# THE COMBINED EFFECT OF GLASS BUFFER STRIPS AND STITCHING ON THE DAMAGE TOLERANCE OF COMPOSITES

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## INTRODUCTION

Recent research has demonstrated that through-the-thickness stitching provides major improvements in the damage tolerance of composite laminates loaded in compression. However, the brittle nature of polymer matrix composites makes them susceptible to damage propagation, requiring special material applications and designs to limit damage growth. Glass buffer strips, embedded within laminates, have shown the potential for improving the damage tolerance of unstitched composite laminates loaded in tension. The glass buffer strips, less stiff than the surrounding carbon fibers, arrest crack growth in composites under tensile loads. The present study investigates the damage tolerance characteristics of laminates that contain both stitching and glass buffer strips.

# EVALUATION OF STITCHED CARBON/EPOXY COMPOSITES CONTAINING GLASS BUFFER STRIPS

Research reported in references 1 and 2 showed that when carbon/epoxy composite panels with buffer strips were subjected to tensile loads, the buffer strips arrested the cracks and increased the residual strengths significantly over those of laminates without buffer strips. The top left sketch in figure 1 shows a composite laminate containing fiberglass buffer strips in the 0° direction and a machined slit in the center of the panel. The laminate is made of carbon uniweave fabric with half inch strips of the carbon fibers replaced with glass fibers. Cracks initiate at the slit, propagate to the buffer strips and stop. The cracks are arrested because the modulus of resilience, or toughness, of the S-glass is greater than that of the carbon fibers. The compression properties of these buffer strip laminates were never completely characterized or documented. The lower left sketch in figure 1 shows an impacted carbon/epoxy composite panel with through-the-thickness stitching. Results reported in reference 3 showed that stitching improves the compression-after-impact strength of composites. The objective of this study was to evaluate the laminate mechanical properties of composites containing both glass buffer strips and stitching.

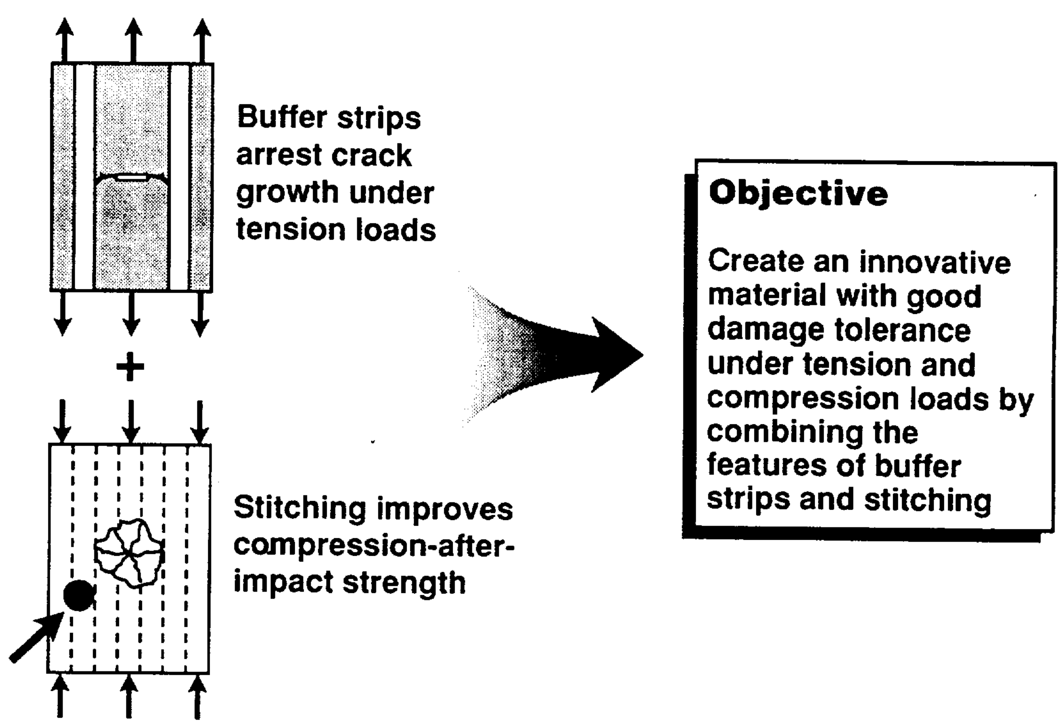



Figure 1

## SPECIFIC OBJECTIVES

In order to assess the potential benefits of combining stitching and glass buffer strips to improve the damage tolerance of composites, three variables were investigated. The variables are listed in figure 2 and include buffer strip placement, buffer strip orientation, and a combination of stitching and buffer strip placement. All test panels were either 16- or 40-ply, quasi-isotropic laminates with buffer strips placed in either the 0° plies only, or in all plies (+45°, 0°, -45°, 90°). Laminates with buffer strips in the 0° plies only had the strips oriented (stacked) on top of each other, or aligned, through the thickness. Laminates with buffer strips in all plies were fabricated with the strips aligned through the thickness, as well as unaligned, or randomly placed through the thickness. Stitched and unstitched panels of each configuration were tested to determine the best combination of stitching and buffer strip placement.

**Assess potenial benefits of combining stitching and glass buffer strips to improve damage tolerance and bearing strength**

- **Buffer strip placements**
- **Buffer strip orientations**
- **Combinations of stitching and buffer strips**

Figure 2

## APPROACH

Figure 3 shows the approach used to characterize the material properties of composites containing fiberglass buffer strips and through-the-thickness stitching. Because the compressive properties of buffer strip composites have not been completely characterized or documented, the first task was to complete basic mechanical property tests such as short block compression, compression-after-impact and open-hole compression, in addition to tension and open-hole tension. These tests have been completed and the results are the subject of this paper. Tests remaining to be performed include single bolt bearing and multiple-hole bolted joint tests, as well as transverse tension and compression tests, with loads 90° to the buffer strips. Additionally, the tension fracture tests performed in references 1 and 2 will be repeated to determine whether stitching degrades the crack arresting capability of buffer strips.

