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Sublaminate Buckling and Compression Strength of Stitched Uniweave Graphite/Epoxy Laminates

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ABSTRACT: Effects of through-the-thickness stitching on the sublaminate buckling and residual compression strength (often referred as compression-after-impact or CAI strength) of graphite/epoxy uniweave laminates are experimentally investigated. Primarily, three stitching variables: type of stitch yarn, linear density of stitch yarn and stitch density were studied. Delaminations were created by implanting teflon inserts during processing. The improvement in the CAI strength of the stitched laminates was up to 400% compared to the unstitched laminates. Stitching was observed to effectively restrict sublaminate buckling failure of the laminates. The CAI strength increases rapidly with increase in stitch density. It reaches a peak CAI strength that is very close to the compression strength of the undamaged material. All the stitch yarns in this study demonstrated very close performance in improving the CAI strength. It appears that any stitch yarn with adequate breaking strength and stiffness successfully restricts the sublaminate buckling.

INTRODUCTION

ONE OF THE primary obstacles to using fiber composite laminates is their vulnerability to delaminate easily, especially due to low velocity impact of a foreign object. These delaminations create sublaminates of different thickness and sizes within the laminate. The sublaminates buckle at much smaller compressive loads. The residual compressive strength of an impact damaged structure (or the CAI strength) is considered critical in the design of the composite structures, particularly in the aircraft. Therefore, sublaminate buckling failure in

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fiber composite laminates has been studied by many researchers in past several years [1,2]. One of the more feasible solution to overcome this problem seems to be through-the-thickness reinforcement by stitching [3–5]. This study experimentally investigated effects of various stitching parameters on sublaminate buckling behavior which is expected to correlate with the CAI strength.

MATERIAL SYSTEM

Forty-eight ply AS4 uniweave graphite fabric preforms were stitched using automated sewing machines and impregnated with 3501-6 epoxy using resin-transfer-molding (RTM) process to fabricate plates from which the specimens were machined. The delaminations simulating the impact damage were created by inserting teflon film strips at various ply interfaces prior to stitching. Four different delaminations (serially numbered as Damage Type 1–4 for the purpose of this paper) were incorporated simulating varying extent of damage. The undamaged and unstitched laminates were also processed as control. Details of a typical resin-transfer-molded plate indicating lay up and the position of teflon inserts are shown in Figure 1. The plates were ultrasonically C-scanned for quality and location of teflon inserts. A modified stitch lock was used while stitching (Figure 2).

Three different bobbin stitch yarns each with two different stitching densities of 4 × 1/4″ (i.e., 4 stitches per inch and the spacing between each stitch row being 1/4″ = 16 stitches/in²) and 8 × 18″ (=64 stitches/in²) were used for stitching.

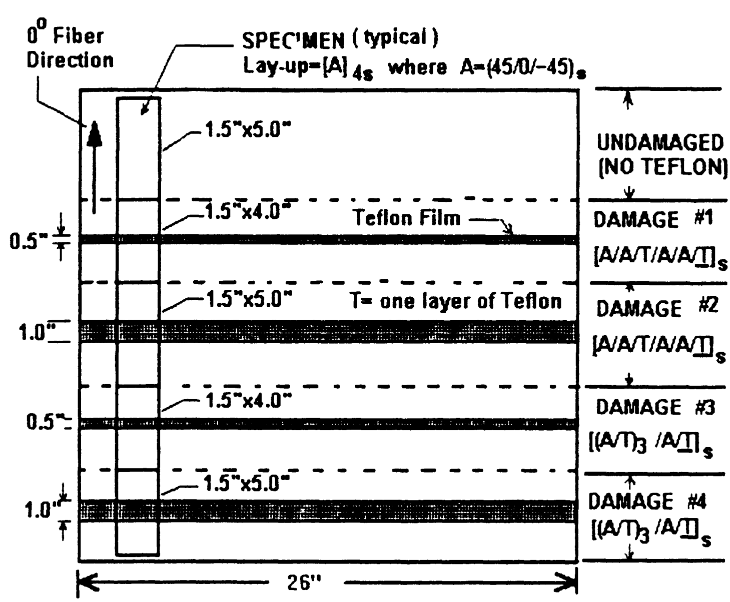


Figure 1. Details of a typical resin-transfer-molded plate processed for the specimens.

