Effect of Stitching on the Strength of Bonded Composite Single Lap Joints

James Wayne Sawyer*
NASA Langley Research Center, Hampton, Virginia

An experimental investigation has been conducted to determine the effect of stitching on the static and fatigue failure load of bonded composite single lap joints. The variables considered in the static tests included adherend thickness, overlap length, stitch spacing, and number of rows of stitches. A limited fatigue program was conducted for one configuration to compare the fatigue life of stitched and unstitched joints. Up to a 38% improvement in static failure load and an order of magnitude increase in fatigue life compared with unstiffened results are obtained by a single row of stitches near the end of the overlap. Additional rows of stitching or different stitch spacing has little effect on static joint failure load. Thicker adherends and larger overlap length result in larger improvements in static failure load with stitching. Further research is needed to refine the stitching process in order to obtain the maximum improvements in joint failure load.

Introduction

COMPOSITE materials are widely used to make lightweight structures, and bonded joints are potentially the most efficient joints to use with composite materials. However, despite their potential efficiency, bonded joints develop high peel and shear stress concentrations near the edges of the joints.[1] For example, the normalized peel stress distribution through the center of the adhesive in a single lap joint is shown in Fig. 1.[2] The maximum peel stress occurs at the edge of the overlap and is larger than the average adherend tensile stress. Since composite materials have relatively weak interlaminar properties, most bonded joint failures occur in the adherend as interlaminar failures caused by peel stress concentrations. Several design techniques for reducing peel stress concentrations and increasing joint strength of bonded single lap joints have been investigated as discussed in Refs. 3-5. Techniques such as preforming the adherends, tapering the adherends, or adding softening strips to the joint can increase joint strength.

Another technique for increasing the strength of bonded single lap joints consists of applying a transverse compressive restraining force to the ends of the adherends to counteract the high peel stress concentrations. Limited tests were conducted on bonded titanium single lap joints using the test specimen described in Fig. 2. Results of the tests are shown in Fig. 3, where the normalized failure loads for joints with transverse normal restraining forces applied are shown as a function of the normalized restraining force. Each circle represents a single data point, and the curve is drawn through the average of the data points. Only one data point was obtained for the maximum restraining load. A large improvement in joint failure load was obtained. For example, a transverse normal force of 25% of the unrestrained joint failure load doubled the joint failure load. The technique shown in Fig. 2, however, is not practical for most bonded joints. One technique that appears practical for many bonded joints and may provide the transverse compressive force needed to counteract the peel stress concentrations consists of stitching the specimens together close to the edges of the overlap.

Results are presented from an experimental investigation of the effects of stitching on the static and fatigue failure load of bonded single lap joints. The variables considered in the static tests included adherend thickness, overlap length, stitch spacing, and number of rows of stitches. A limited fatigue program was conducted for one configuration to compare the fatigue life of stitched and unstitched single lap joints. Any reduction in the peel stress concentrations due to stitching should have a significant effect on the joint fatigue behavior.

Experimental Procedure

Specimens

A sketch of the test specimens is given in Fig. 4. The adherends were made of 16 and 24 plies of Hercules AS1/3501-6 graphite/epoxy with a quasi-isotropic ply orientation.† Specimens were made in groups by laying up two panels sufficiently wide to obtain the desired number of specimens, applying an adhesive layer between the panels, stitching the panel together, curing and C-scanning the panel assembly, and then cutting the panel into 2-in.- wide specimens. Most of the adherends were bonded together using American Cyanimide FM-400 film adhesive, but a limited number of adherends were bonded together by co-curing. The stitching was done with a shoe sewing machine using a 0.097- in. diameter needle and a 0.031-in. diameter Kevlar thread. A chain stitch was used and the thread tension was zero during the stitching process. Fiberglass end tabs were bonded to the adherends using Switzer A-1273B room temperature curing adhesive.

A summary of the configurations tested is given in Table 1. Specimens with joint overlap lengths of 1, 2, 3, and 4 in. were tested. A series of specimens were made with one, two, and three rows of stitches (see Fig. 4) spaced 1/4 in. apart, and the distance between stitches (pitch) was 3/16, 1/4, or 5/16 in. The stitch row closest to the end of the overlap was approximately 1/4 in. from the edge. Specimens without stitches were also made and tested for comparison with the stitched specimen results. Three or more replicate tests were performed for each test configuration. Typical stitched and unstitched specimens are shown in Fig. 5.

