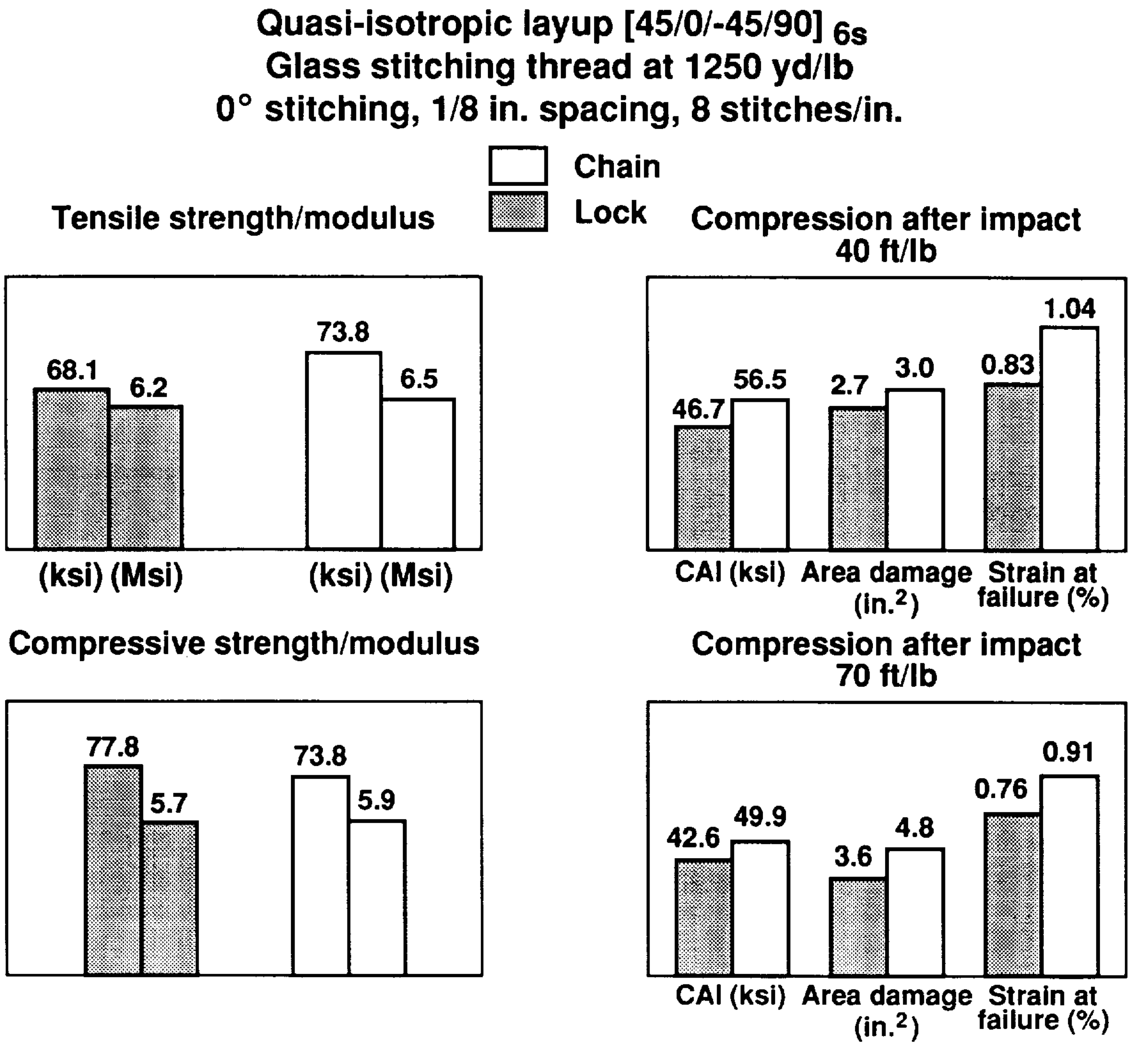
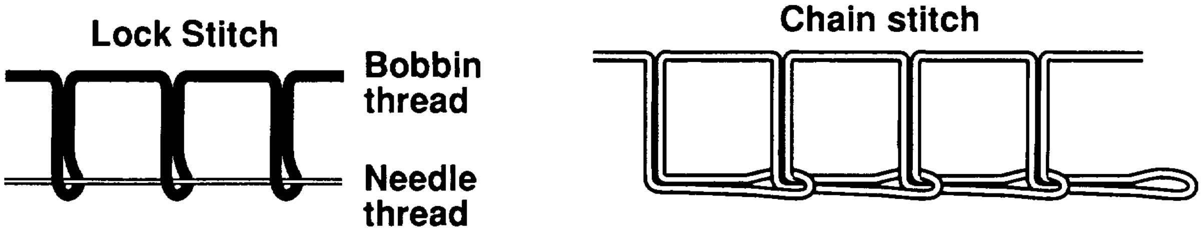


Figure 13

In the various tests to compare stitch types, specimens with chain stitching performed as well as those with lock stitching. Nonetheless, lock stitching was selected for subsequent developments for the reasons listed in figure 14. Although lock stitching machines employ bobbins requiring frequent replacement, these machines have the ability to sew in any direction (straight lines, curves, circles, etc). The use of stitched preforms in actual wing structure was the major consideration in the selection. Actual wing preforms will require numerous cutouts, access openings, padup areas, etc. Lock stitching machines were judged to have the best capability to meet the varied stitching requirements. Lock stitching uses less heavy thread than chain stitching and, thus for a given stitching density, would provide a weight savings. Lock stitching machines provide the capability to stitch identification codes into the laminates during the manufacturing process. Stitching in this manner is useful for parts records and traceability.