**Characterize mechanical properties of composites containing fiberglass buffer strips and through-the-thickness stitching**

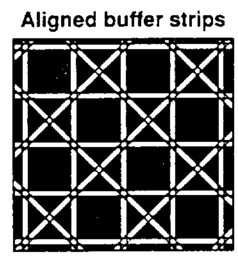
- **Completed tests**
  - Compression
  - Compression after Impact
  - Open hole compression
  - Tension
  - Open hole tension
- **Tests remaining**
  - Bearing
  - Multiple hole bolted joint
  - Off-axis properties
  - Tension fracture strength

Figure 3

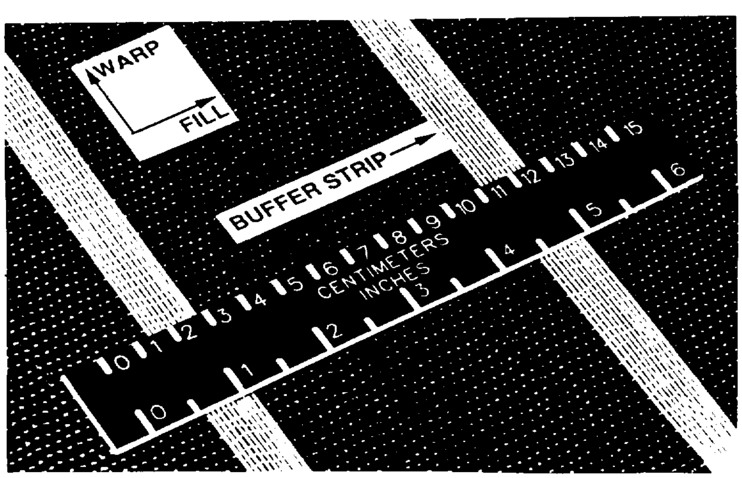
# MATERIALS EVALUATED

The laminates used in this investigation were fabricated with a 3K AS4 uniweave fabric with integrally woven 0.5-inch wide S-2 fiberglass buffer strips as shown in figure 4(a). Results in reference 1 showed that the S-glass buffer strip material had the highest tension fracture strength. A photograph of the fabric is shown in figure 4(b). Three different buffer strip spacings were selected, as listed in figure 4(a). Fabric with buffer strips on 2 1/2-inch centers was tested in reference 2 and was chosen for the 0° buffer strip laminates in this study. The 2 1/2-inch buffer strip spacing was also used for the laminates with unaligned buffer strips in all plies. Buffer strips spaced at both 2 3/4-inches and 3 7/8-inches were used to make the quasi-isotropic laminate with aligned buffer strips in all plies shown in figure 4(a). The 2 3/4-inch buffer strip fabric was used for the 0° and 90° plies; the buffer strips form the two sides of a right triangle. The 3 7/8-inch buffer strip fabric was used for the +45° and -45° plies; the buffer strips form the hypotenuse of this right triangle, resulting in a uniform pattern of intersecting buffer strips. The buffer strip uniweave fabric layers for all configurations were stacked in a quasi-isotropic orientation $[+45°/0°/-45°/90°]_{ns}$ and then stitched with S-2 glass (1250 yd/lb) thread. Both stitched and unstitched preforms were then resin transfer molded using BP E905L resin. Stitching and processing parameters will be discussed subsequently.

- 3K AS4 uniweave carbon fabric
- Integrally woven 1/2" wide S-2 glass strips
- Glass buffer strip spacing
  - 2 1/2 in. centers
  - 2 3/4 in. centers
  - 3 7/8 in. centers
- Fabric layers stacked in $[+45/0/-45/90]_{ns}$ orientation
- Stitched and unstitched preforms
- Stitching thread S-2 glass 1250 yd/lb
- Resin transfer molded using BP E905L resin




(a)



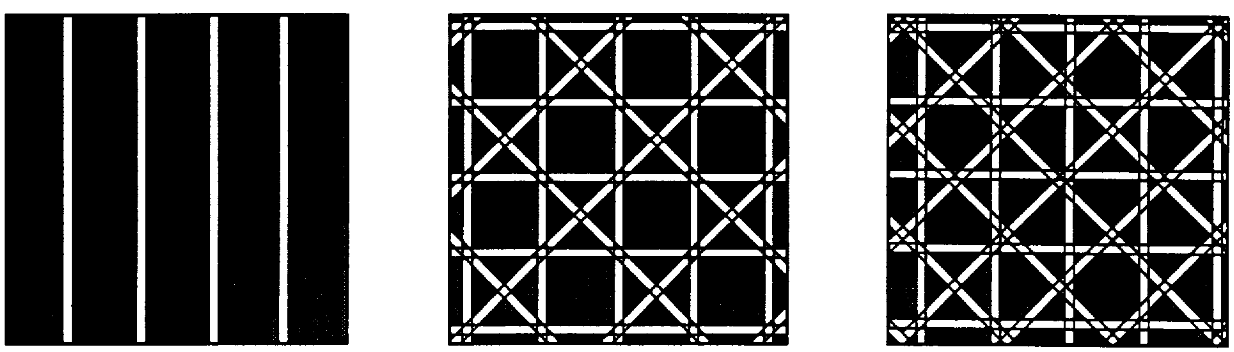

(b)

Figure 4

# BUFFER STRIP CONFIGURATIONS

Figure 5 shows the three buffer strip configurations described earlier. All test panels were quasi-isotropic laminates. A series of unstitched, 16-ply laminates of each configuration were tested in tension to establish baseline properties and for comparison to results reported in reference 2. Additionally, both stitched and unstitched 40-ply laminates of each configuration were tested to evaluate tension and compression properties, as well as open-hole properties of these materials. Laminates with 0° buffer plies contained 5% glass by volume and were 2% heavier than uniweave. The laminates with aligned buffer strips in all plies added 15% glass by volume and had a weight penalty of 5.5%, whereas the laminates with unaligned buffer strips in all plies contained 20% glass by volume and were 7% heavier than plain uniweave.

**Quasi-isotropic laminates**



| 0° buffer plies | All buffer plies aligned | All buffer plies unaligned |
|---|---|---|
| Stitched and Unstitched | Stitched and Unstitched | Stitched and Unstitched |
| 5% glass by volume | 15% glass by volume | 20% glass by volume |
| (2% heavier than uniweave) | (5.5% heavier) | (7% heavier) |

Figure 5

## FABRICATION OF STITCHED BUFFER STRIP TEST PANELS

The fabrication process for the buffer strip laminates is shown in figure 6. Single plies of the dry, plain uniweave and buffer strip uniweave fabrics were cut and stacked in $[+45°/0°/-45°/90°]_{2S}$ orientations to form 16-ply quasi-isotropic laminates and in $[+45°/0°/-45°/90°]_{5S}$ orientations to form 40-ply quasi-isotropic laminates. All three configurations shown in figure 5 were assembled in this manner. The 40-ply stacks were then stitched with a modified lock stitch using S-2 glass (1250 yd/lb) as the needle thread and 200 denier Kevlar 29 as the bobbin thread. The stitch row spacing was 3/16-inch and the stitch density was eight penetrations per inch. Both stitched and unstitched preforms were then resin transfer molded using a pressure injection process with BP E905L resin. The mold cavity depth was the same for all laminates of each thickness, resulting in 60% in-plane fibers for the 16-ply laminates and 56% in-plane fibers for the 40-ply laminates.