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*Aerospace Engineer, Structures and Dynamics Division.

†Identification of commercial products and companies in this paper is used to describe the test materials adequately. Identification of these commercial products does not constitute endorsement, expressed or implied, of such products by the National Aeronautics and Space Administration.

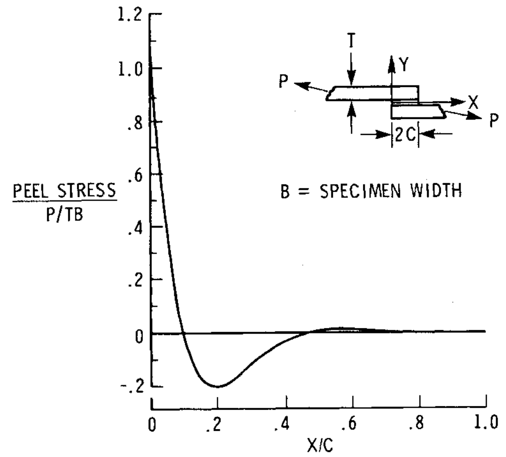


Fig. 1 Normalized peel stress distribution in center of adhesive (Ref. 2).

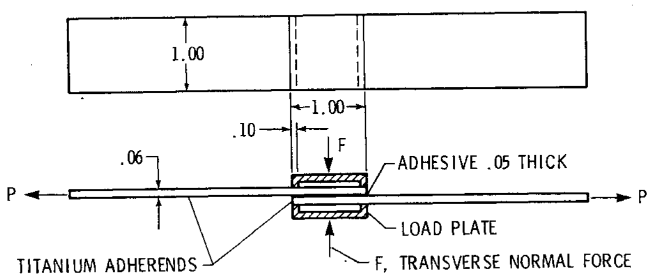


Fig. 2 Titanium single lap joint with applied transverse normal force; dimensions in inches.

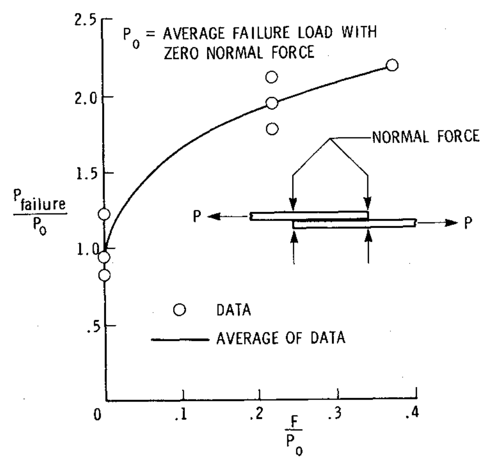


Fig. 3 Effect of transverse normal force on failure load of bonded single lap joints.

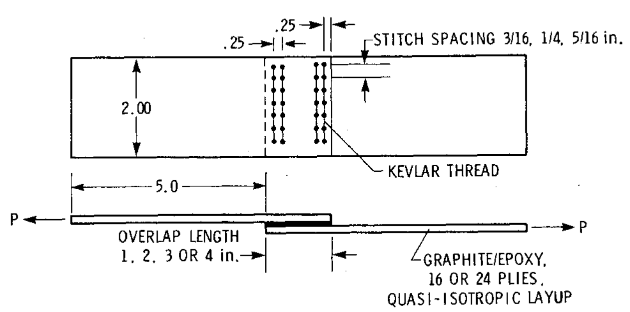


Fig. 4 Graphite/epoxy stitched test specimens; dimensions in inches.

Tests

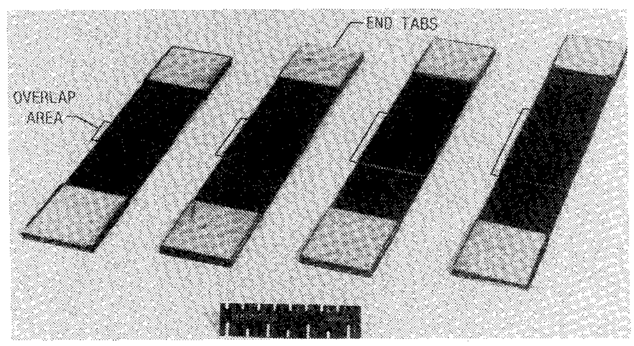
All the specimens were tested in a hydraulically actuated universal test machine. The static tests were conducted at a constant displacement rate of 0.05 in./min and were tested to failure in tension. Swivel joints were used at each end of the specimen test fixture to insure proper load alignment. The failure load and machine cross-head displacement were recorded using a *x-y* recorder.