Lock stitching selected for future fabrication:

- **Accomodates multidirectional stitching-cutouts, padups, etc.**
- **Uses less heavy stitching thread.**
- **Potential for stitching part identification codes-permanent records and traceability.**

Figure 14

EFFECT OF STITCHING THREAD ON STRENGTH PROPERTIES

For this investigation, the 48-ply quasi-isotropic laminates were all lock stitched in rows spaced 1/8 in. apart with eight penetrations per inch, a stitching density of 64 penetrations per square inch. Also, the preforms were made using the dry fabric no. 2, containing 2.5 percent fiberglass fill yarns. The variables were the four stitching threads used: Kevlar-29 at 4470 yd/lb (1000d) and three weights of S-2 glass at 1875, 1500 and 750 yd/lb.

Strength and stiffness data from the tension and compression tests are shown in figure 15. The values are the average from three test specimens. The best results were obtained from laminates stitched with Kevlar thread. In laminates stitched with glass threads, the strength values decreased with increased thread weight. Strength and modulus values obtained with the three lightest stitching threads (Kevlar-29, 1875 glass and 1500 glass) show considerable improvement over the values obtained with carbon fabric no. 1, figure 13. Part of the property improvement is attributed to lighter stitching threads, which cause less kinking and breaking of the carbon fibers; the remainder is contributed by the carbon fabric itself, which has fewer fiberglass fill yarns and less carbon tow crimping.

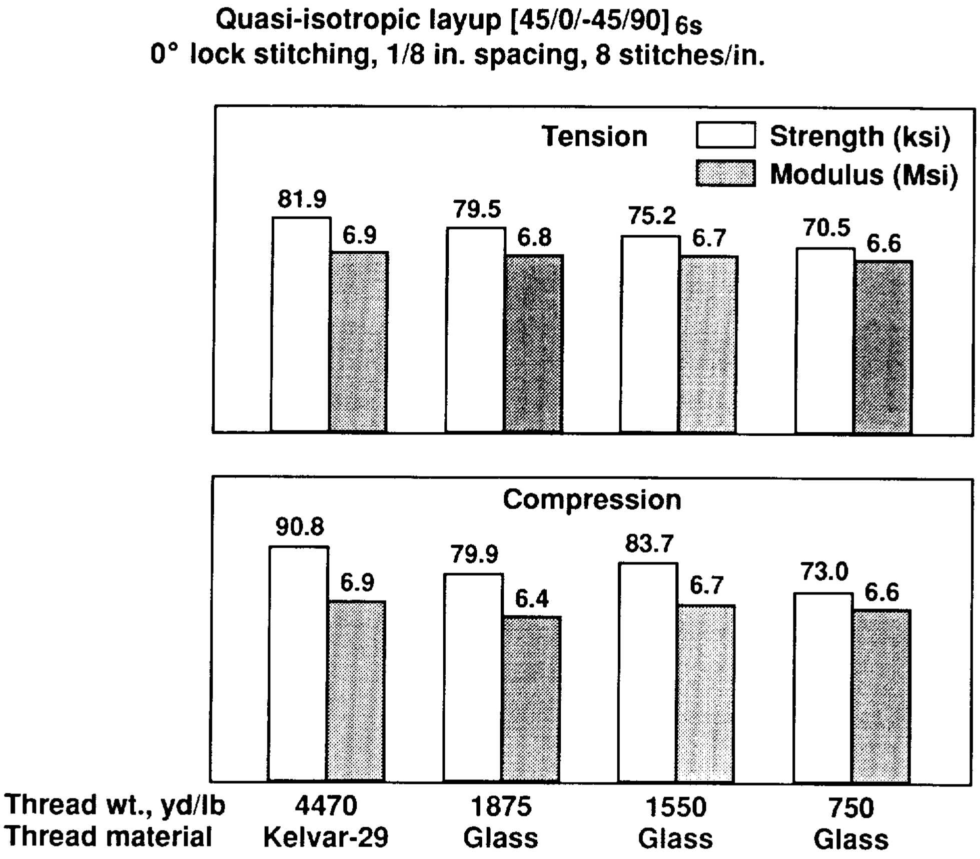


Figure 15

EFFECT OF STITCHING THREAD ON COMPRESSION AFTER IMPACT STRENGTH

Figure 16 shows the results of compression after impact (CAI) tests on 48-ply laminates fabricated as described in the narrative for figure 15. To repeat, the variables were stitching thread material and stitching thread weight. The specimens were impacted by drop weight at energy levels of 40, 70 and 100 ft-lb. These energy levels were chosen to investigate the damage tolerance of stitched laminates under severe conditions. The data show that CAI strength increases with the use of stronger threads. However, only small increases in CAI strength were obtained for large increases in thread strength and weight. For example, CAI strengths with 750 glass are only slightly better than those obtained with 1500 glass, which is half as strong and half as heavy. The laminate stitched with Kevlar thread did not perform as well as those stitched with glass threads but it has a weight advantage over glass thread. These results and those shown in figure 15 indicate that the lighter weight glass threads provided the best combination of strength and damage tolerance.