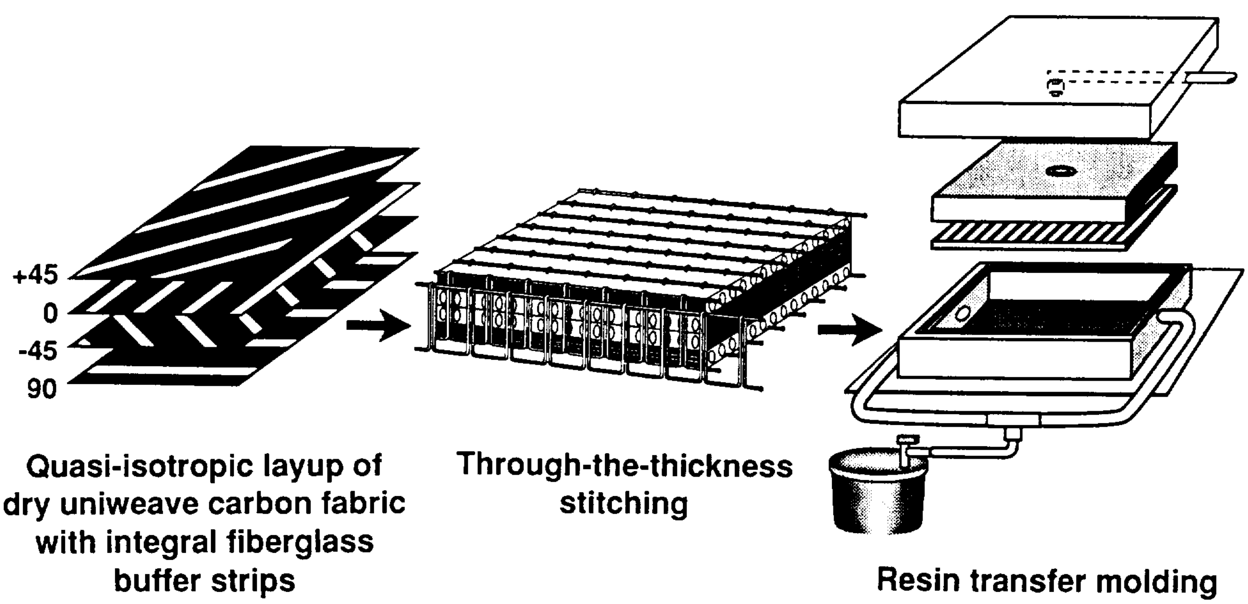



Figure 6

## C-SCAN OF CARBON/EPOXY COMPOSITE CONTAINING ALIGNED FIBERGLASS BUFFER STRIPS

Figure 7 shows an ultrasonic C-scan of a typical composite panel with aligned glass buffer strips. The white region near the center of the panel is a resin-poor (dry) area where resin did not fully saturate the preform during resin transfer molding. Such areas were seen in most of the buffer strip panels. The uniform cross-hatch pattern in the C-scan indicates good alignment of the glass buffer strips through the thickness of the laminate. In general, the C-scans were an excellent tool in assessing the overall quality of the buffer strip laminates.

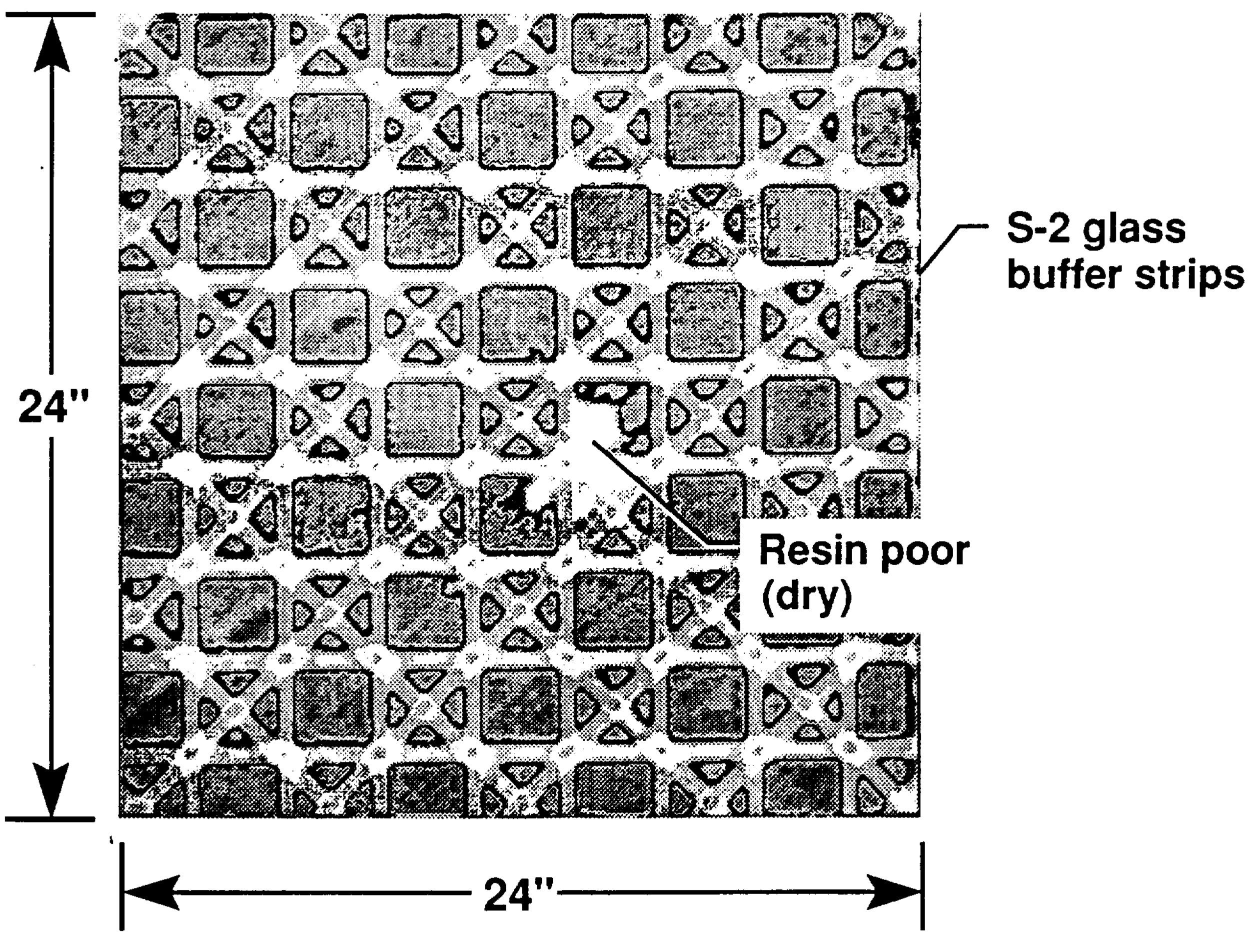



Figure 7

# PHOTOMICROGRAPH OF CARBON/EPOXY COMPOSITE CONTAINING GLASS BUFFER STRIPS

Figure 8 shows a photomicrograph of a typical 40-ply, quasi-isotropic composite laminate containing aligned glass buffer strips in all plies. The carbon fibers appear white in the figure; the fiberglass fibers appear dark gray. The overall laminate thickness is 0.244 inch, which corresponds to a ply thickness of 0.006 inch. Fiber volume fraction was determined by acid digestion and was measured at 56%. Microcracks can be seen in the lower (outer) three plies of the laminate. Microcracks were also seen around stitches in the stitched buffer strip laminates. The microcracking is caused by residual thermal stresses that occur during cool-down of the laminate after the resin is cured.