Fatigue tests were conducted on a limited number of stitched and unstitched specimens with an overlap length of 2.0 in. The fatigue tests were conducted in a load control mode at 5 cycles/s with a ratio of maximum tensile load to minimum tensile load of 0.1 ($R=0.1$). The specimens were tested to failure or 10^6 cycles.

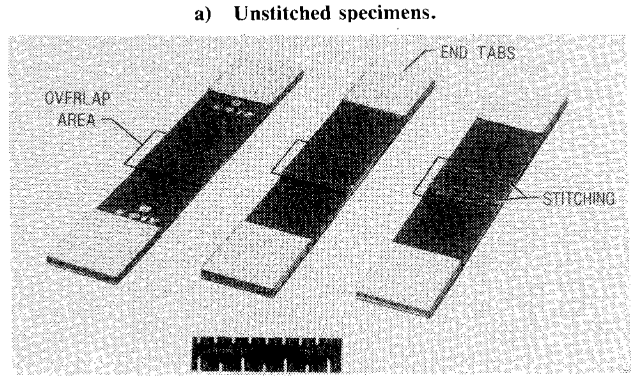
Results and Discussion

Static Results

Results for 24-ply and 16-ply adhesively bonded specimens are shown in Fig. 6 and 7, respectively. Failure loads for stitched and unstitched specimens normalized by the average failure load for unstitched specimens with a 1-in. overlap length P_0 are shown as a function of overlap length. Increasing the overlap length generally increases the joint failure load for the configurations tested, but the joint failure load has a maximum value beyond which additional overlap length will not increase joint failure load. Stitching also generally improves the joint failure load compared to unstitched results, and the improvement becomes greater for larger overlap lengths. However, the improvements due to stitching also approach a maximum value for the larger overlap lengths. For a 1-in. overlap, stitching only slightly improves, or has no effect on, the joint failure load. For the 24-ply specimens (Fig. 6), stitching results in improvement of up to 38% in joint failure load for overlap lengths of 3 and 4 in. when compared to similar unstitched joints. For the 16-ply specimen (Fig. 7), stitching results in a 30% improvement in joint failure load for overlap length of 2 and 3 in. when compared to similar unstitched joints, but for a 4-in. overlap length, the stitched specimens failed at lower failure loads than the corresponding unstitched specimens. The lower failure loads were due to



a) Unstitched specimens.



b) Stitched specimens.

Fig. 5 Photographs of single lap joint specimens.

failure occurring in the adherends at the stitch line, whereas the other specimens had interlaminar failure in the adherend. The adherend failure along the stitch line was due to the damage caused by the needle during the stitching process and is discussed in the Failure Modes section.

Varying the pitch of the stitches did not have a significant effect on the joint failure loads, as shown in Fig. 6 and 7, for the specimens with 3/16 and 5/16-in. pitch. However, the 24-ply specimens (Fig. 6) with a 1/4-in. pitch had significantly higher failure loads than the other stitched specimens for overlap lengths greater than 1 in. The specimens with the 1/4-in. pitch had higher interlaminar strength than the other specimens because of better controlled fabrication procedures. The higher failure loads result from the improved interlaminar strength and do not reflect an improvement in joint failure load due to the pitch.

Normalized failure loads for adhesively bonded and co-cured joints are shown as a function of overlap length for both stitched and unstitched joints in Fig. 8. The solid curves are for co-cured joints, and the dashed curves are for adhesively bonded joints. No significant difference in failure load is observed for the two sets of specimens. Thus, from these limited tests, the addition of an adhesive does not affect the failure load.

The effect of the number of rows of stitching on joint failure is shown in Table 2. Failure loads for 16-ply specimens with one, two, and three rows of stitching are presented. Only the 16-ply specimens were tested with more than one row of stitching. For most of the test configurations, specimens with two or three rows of stitching had higher failure loads than unstitched specimens but lower failure loads than specimens with one row of stitches. One exception was the 4-in. overlap specimens, where two rows of stitching resulted in slightly higher failure loads than were obtained with one row. However, as was pointed out earlier, the 4-in. overlap specimens with only one row of stitching failed in the adherend at the stitch line, and the failure load for this configuration was less than that for the unstitched specimens. Hence, except as noted, the failure load for specimens with a single row of stitching was usually larger than the corresponding results for specimens with multirow stitching.