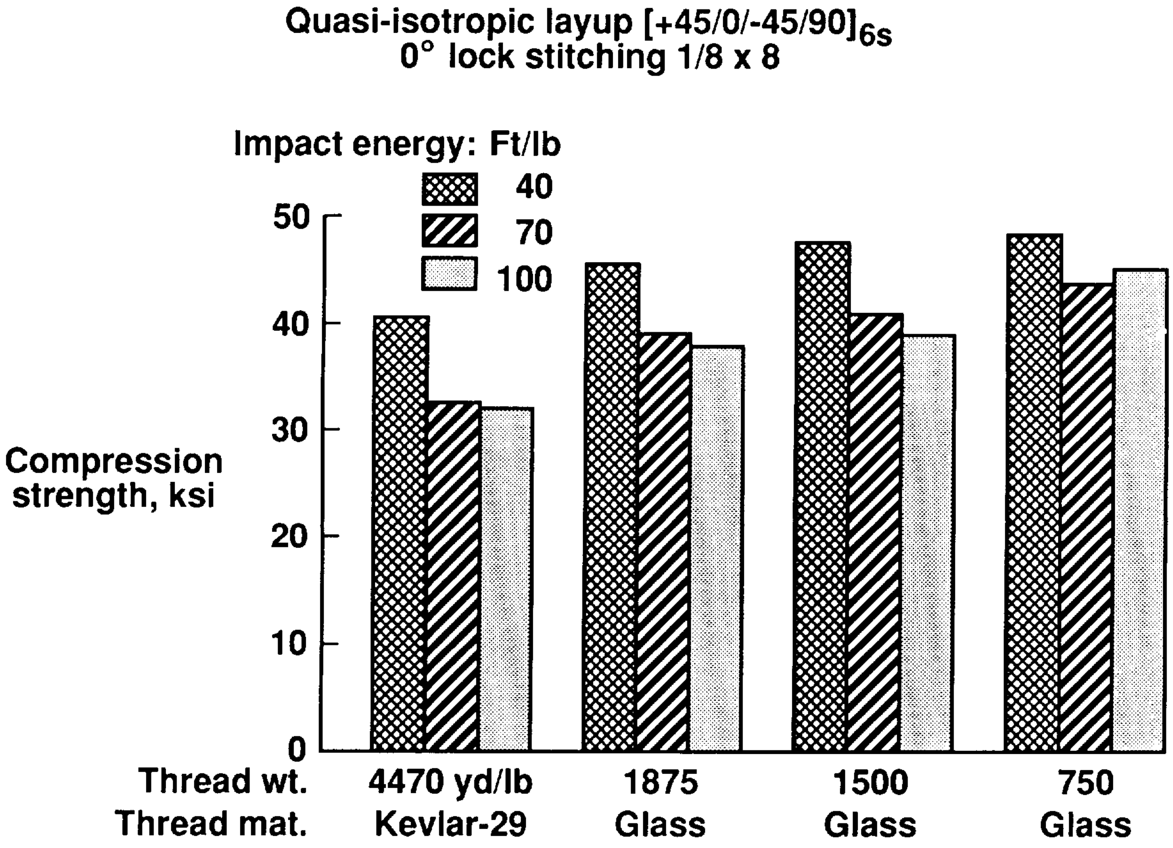


Figure 16

EFFECT OF STITCHING DENSITY ON COMPRESSION AFTER IMPACT STRENGTH

For this evaluation, the stitching density (penetrations per square inch) was the variable with each laminate lock stitched with glass thread at 1250 yd/lb. Stitching density was varied by changing the spacing between rows and by changing the pitch (number of penetrations per inch). The results of CAI tests on these laminates are shown in figure 17. Clearly, increasing the stitching density with a constant thread strength produces an increase in strength. At the highest stitching density, the CAI strength was an impressive 55 ksi at an impact energy of 70 ft-lb. However, the laminate thickness and thus its weight, also increases with increases in stitching density. The Douglas stitching/VIM process for flat plates does not employ fixed volume tooling. Thus, the compaction is limited to that achieved during preform stitching and final autoclave curing. As the amount of stitching thread increases, a thicker preform results and more resin is required to fill the preform during impregnation.