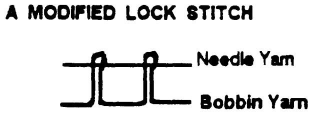


Figure 2. *A modified lock stitch minimizes damage to fibers and preform crimping.*

Needle stitching yarn used in all the cases was Kevlar®-29 (400 denier). Top and bottom plies of the uniweave preform were covered by one layer of plain weave fiberglass cloth to act as retainer cloth for the stitches. The details of the material system used are given in Tables 1 and 2. For the purposes of this document, the three bobbin stitch yarns will be referred as: Kevlar-2790, Glass-1250 and Glass-750.

TEST APPROACH AND DATA REDUCTION

At least 3 specimens each of every damage category were cut, and mounted with back to back strain gages to observe global instabilities during compression. A total of 126 specimens were tested in stroke control mode using facilities at the NASA Langley Research Center, Hampton, VA. The specimens were cut such that the gage length was 1.9″ longer than the length of the implanted delaminations, and the delaminations were located centrally in the specimen. The loading edges were machined flat and parallel to each other. It is important that the fixture surfaces on which the specimen rests are clean and devoid of any foreign matter as these spots may become potential stress concentration points at which the failure may initiate leading to end brooming. Rate of compression loading was 0.03″/min. The University of Florida CAI test fixture was used for the tests. The compression failure could mostly be anticipated by strain gage signals "flaring outward" after the initial superimposed movement indicative of compression. As the strain gage signals begin to flare out significantly (indicative of buckling in the strain gage mounted region), a loud "bang" sound can be heard after a few crackling sounds in quick succession. This is almost immediately accompanied with a drop in load signal. The specimen is unloaded thereafter. The compression strength was computed from the peak load and the average cross-sectional area. Complete details of specimen preparation, test fixture and the test pro-

Table 1. Details of stitch yarns used.

Stitch Yarn	Breaking Strength (Newton)	Breaking Strength (lbf)
Kevlar (1600 denier = 2790 yd/lb) bobbin yarn	347	78
Glass (3570 denier = 1250 yd/lb) bobbin yarn	262	59
Glass (5952 denier = 750 yd/lb) bobbin yarn	436	98
Kevlar (400 denier = 11,160 yd/lb) needle yarn	53	12

Table 2. Material system for sublaminate buckling tests.

Plat E#	Lay Up	Stitch Density	Stitch Yarn	Yarn* Number (yd/lb)	Yarn* Denier (gm/9000 meters)	Average Thickness of Plates (mm)
21	$[(45/0/45)_s]_{4s}$	4 × 1/4″	Kevlar	2790	1600	6.90
32		8 × 1/8″	Kevlar	2790	1600	7.20
33	(Total 48 plies)**	4 × 1/4″	Glass	1250	3570	7.00
34		8 × 1/8″	Glass	1250	3570	7.20
35		4 × 1/4″	Glass	750	5952	6.85
36		8 × 1/8″	Glass	750	5952	7.45
37		None	—	—	—	6.60

*The units for the linear density of a yarn can be Yarn Number (yards/lb) or Denier (grams/9000 meters of yarn). The product of the Yarn Number and Denier will be a constant approximately equal to 4,463,728.
**Each ply is AS4 uniweave graphite fabric. The stitching is in 0° fiber direction.

cedures are given in [6]. A representative stress-strain curve obtained for a compression test is shown in Figure 3.

RESULTS AND DISCUSSION

The variation in CAI strength data was not exceeding 5% in 90 specimens out of the 126 tests, and it did not exceed 10% in the remaining showing good consistency. The average CAI strength results normalized for a gage length of 2.4″ are given in Table 3.

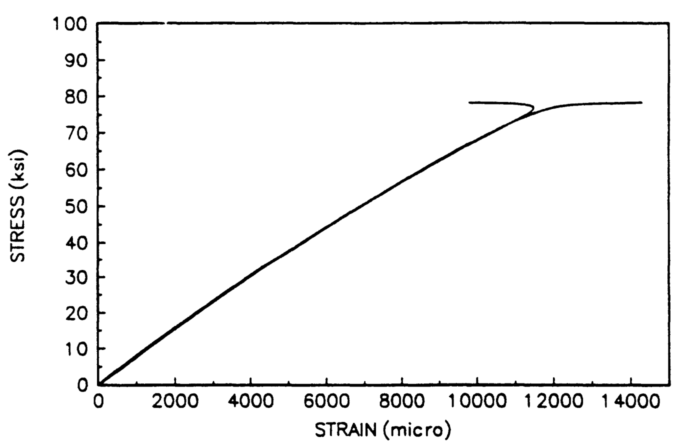


***Figure 3.** A typical stress-strain response for an unstitched or a stitched laminate during the sublaminate buckling test.*

Table 3. Effect of stitch yarn and stitch density on CAI strength.