Table 1a Summary of test matrix for bonded and co-cured single lab joints, 24-ply specimens

Specimen description	Stitch spacing, in.	Static tests: No. of specimens tested, Overlap length, in. 1.0	2.0	3.0	4.0
Adhesive bonded joints	0[a]	3	3	3	3
	3/16	3	3	3	3
	4/16	6	6	6	6
	5/16	3	3	3	3
Co-cured joints	0	3	3	3	3
	3/16	3	3	3	3
	5/16	3	3	3	3
		Fatigue tests			
Adhesive bonded joints	0	0	12	0	0
	4/16	0	12	0	0

[a]No stitching.

Table 1b Summary of test matrix for adhesive bonded joints, 16-ply specimen

Static tests: Stitch spacing, in. Row 1	Row 2	Row 3	No. of specimens tested, Overlap length, in. 1.0	2.0	3.0	4.0
0[a]	—	—	3	12	3	3
3/16	—	—	3	3	3	3
5/16	—	—	3	12	3	3
3/16	3/16	—	3	3	—	3
3/16	5/16	—	—	3	—	3
5/16	3/16	—	3	—	—	3
5/16	5/16	5/16	—	3	—	—

[a]No stitching.

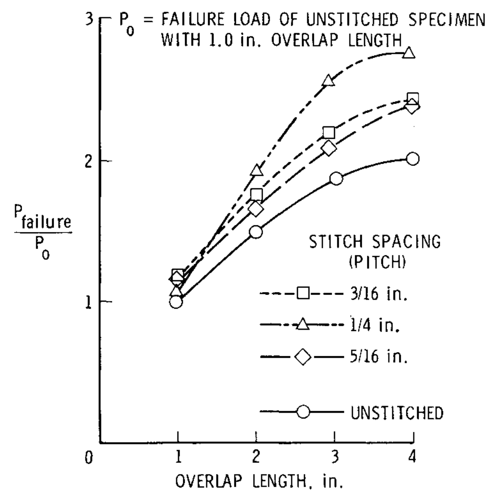


Fig. 6 Failure loads for co-cured stitched and unstitched single lap joint specimens. Adherends have 24-plies of graphite/epoxy with quasi-isotropic layup. Data points represent an average of three or more replicate tests.

Table 2 Effect of multiple rows of stitching on failure load of single lap joints; adherends have plies of graphite/epoxy with quasi-isotropic layup

Overlap length, in.	One row of stitches: Stitch spacing, in.	Average failure, load, lb	Two rows of stitches[a]: Stitch spacing, in.	Average failure, load, lb	Three rows of stitches[a]: Stitch spacing, in.	Average failure load, lb
1.00	3/16	3736	3/16, 3/16	4360		
	5/16	3643	5/16, 3/16	3090		
2.00	3/16	6410	3/16, 3/16	5883		
	5/16	5902	3/16, 5/16	6406	5/16, 5/16, 5/16	5276
3.00	3/16	7363				
	5/16	7520				
4.00	3/16	5573	3/16, 3/16	6963		
	5/16	6610	3/16, 5/16	6896		
			5/16, 3/16	6880		

[a]Stitch rows ¼ in. apart.

Fatigue Results

A limited number of fatigue tests were conducted on stitched and unstitched single lap joint specimens. Results of the fatigue tests are presented in Fig. 9, where the normalized load is shown as a function of the number of cycles to failure for both the stitched and unstitched configurations. The solid lines are faired through the average test results. Specimens surviving 10^6 cycles were tested statically to failure and had a residual strength comparable with the uncycled specimens. Stitching results in at least an order of magnitude increase in fatigue life compared to unstitched results for cyclic levels up to 10^6 cycles or, for a given cyclic life, stitched specimens will carry a significantly higher load than unstitched specimens.

Failure Modes

Typical joint failures are shown in Fig. 10. Inspection of the failure surfaces for the stitched joints indicated that all the specimens had some fiber damages where the needle penetrated the adherends. Joint failure occurred by interlaminar failure of the adherends along the length of the joint. The parallel strips along the failure surface are locations where delaminations occurred in the adherend. The strip delaminations were initiated at needle penetrations and may have reduced the failure loads. Higher failure loads than observed in this study might be possible with an improved stitching technique.