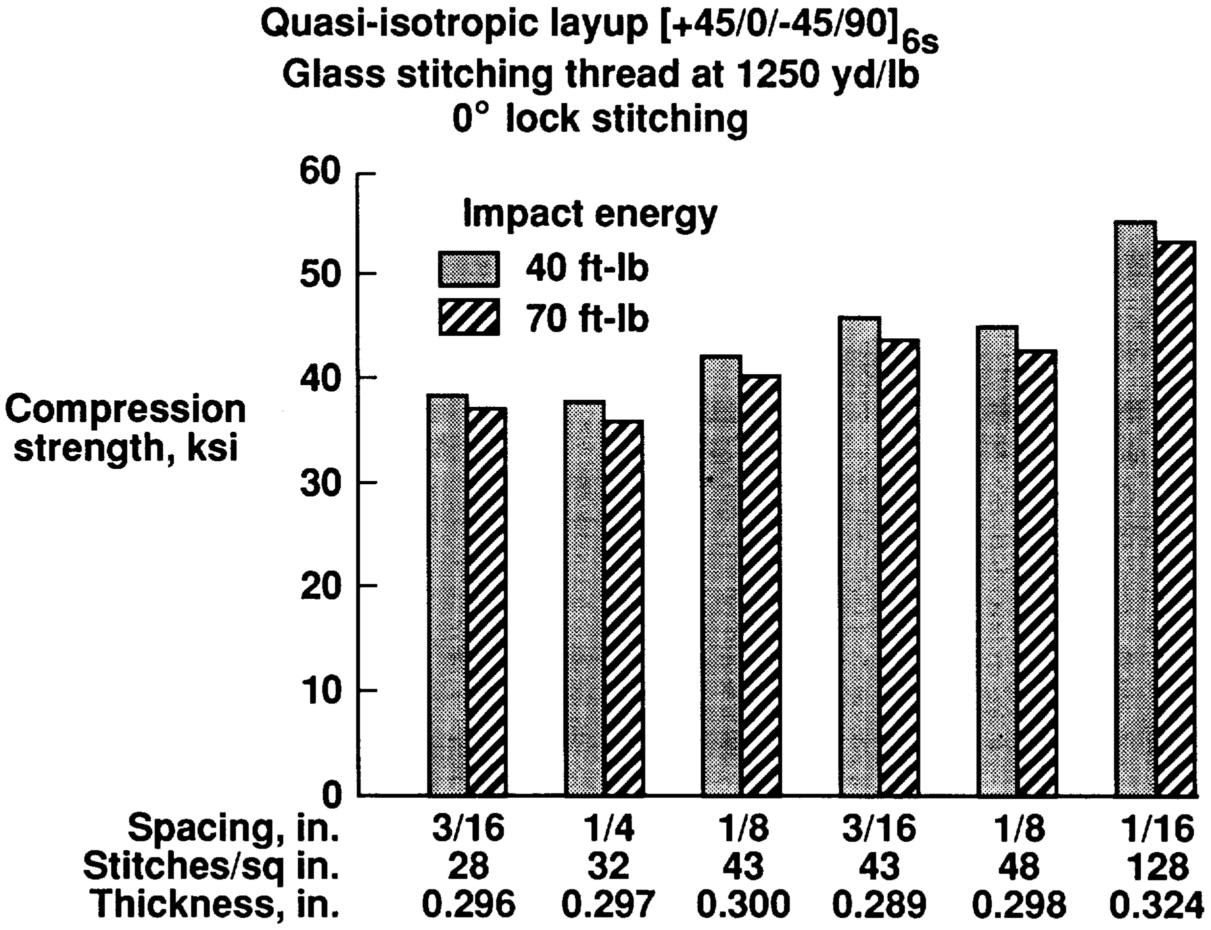


Figure 17

STITCHING DENSITY COMPARISON

A series of specimens was tested to measure strength and stiffness as a function of stitching density. Results are shown in figure 18. The laminates were identical to those discussed in figure 17. Each value is an average of three tests. At the highest stitching density of 128 stitches per square inch, there is a significant reduction in tension and compression properties. Interesting results were obtained in tests of laminates with 43 stitches per square inch. Better strength values were obtained with a 3/16 in. row spacing and 8 stitches per inch than with 1/8 in. row spacing and a stitch every 3/16 in. The results at a density of 28 stitches per square inch indicate also that 3/16 in. is a good spacing for mechanical properties and damage tolerance.