Type of Damage*	CAI (ksi) Plate #31, Stitched: Kevlar 2790, 4 × 1/4	CAI (ksi) Plate #32, Stitched Kevlar 2790, 8 × 1/8	CAI (ksi) Plate #33, Stitched: Glass 1250, 4 × 1/4	CAI (ksi) Plate #34, Stitched: Glass 1250, 8 × 1/8	CAI (ksi) Plate #35, Stitched: Glass 750, 4 × 1/4	CAI (ksi) Plate #36, Stitched: Glass 750, 8 × 1/8	CAI (ksi) Plate #37, Unstitched
Zero (No Damage)	72.88	69.24	75.04	69.72	73.53	71.53	80.92
1	71.28	68.69	68.33	60.51	66.58	58.77	76.36
2	54.44	63.96	56.86	69.51	54.68	62.91	48.76
3	43.27	65.11	47.65	62.22	45.71	57.24	41.7
4	33.37	60.04	39.46	69.54	38.82	63.01	16.9

*Damage Type #1 = 3 teflon film inserts, each of 0.5″ height running through the entire width of the specimen and located at $[A/A/TT/A/A/T]_S$ where A = $(45/0/45)_S$ and T is a teflon insert. Thickness of teflon film in all cases was 0.0005″.
Damage Type #2 = same as Damage Type #1 but the teflon film inserts are of 1.0″ height each.
Damage Type #3 = 7 teflon film inserts, each of 0.5″ height and located at $[(A/T)_3/A/T]_S$.
Damage Type #4 = same as Damage Type #3 but the teflon film inserts were of 1.0″ height each.

Effect of Different Stitch Yarns on CAI Strength. The CAI strength drops significantly with increase in delaminations for unstitched laminates as shown in Figure 4. The effect of stitching with different yarns of 4 × 1/4″ and 8 × 1/8″ stitch density can also be observed from the results data and is graphically shown in Figures 5 and 6. It is clear that all the three different stitch yarns seem to improve the CAI strength to about same extent when their stitch densities are equal. This may be due to the fact that any through-the-thickness stitch yarn with sufficient breaking strength and stiffness is able to restrain buckling of the sublaminates by holding them together.

Effect of Stitch Density. The CAI strength of delaminated stitched laminates showed excellent improvement over the delaminated unstitched laminates. The improvement in case of the worst delaminated specimens (Damage type #4) stitched with high stitch density like 8 × 1/8″ was as much as 400% over the unstitched laminates. To study a comparative trend of the improvement in CAI strength data due to stitch density, the data were curve fitted using a locally weighted linear regression (Axum software) and the curves are plotted in Figure 7. Here, it was assumed that the different delaminated states (i.e., Damage types #0 to 4) simulate impact damage of an increasing order.

Apparent Loss of Initial Compressive Strength. There seems to be a slight loss of initial compressive strength due to stitching in case of undamaged specimens (about 6% for 4 × 1/4″ stitch density and about 12% for 8 × 1/8″ stitch density). This compares well with earlier studies but we consider this loss as apparent due to the increased thickness of stitched laminates. The nominal increase in thickness of 4 × 1/4″ stitch density laminates was 7% and for the 8 × 1/8″ laminates was about 14%. It is to be noted that the stitch yarns are not in the compressive load bearing direction. The added thickness due to stitch yarn gives an impression as if stitching degrades in-plane compressive properties. Therefore,