The 16-ply specimens with 4-in. overlap length had adherend failures along the stitch line, as shown in Fig. 11. The needle broke fibers during stitching, causing adherend failures along the stitch line. The load associated with this failure was lower than the failure loads obtained with specimens that had interlaminar failure. Because of the larger thickness, the 24-ply laminates did not have these adherend failures.

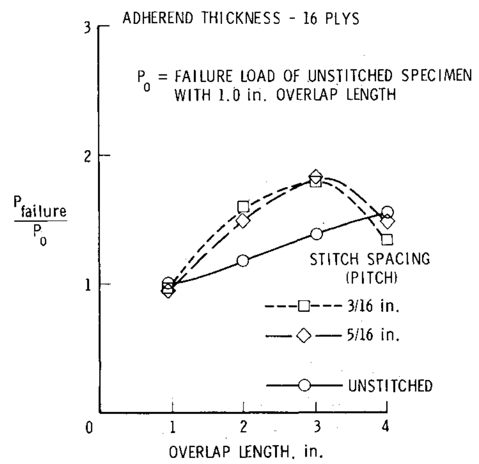


Fig. 7 Failure loads for co-cured stitched and unstitched single lap joint specimens. Adherends have 16-plies of graphite/epoxy with quasi-isotropic layup. Data points represent an average of three or more replicate tests.

Recommendations

The fiber damage due to stitching discussed previously may be minimized by improvements in the stitching process. The needle used in this investigation had a diameter of 0.097 in., which was larger than required. The stitching was done at room temperature, and the needle was pushed through the uncured material without any attempt to move the fibers aside. Using a smaller needle, vibrating the needle while stitching, and heating the material should permit many of the fibers to shift around the needle and result in fewer broken fibers. This procedure could increase the strength of the stitched joints in this study and should eliminate adherend failure at the stitch line.

In addition to improvements in the stitching process, applying tension to the stitch thread would result in an initial clamping force similar to the clamped specimens discussed in the Introduction. Since the tension in the stitching thread was zero for the specimens tested, the stitching did not provide any clamping force to the unloaded joint but provided a restraining force to prevent the adherends from separating under load. Thus, the stitched results in Fig. 6-9 are probably a lower bound for the improvements in joint failure load from stitching. Applying tension to the stitching thread may result in greater improvements in joint failure load than obtained in the present tests.

Since the maximum peel stress concentration in a single lap joint occurs at the end of the overlap, the stitch line should be close to the end of the overlap to counteract the high peel stress. The specimens for this investigation had the stitch line approximately 1/4 in. from the end of the overlap. By better controlling the stitching process or trimming the ends of the adherends after stitching, the stitch line can be located closer to the end of the overlap, which may result in higher joint failure loads than obtained from the present tests.

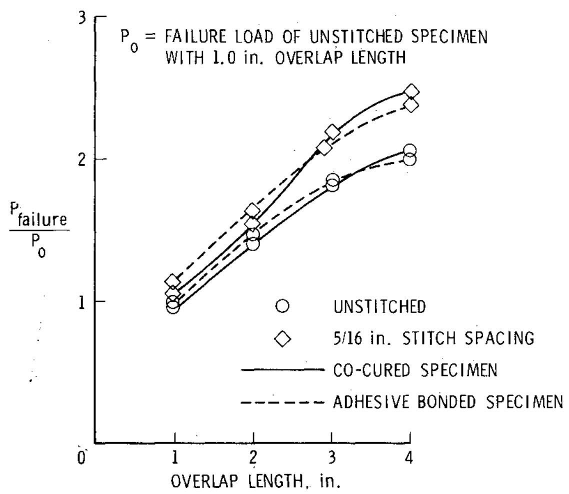


Fig. 8 Failure loads for adhesively bonded and co-cured stitched and unstitched single lap joints. Adherends have 24-plies of graphite/epoxy with quasi-isotropic layup.