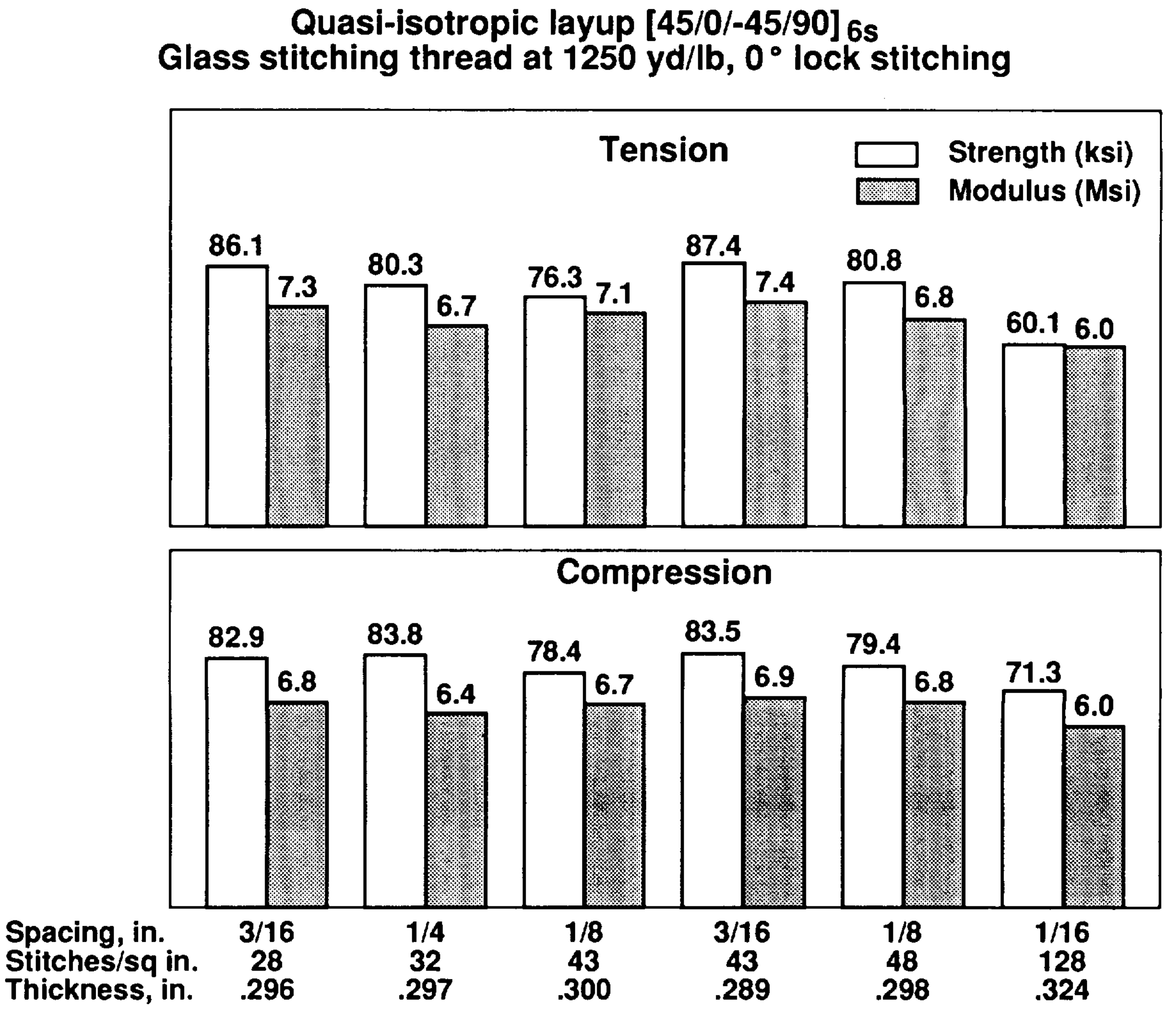


Figure 18

LAMINATE THICKNESS AS A PENALTY IN STRENGTH COMPARISON

The same amount of load carrying carbon fibers was contained in each laminate tested to investigate the effect of stitching density on strength properties. However, a preferred stitching density was not evident from the CAI data (fig. 17) and the strength values (fig. 18). Therefore, the following arbitrary guidelines were used: (1) the stitched laminate must demonstrate a CAI strength equal to or greater than 40 ksi following impact at an energy level of 40 ft-lb, and (2) the laminate must provide the best tension and compression properties for the least weight. For the second guideline, it was assumed that laminate weight varied directly with the thickness. Accordingly, laminate thickness could be considered a penalty in the strength comparison.

In figure 19, the tension and compression strength values from figure 18 are divided by the laminate thickness. This procedure shows that 3/16 in. is a preferred spacing. When the CAI guideline is applied, the stitching density of 43 penetrations per square inch at a spacing of 3/16 in. provides the best combination of properties.

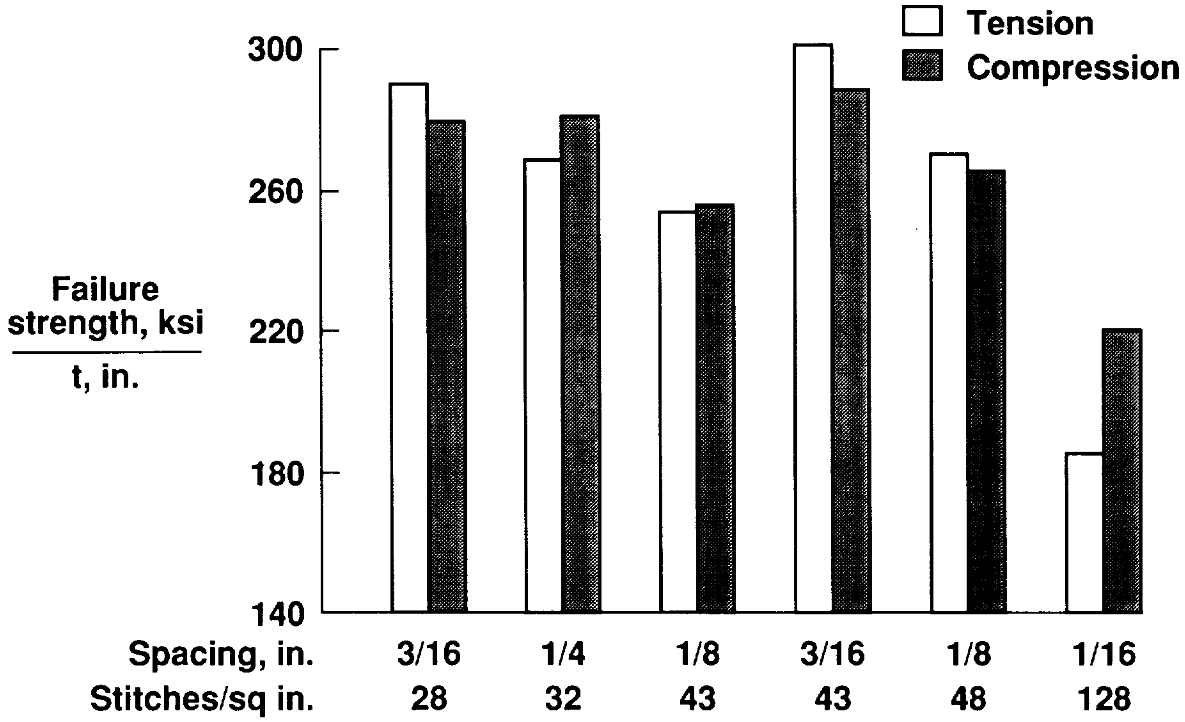


Figure 19

EFFECT OF HOT WATER SOAK ON COMPRESSION AFTER IMPACT STRENGTH

Stitched laminates identical to those discussed with figure 17 were tested at 180°F in a wet condition. The CAI results are shown in figure 20 which also shows the room temperature, dry (RTD) values from figure 17. The RTD condition means the specimens were at room temperature and contained moisture acquired only during exposure to shop and laboratory environments. Hot, wet test specimens were impacted, machined to the required 5 in. by 10 in. size, and immersed for 45 days in water at 160°F. Small follower specimens weighed before and after immersion indicated that moisture gains ranged from 0.9 percent to 1.1 percent, with the lowest weight gain in the laminate stitched with Kevlar-29 thread. Wet specimens were strain gauged after removal from the water and were tested in an expeditious manner (usually in 1 hr). The specimens were heated to 180°F in a heating chamber attached to the test machine.