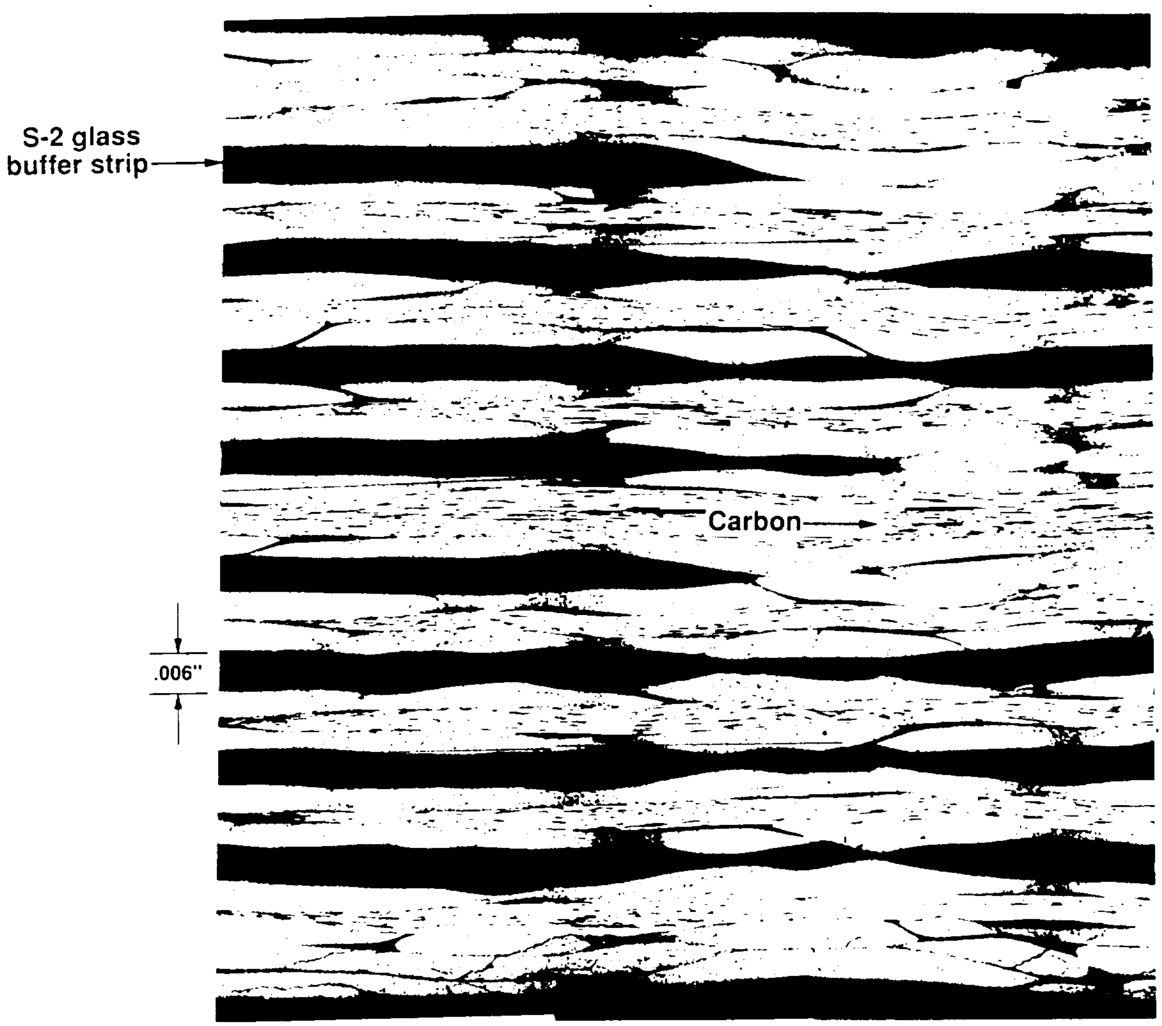



Figure 8

## TEST SPECIMENS

Test specimen geometries are shown in figure 9. All specimens were untabbed. The 1.75-inch by 1.5-inch short block compression specimen is a NASA Langley configuration suitable for tests of angle ply laminates. A 10-inch by 1-inch specimen was used for the tension tests. The open-hole tension and open-hole compression specimens had 0.25-inch holes were 10 inches long and 1.5 inches and 3 inches wide, respectively. The compression-after-impact (CAI) specimen was 6 inches by 4 inches as recommended in reference 4. The CAI specimens were drop-weight impacted at 1500 inch-pounds/inch impact energy with a ten pound weight and 0.5-inch spherical impactor.

The short block compression, open-hole compression and CAI specimens were end-clamped to prevent brooming and were tested to failure at 0.05 inch/minute in a 120-kip hydraulic test machine. The open-hole compression and CAI fixtures also had knife-edge side supports to inhibit specimen buckling. The tension and open-hole tension specimens were end-gripped in a 50-kip hydraulic test machine and also loaded to failure at 0.05 inch/minute. Load, strain and displacement were recorded continuously for all tests using an IBM PC-based data acquisition system.