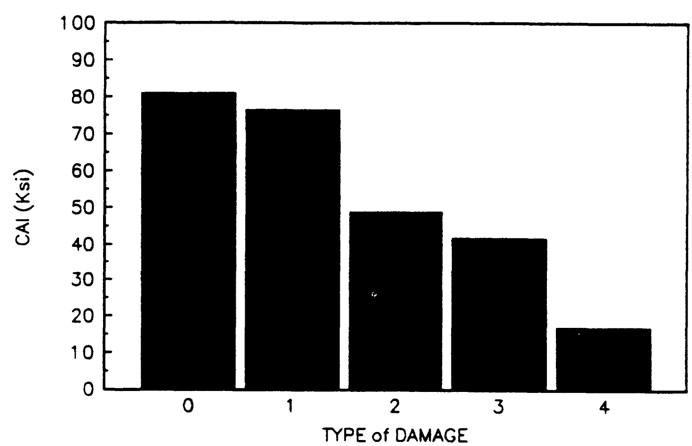


Figure 4. *The compression strength of unstitched laminates drops drastically with increase in delaminations.*

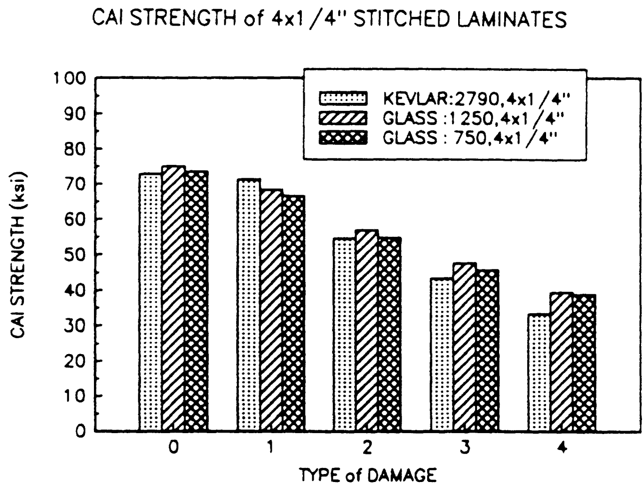


Figure 5. *Effect of different stitching yarns with a low stitch density (16 stitches/in²) on the CAI strength.*

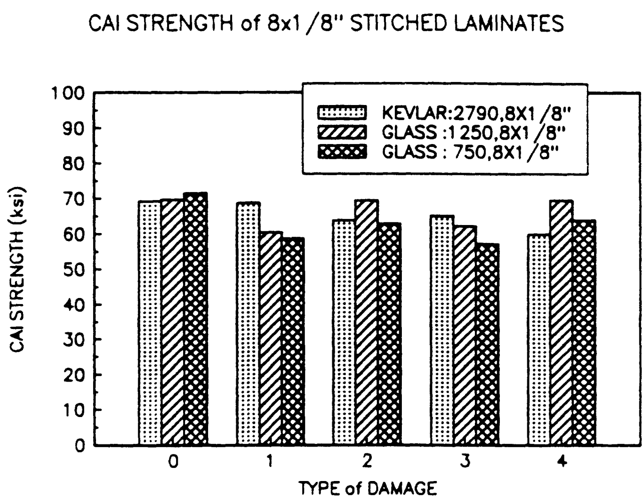


Figure 6. *Effect of different stitching yarns with a high stitch density (64 stitches/in²) on the CAI strength.*