The hot, wet test results show a substantial reduction in CAI strengths compared to RTD values. The specimens stitched with Kevlar-29 thread experienced the least strength reduction (11 to 16 percent) whereas the greatest strength reduction (20 to 32 percent) occurred in the specimens stitched with the heaviest glass thread, 750 yd/lb. However, these strength reductions are comparable to those measured in similar tests on toughened matrix composite materials, reference 7.

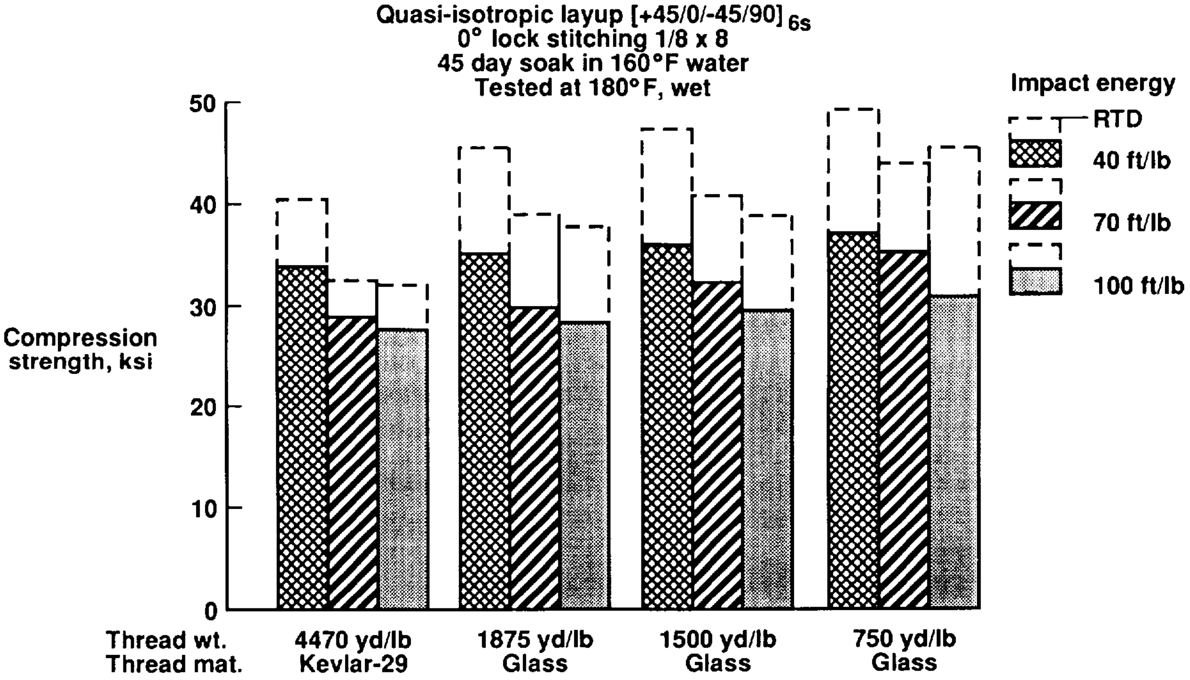


Figure 20

EFFECT OF MOISTURE AND HEAT ON COMPRESSION STRENGTH OF UNSTITCHED AND STITCHED LAMINATES

Tests were performed to determine if the CAI strength reductions measured on stitched specimens in a hot, wet condition (fig. 20) were characteristic of AS4/3501-6 composite material itself or related to the stitching. Quasi-isotropic laminates 48-plies thick were fabricated using the carbon fabric no. 2 with and without stitching. Small 1.75 in. by 1.5 in. compression specimens were machined from the laminates, conditioned variously and tested. The results are shown in figure 21. The water soak was 45 days in water at 160°F; the humidity chamber exposure was 30 days at a relative humidity of 95 percent and a temperature of 140°F. Again, the dry condition means the specimens contained moisture acquired only during exposure to shop and laboratory environments. The test results support the following observations:

1. The unstitched AS4/3501-6 composite material by itself experienced a significant reduction (over 30 percent) in compression strength under hot, wet conditions.
2. In the hot, wet condition the stitched specimen performed as well as the unstitched specimen; therefore, the through-the-thickness stitching appears to have had little harmful effect on the laminate compression strength.
3. The hot, wet strength of unstitched specimens following water soak was only marginally less than that measured following humidity chamber conditioning.