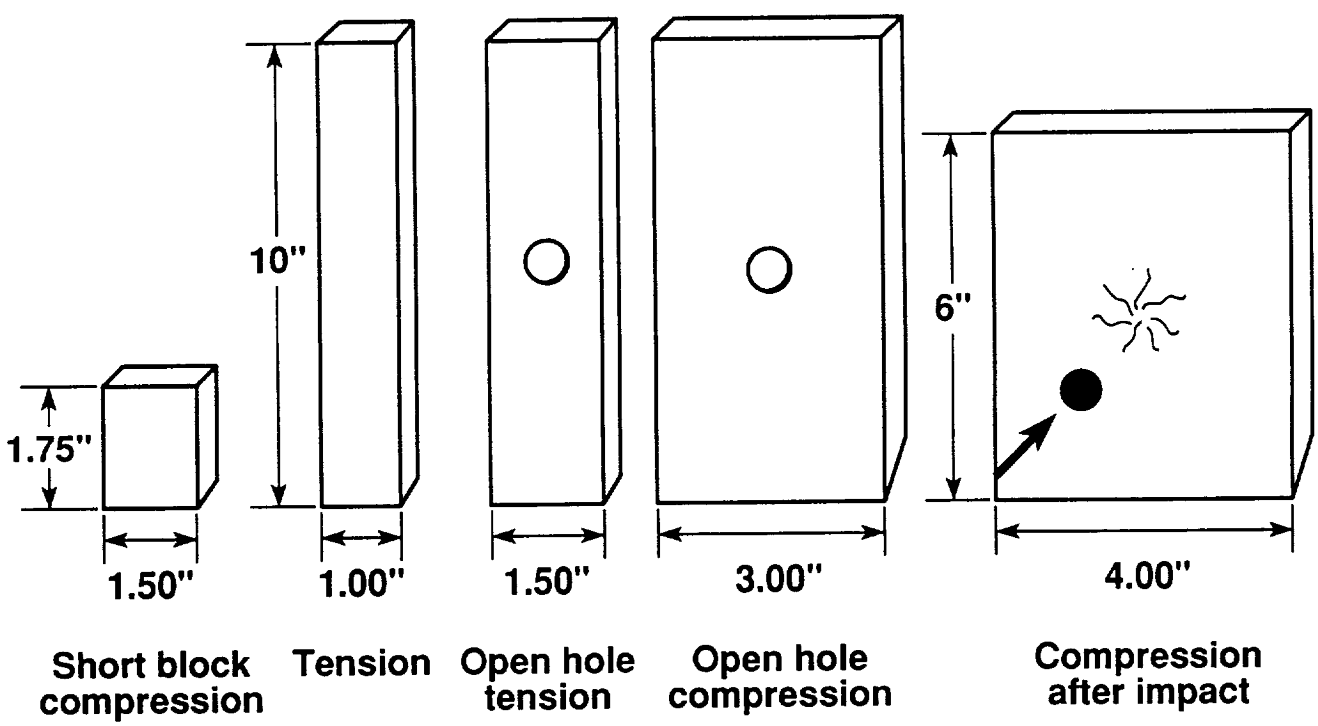



Figure 9

# TENSION PROPERTIES OF UNSTITCHED COMPOSITES CONTAINING GLASS BUFFER STRIPS

Strength and stiffness data for 16-ply, quasi-isotropic, unstitched composites containing glass buffer strips are shown in figure 10. The data shown on the left are results reported in reference 2 for T300/S-1014 uniweave buffer strip fabric that was resin transfer molded with 5208 resin. The results shown on the right are for AS4/S-2 buffer strip uniweave fabric laminates that were resin transfer molded with BP E905L resin for this investigation. Each bar on the right represents the average of ten replicates, and the nominal fiber volume fraction was 60%. The AS4/S-2 laminates are considerably stronger and somewhat stiffer than the T300/S-1014 laminates. One reason for these differences is that the AS4/S-2 uniweave·fabric was woven with fewer glass fill yarns and thus the carbon warp fibers had less crimp than the T300/S-1014 uniweave fabric. Also, reference 1 did not report the fiber volume fraction of the T300/S-1014 laminates. A lower fiber volume fraction might also explain the lower strengths and stiffnesses for the T300/S-1014 laminates.

The AS4/S-2 laminates with no buffer strips (plain uniweave) had a tension strength of 98 ksi. Adding buffer strips in the 0° plies (5% glass by volume) resulted in a 15% reduction in strength and 13% reduction in modulus. Adding buffer strips in all plies (20% glass by volume) resulted in a 26% reduction in strength and a 17% reduction in modulus.