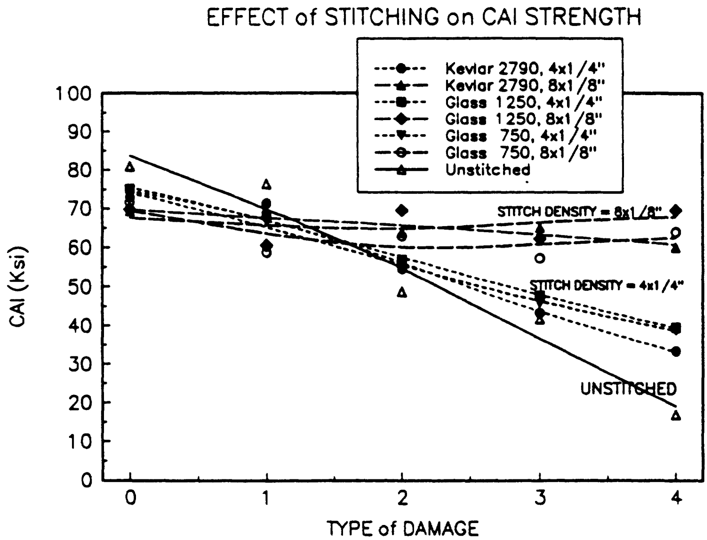


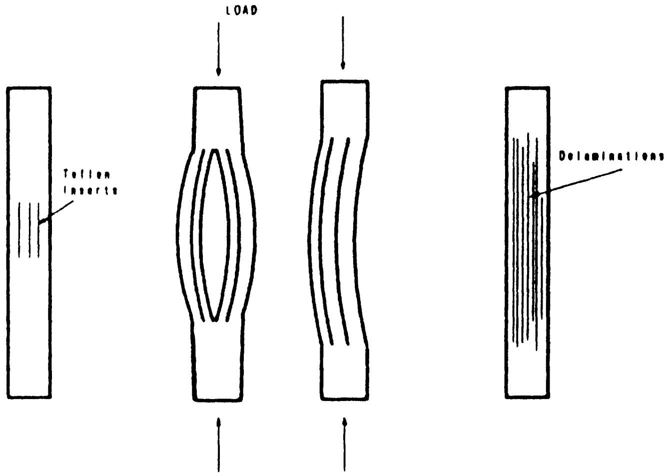
Figure 7. *A trend of the effect of stitch density on the CAI strength.*

this loss of initial compressive strength has to be considered with care. The penalty for stitching is the added thickness of the structure and not reduced compressive strength.

Effect of Stitching on Failure Mode. It was observed that the damaged unstitched laminates tend to fail by buckling of the sublaminates (Figure 8). This could be observed from the white painted side edge surfaces. The painted surface opens up at the teflon inserted interplies and the laminate buckles, but the laminate regains its geometry after the unloading. However, stitching tends to hold the sublaminates together thus prevent buckling. The stitch yarns will be subjected to tensile loading in the process of trying to restraint sublaminate buckling. Therefore, the failure mode is changed to typical small kink zone formation and subsequent fiber fracture (Figure 9). This also explains the impressive gains in CAI strength due to 8 × 1/8″ stitch density as compared to 4 × 1/4″ density.

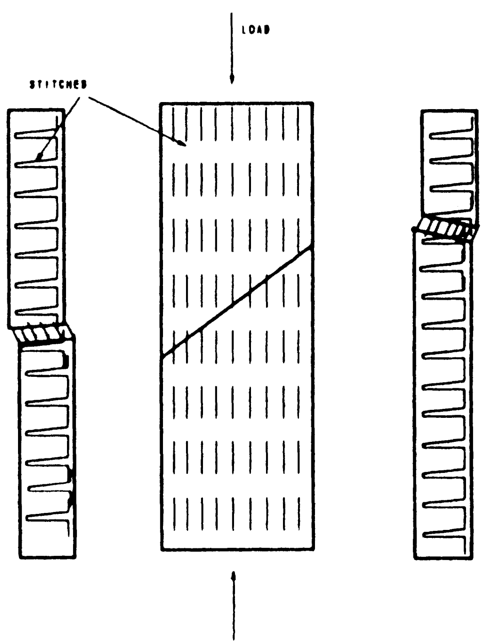
CONCLUSIONS

The improvement in the CAI strength of the stitched laminates with 8 × 1/8″ stitch density was as high as 400% compared to the unstitched laminates for the worst case of delamination studied. Stitching was observed to effectively restrict sublaminate buckling failure of uniweave laminates with teflon implanted delaminations. The CAI strength increases rapidly with increase in stitch density. It reaches a peak CAI strength that is very close to the original compression strength of the material. For the highest stitch density studied i.e., 8 × 1/8″, the CAI strength of the stitched uniweave laminates for the worst damage case was



(a) Specimen before loading (b) Sublaminates buckle & delaminations increase during compression (c) Specimen regains original shape after unloading

Figure 8. *Sublaminate buckling of unstitched laminates.*



(a) LEFT SIDE VIEW (b) FRONT VIEW (c) RIGHT SIDE VIEW

Figure 9. *Buckling failure mode changes in case of stitched laminates.*

about 65 ksi as compared to about 70 ksi of the undamaged stitched control specimens. All the stitch yarns investigated demonstrated very close performance in improving the CAI strength. It appears that any stitch yarn with adequate breaking strength and stiffness successfully restricts the sublaminate buckling.

ACKNOWLEDGEMENTS

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