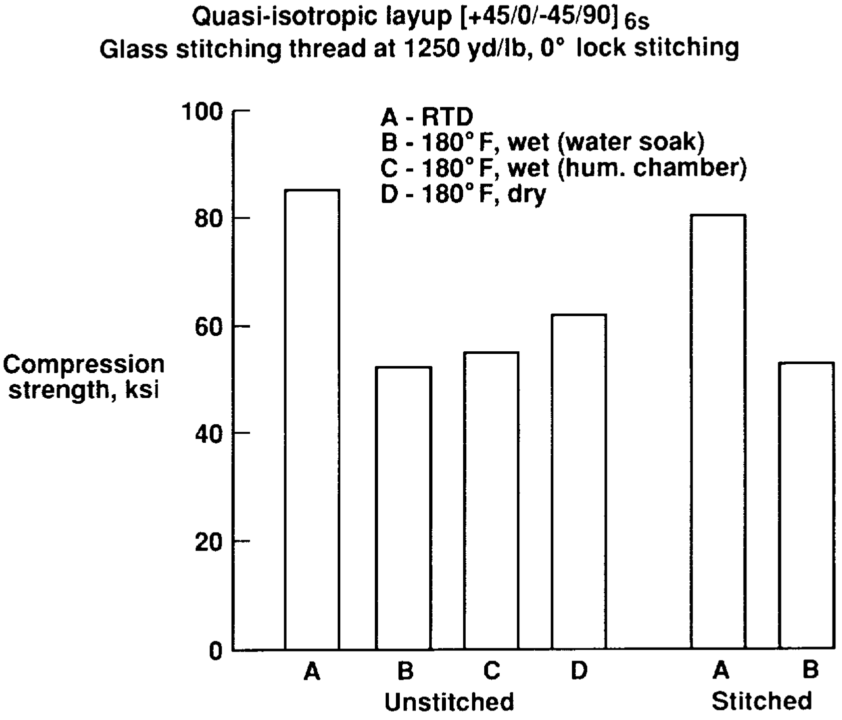


Figure 21

POST IMPACT COMPRESSION FATIGUE OF STITCHED AND UNSTITCHED LAMINATES

Figure 22 shows data from reference 5 on the post impact compression fatigue behavior of 48-ply laminates of a toughened system, IM7/8551-7 (tape prepreg), and AS4/3501-6 stitched with S-2 threads (1250 yards per pound) at a density of 64 penetrations per square inch. In accordance with reference 6, the laminate specimens were impacted by the drop weight and tested in a compression fixture. The fatigue tests were conducted at room temperature in a closed-loop servo-hydraulic test machine at a frequency of 5 Hz. Except for the initial static test (10° cycles) all specimens were loaded in compression-compression fatigue with an R-ratio (minimum/maximum) of 10.

Figure 22 shows that both the stitched material and the toughened tape system experienced a reduction in compression strength with constant amplitude compressive fatigue of about 33 percent at a million cycles. Static compression and fatigue strengths of the stitched and unstitched laminates were about equal. The significant finding (ref. 5) was that the crimp and puncture type damage from the stitching had no net effect on the compression fatigue strength.