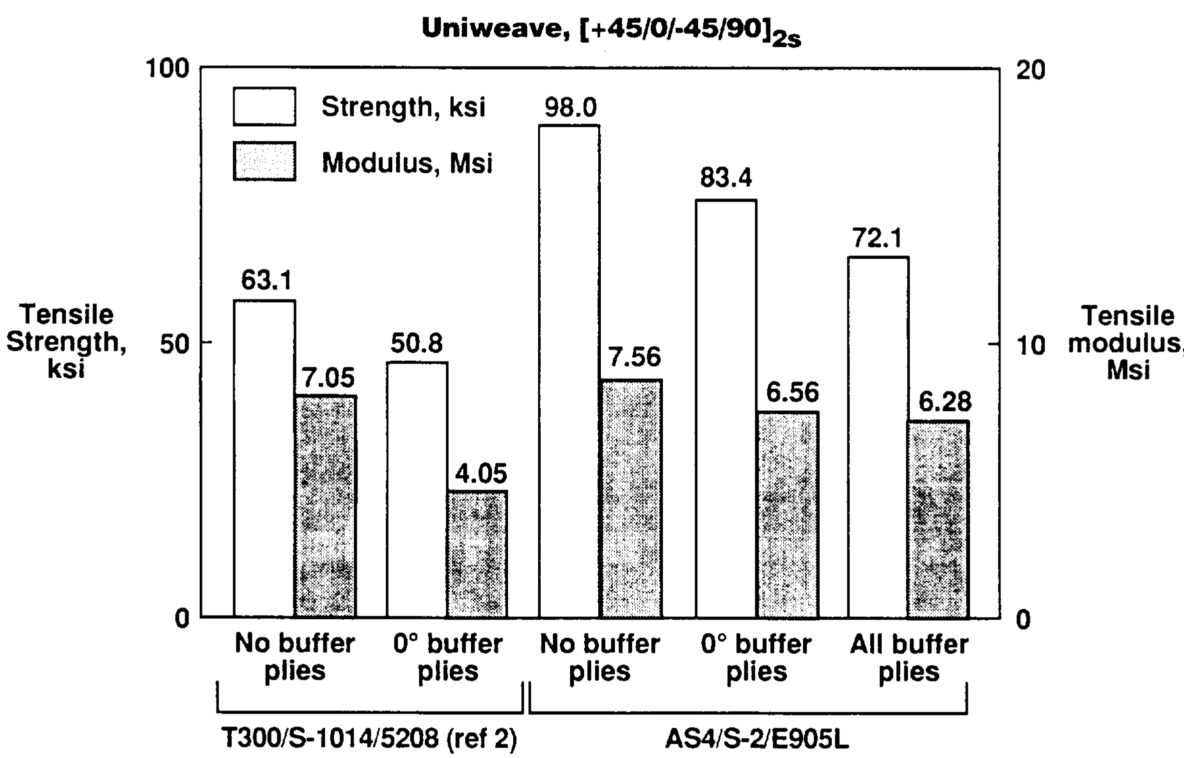



Figure 10

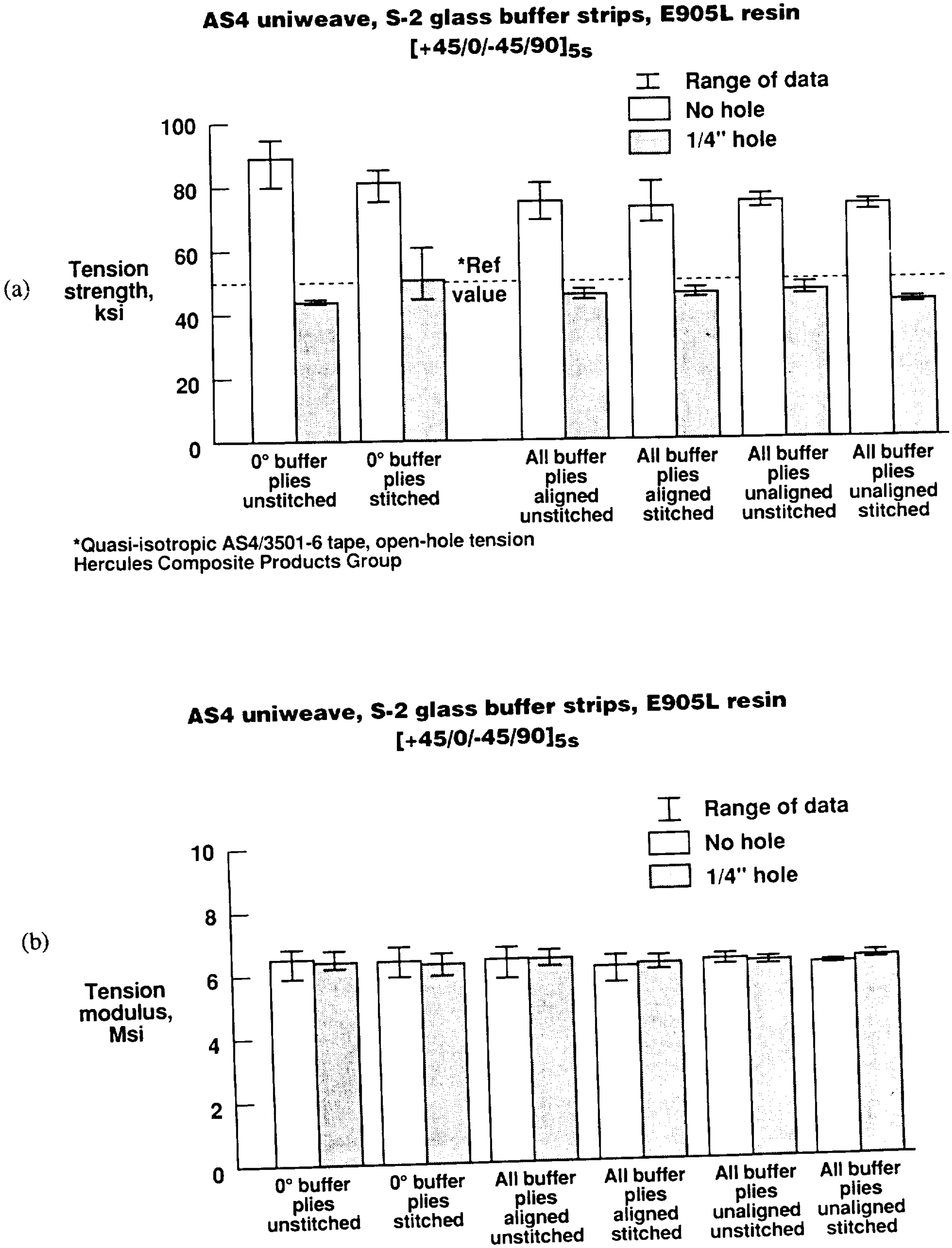
# TENSION AND OPEN-HOLE TENSION STRENGTH OF CARBON/EPOXY COMPOSITES CONTAINING GLASS BUFFER STRIPS AND STITCHING

Tension strength and stiffness data for 40-ply quasi-isotropic composites containing glass buffer strips and stitching are shown in figures 11(a) and 11(b). Each bar represents the average of three replicates with the range of data shown. Figure 11(a) shows the tension and open-hole tension strengths compared to a 50 ksi reference value for AS4/3501-6 tape. Except for the stitched laminate with buffer strips in the 0° plies, open-hole tension strengths for all laminates fell below the 50 ksi reference value. The results show that laminates with buffer strips have lower open-hole tension strengths than the reference value, and that the open-hole strengths are relatively unaffected by stitching. The results show no strength benefit from careful buffer strip placement, or from having buffer strips in all plies. This is not in agreement with reference 2 which showed higher strengths for laminates with buffer strips in all plies. The results also show a high degree of variability in the strengths. There are several possible explanations for the variability and discrepancy with reference 2. First, the specimens were cut randomly from the panels with no regard to the amount or location of buffer strips within the specimen. Additionally, the hole location with respect to the buffer strip location was random and not consistent from specimen to specimen. Moreover, the hole size and specimen width may not have been large enough to adequately characterize the open-hole properties of the buffer strip material. These issues will be investigated in future work.

Figure 11(b) shows the tension modulus of composites containing glass buffer strips. The results show that adding more glass by means of buffer strips and/or stitching does not affect the stiffness properties of glass buffer strip/carbon fiber composites, as might be expected due to the lower stiffness of the glass fibers. These results agree with those published in references 1 and 2 for laminates without stitching.

(Figures 11a and 11b are shown on the next page.)

(a)


AS4 uniweave, S-2 glass buffer strips, E905L resin
[+45/0/-45/90]5s
Range of data
No hole
1/4" hole
Tension strength, ksi
100
80
60
40
20
0
*Ref value
0° buffer plies unstitched
0° buffer plies stitched
All buffer plies aligned unstitched
All buffer plies aligned stitched
All buffer plies unaligned unstitched
All buffer plies unaligned stitched
*Quasi-isotropic AS4/3501-6 tape, open-hole tension
Hercules Composite Products Group

(b)

AS4 uniweave, S-2 glass buffer strips, E905L resin
[+45/0/-45/90]5s
Range of data
No hole
1/4" hole
Tension modulus, Msi
10
8
6
4
2
0
0° buffer plies unstitched
0° buffer plies stitched
All buffer plies aligned unstitched
All buffer plies aligned stitched
All buffer plies unaligned unstitched
All buffer plies unaligned stitched

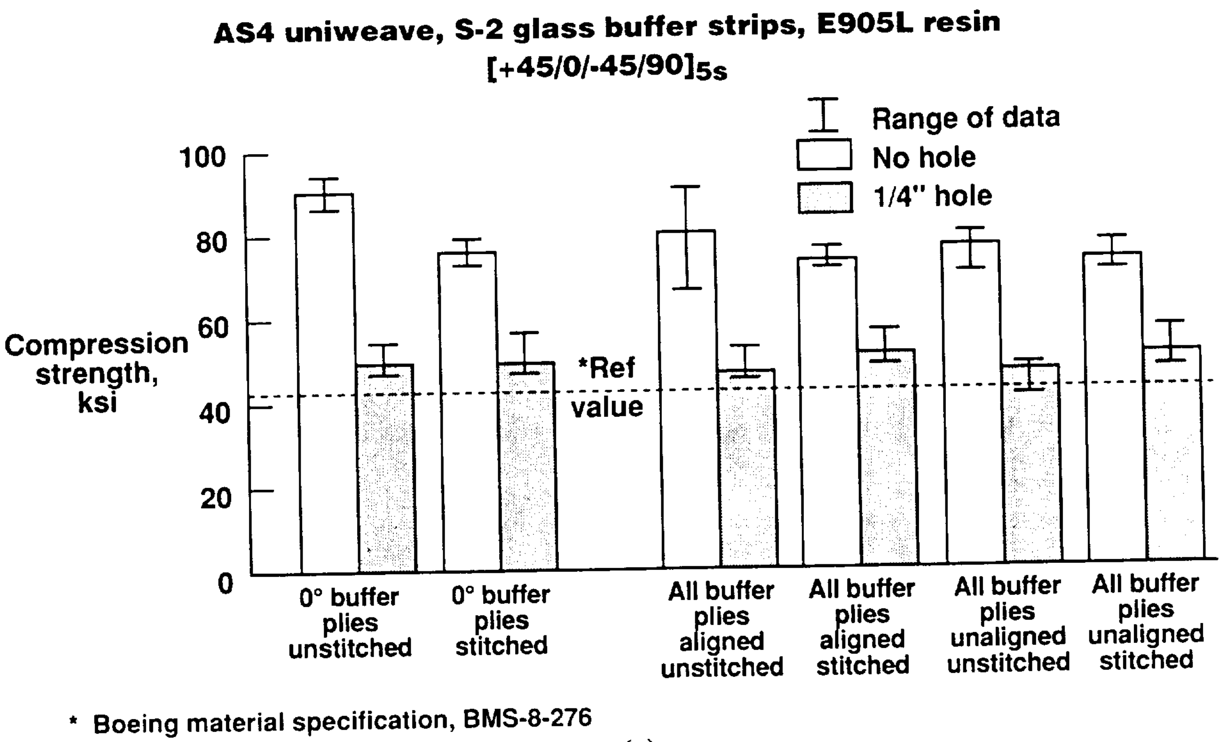
Figure 11

# COMPRESSION AND OPEN-HOLE COMPRESSION STRENGTH OF CARBON/EPOXY COMPOSITES CONTAINING GLASS BUFFER STRIPS AND STITCHING

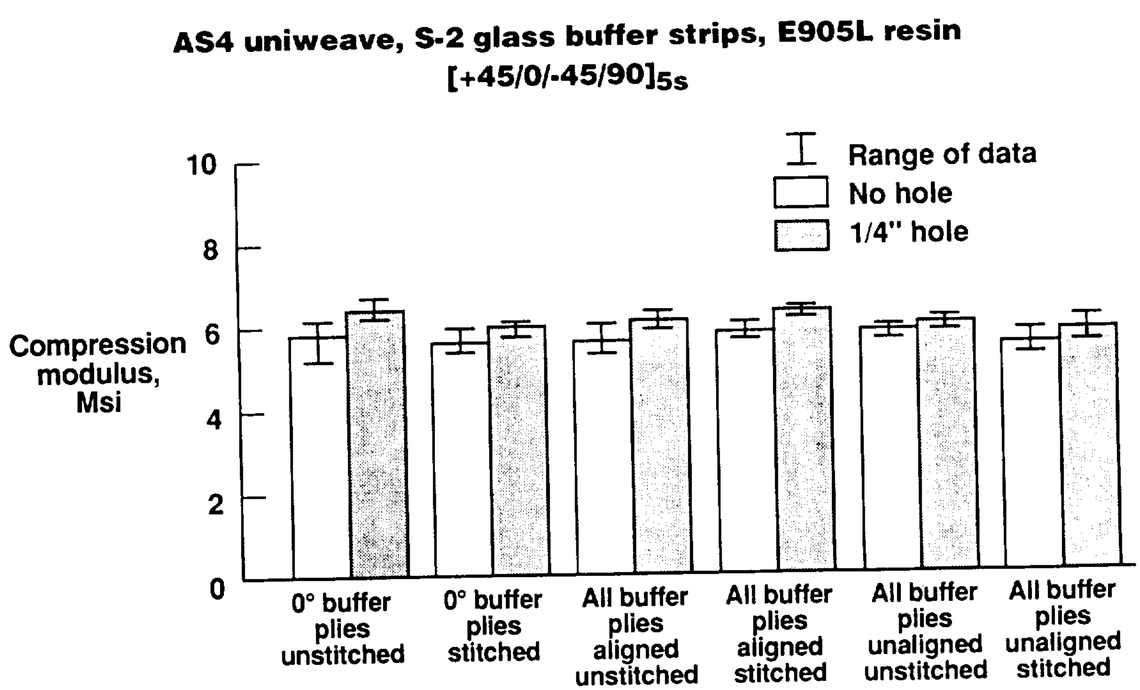
Compression strength and stiffness data for 40-ply quasi-isotropic composites containing glass buffer strips and stitching are shown in figures 12(a) and 12(b). Each bar represents the average of three replicates with the range of data shown. Figure 12(a) shows the compression and open-hole compression strengths compared to a 42 ksi reference value (Boeing Material Specification, BMS-8-276). The highest compression strength was 89 ksi for the unstitched laminates with 0° buffer plies. Open-hole compression strengths for all laminates exceeded the 42 ksi reference value. The results show that buffer strip laminates have acceptable open-hole compression strength and that the open-hole strengths are unaffected by stitching. The open-hole compression results show no strength benefit from careful buffer strip placement, or from having buffer strips in all plies. The results show the same high degree of variability as seen in the tension data. Specimen geometry, notch location and buffer strip location are, again, factors contributing to the scatter in the data and will be investigated in future work.

Figure 12(b) shows the compression modulus of composites containing glass buffer strips. As with the tension results, adding more glass by means of buffer strips and/or stitching does not degrade the compressive stiffness properties of composites.

(Figures 12a and 12b are shown on the next page.)