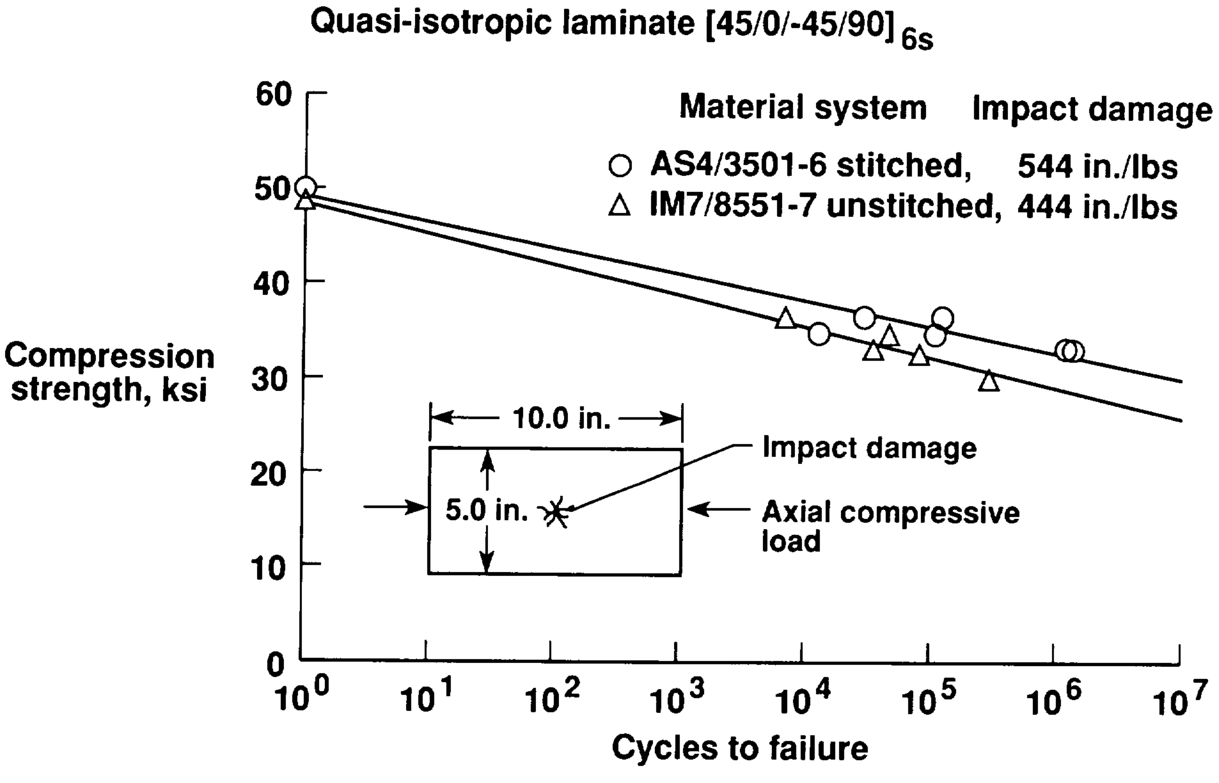

Quasi-isotropic laminate $[45/0/-45/90]_{6s}$

Figure 22

STITCHING CAN SIGNIFICANTLY IMPROVE DAMAGE TOLERANCE OF COMPOSITES

The findings of the ICAPS stitching development are summarized in figure 23. The results obtained clearly show that major improvements in damage tolerance are produced by stitching. Figure 23 shows the compression after impact (CAI) strength of unstitched AS4/3501-6 (curve A) and indicates the drastic loss of strength typical for brittle resin composites. The shaded region B shows the CAI strengths developed by state-of-the-art toughened matrix composites. These materials provide a considerable improvement in CAI strength over the brittle system, but the toughened materials are 2 to 3 times more expensive. Curve C shows the dramatic increase in CAI values obtained with stitched AS4/3501-6 using glass stitching threads at 1250, 1500 and 1875 yards per pound and a stitching density of 64 penetrations per square inch. Data obtained in this study show that stitching reinforcement can produce a 100 percent increase in the CAI strength of a brittle composite such as 3501-6 while incurring a weight increase of only 5–10 percent.

Composite materials are judged to hold great promise when they have a CAI strength of 50 ksi after being impacted at an energy level of 30 ft-lb (1500 in-lb per inch of plate thickness). The stitched materials exceeded the target value. The results to date indicate that stitching combined with RTM processing holds attractive potential for fabricating damage tolerant aircraft structures.

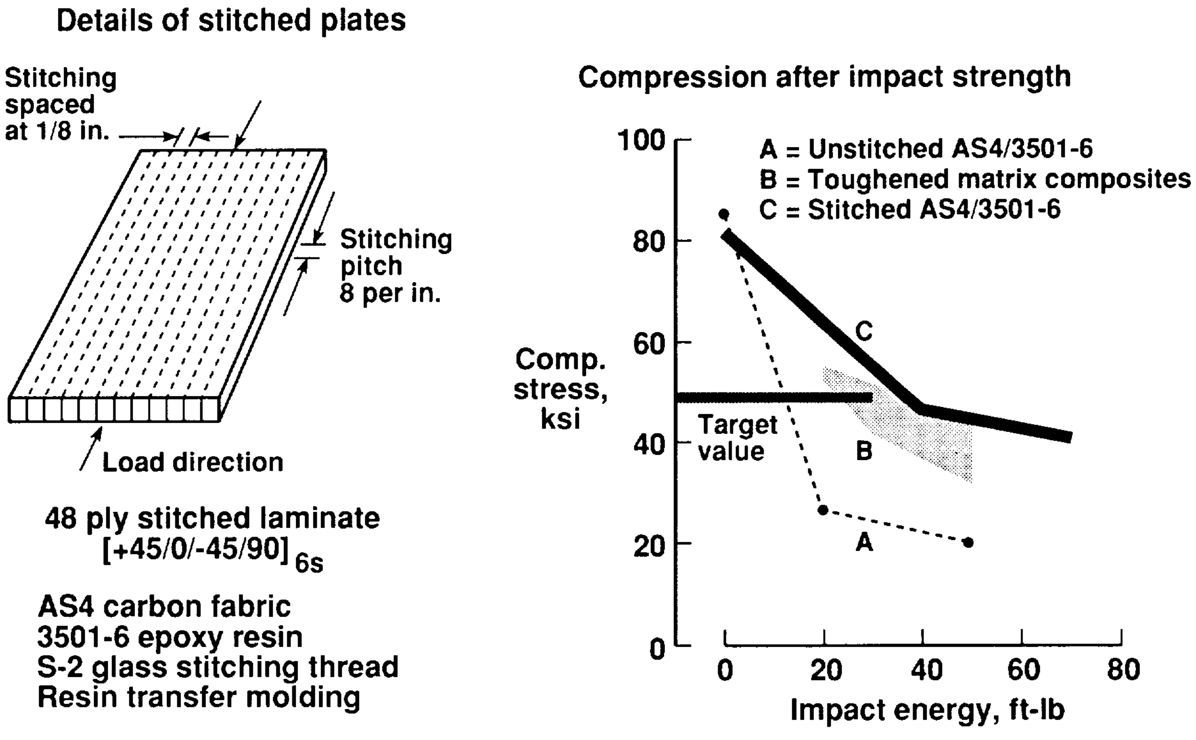


Figure 23

CONCLUDING REMARKS

The findings to date on stitched composites and planned evaluations are summarized in figure 24. To establish the full potential of stitching and vacuum impregnation molding will require an expanded testing effort. Structural integrity and efficiency of wing structures need to be explored. Another important area to explore is the use of low-cost resin matrix materials which can be oven cured. Composite fabrication of the type discussed in this paper are believed to offer exciting possibilities for cost-effective, damage tolerant structures.

- Completed tests on stitched flat laminates showed:
    - Outstanding damage tolerance
    - Acceptable fatigue behavior
    - Acceptable hot-wet performance
- Lock stitching selected for reinforcement.
- Guidelines data obtained for strength vs damage tolerance.
- Increased laminate thickness (greater weight) is the price for improved damage tolerance.
- Planned evaluations:
    - Stiffener pull off
    - Candidate RTM resins
    - Thin (16 plies) and thick (96 plies) laminates
    - Stiffened panels with and without damage

Figure 24

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