AS4 uniweave, S-2 glass buffer strips, E905L resin
[+45/0/-45/90]5s
Range of data
No hole
1/4" hole
Compression strength, ksi
100
80
60
40
20
0
*Ref value
0° buffer plies unstitched
0° buffer plies stitched
All buffer plies aligned unstitched
All buffer plies aligned stitched
All buffer plies unaligned unstitched
All buffer plies unaligned stitched
* Boeing material specification, BMS-8-276

(a)


AS4 uniweave, S-2 glass buffer strips, E905L resin
[+45/0/-45/90]5s
Range of data
No hole
1/4" hole
Compression modulus, Msi
10
8
6
4
2
0
0° buffer plies unstitched
0° buffer plies stitched
All buffer plies aligned unstitched
All buffer plies aligned stitched
All buffer plies unaligned unstitched
All buffer plies unaligned stitched

(b)

Figure 12

# COMPRESSION AND COMPRESSION AFTER IMPACT STRENGTH OF CARBON/EPOXY COMPOSITES CONTAINING GLASS BUFFER STRIPS AND STITCHING

Compression and compression-after-impact (CAI) strengths for 40-ply quasi-isotropic composites containing glass buffer strips and stitching are shown in figure 13. Each bar represents the average of three replicates with the range of data shown. Specimen dimensions are 6 inches by 4 inches and were drop weight impacted at an energy level of 1500 inch-pounds/inch, as recommended by reference 4. The CAI strengths are compared to a 40 ksi target value for acceptable damage tolerance reported in Boeing Material Specification BMS-8-276. All of the unstitched laminates had a CAI strength of about 20 ksi, which is typical for tape or woven composites without stitching. All of the stitched laminates met the 40 ksi target value and demonstrated acceptable damage tolerance. The compression strengths show the same degree of variability as seen in the tension specimens, but the CAI results show very little scatter, for both the stitched and unstitched laminates. Additionally, the results show no strength benefit from careful buffer strip alignment or from having buffer strips in all plies, as was the case for the open-hole tension and open-hole compression specimens, described earlier.

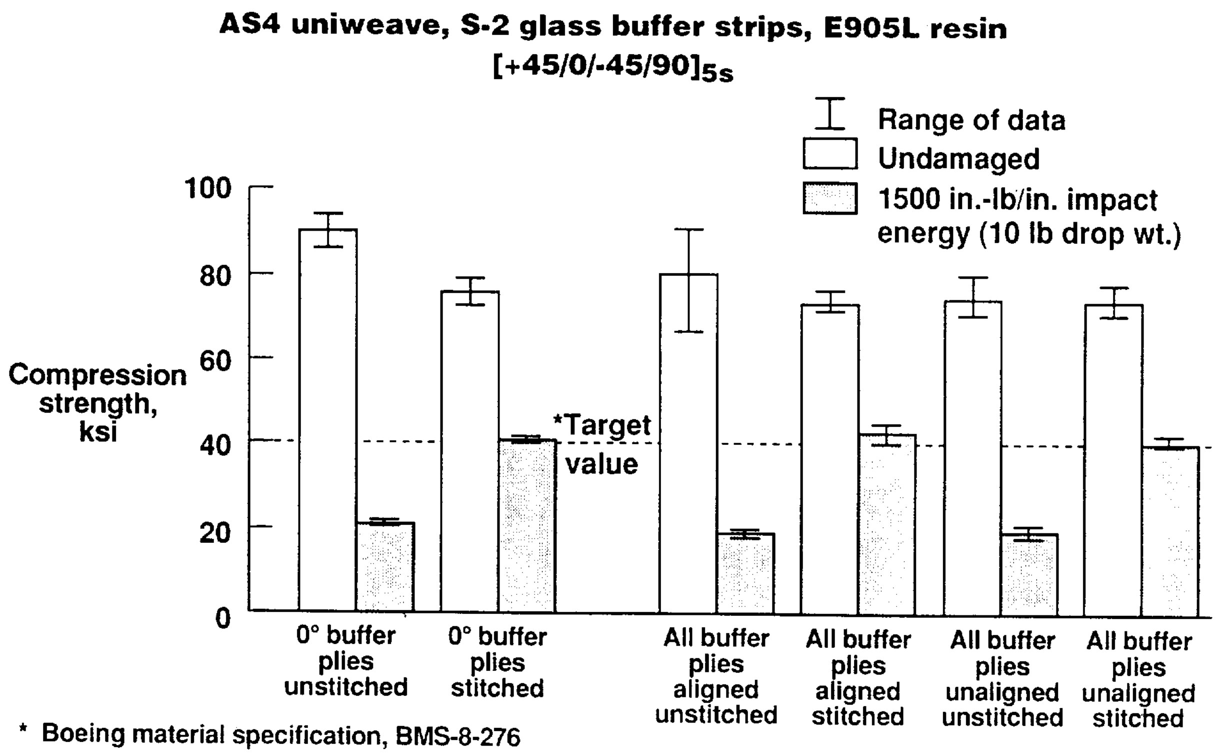



Figure 13

## INTERIM FINDINGS

When this study was started, there was concern that buffer strips would degrade the compression after impact strength of composites; however, as outlined in Figure 14, the results show that composites containing glass buffer strips and stitching have good compression damage tolerance. Additionally, buffer strip laminates have acceptable open-hole compression strengths, and the open-hole strengths are unaffected by stitching. The results also show that composites with buffer strips have marginal open-hole tension strengths, and the open-hole strengths are unaffected by stitching. Finally, the results show no strength benefit from careful buffer strip alignment and no performance benefit from having buffer strips in all plies.

- **Buffer strip laminates with stitching have good damage tolerance.**
- **Buffer strip laminates have acceptable open-hole compression strength. Strengths are unaffected by stitching.**
- **Laminates with buffer strips have marginal open-hole tension strengths. Strengths are unaffected by stitching.**
- **Data reveals no strength benefits from careful buffer strip alignment and no performance benefit from having buffer strips in all plies.**

Figure 14

# FUTURE WORK

Figure 15 outlines the tasks remaining in the evaluation of stitched composites containing glass buffer strips. The first task is to assess the tension fracture strength of laminates containing buffer strips and stitching and will involve performing tension tests with center slits to determine if stitching degrades the crack arresting capability of buffer strips. Secondly, tests will be performed to determine the effect of hole and buffer strip location on laminate tension properties. Holes will be placed at various locations to determine if there is an effect on laminate properties. Third, tests will be performed to assess the bearing strength and bolted joint strength of stitched composites containing glass buffer strips. Finally, tests will be performed on laminates containing 0° buffer strips, with the loads applied transversely to the strips to evaluate the effect of off-axis loads on laminate strength.

- **Assess tension fracture strength of laminates with buffer strips and stitching**
- **Determine effect of hole and buffer strip location on laminate tension properties**
- **Assess bearing strength and multiple hole bolted joint strength of stitched composites containing glass buffer strips**
- **Assess effect of off-axis loads on strength of laminates with 0° buffer strips**

Figure 15

## ACKNOWLEDGMENT

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## REFERENCES

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