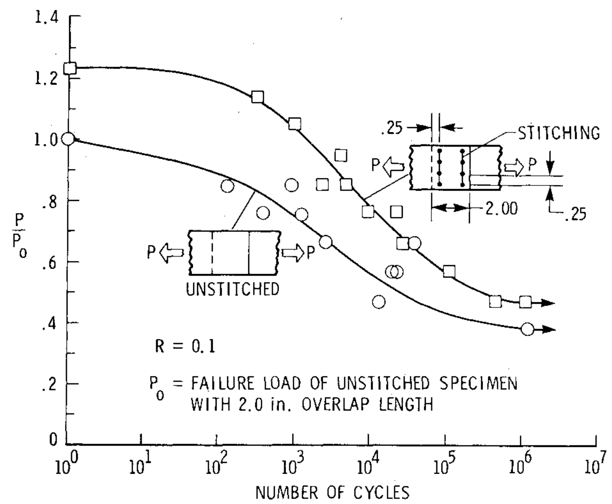


Fig. 9 Effect of stitching on fatigue strength of single lap joints. Adherends have 24-plies of graphite/epoxy with quasi-isotropic layup. All dimensions in inches.

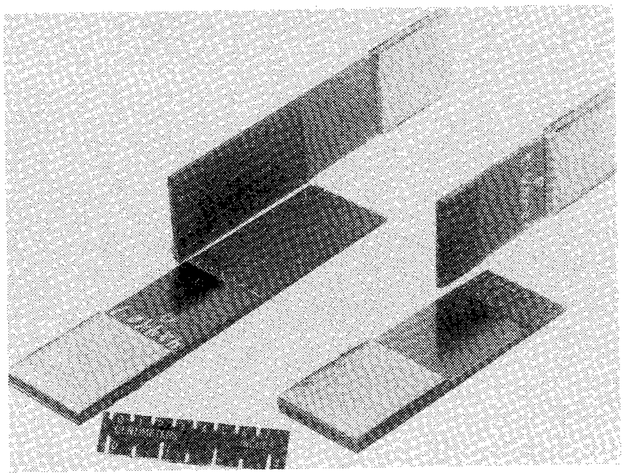


Fig. 10 Typical failures of stitched single lap joint specimens.

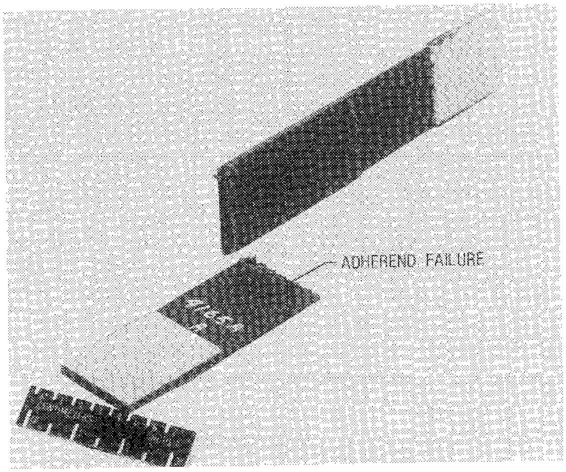


Fig. 11 Adherend failure of stitched single lap joint specimen.

Although significant improvements in static and fatigue joint failure loads have been demonstrated by stitching, even greater improvements may be possible with the refinements suggested above. Further research in stitched joints is needed to determine the optimum needle size, the optimum material temperature for stitching, the best needle manipulation to reduce the number of broken fibers, the effect of applying tension to the stitching thread, and the best location of the stitch line relative to the end of the adherend.

Concluding Remarks

An experimental investigation has been conducted to determine the effect of stitching on the static and fatigue failure load of bonded single lap joints. The variables considered in the static tests included adherend thickness, overlap length, stitch spacing, and number of rows of stitches. A limited fatigue program was conducted for one configuration to compare the fatigue life of stitched and unstitched single lap joints.

The results show that improvement of up to 38% in static failure load compared to unstitched results is obtained by a single row of stitches near each end of the overlap. The improvement in static failure load is generally greater for longer overlap lengths and for thicker adherends. Stitch spacing (pitch) does not have a significant effect on the static failure load for the range investigated. Additional rows of stitching do not result in any further improvements in joint failure load. Co-cured and bonded joints had the same static failure loads and showed the same improvement with stitching. Stitching also increased the fatigue life by an order of magnitude or more compared to unstitched joints for joints with a 2-in. overlap length.

The stitched specimens used for this investigation do not represent optimum configurations, and the results probably represent a lower bound for improvements in joint failure load due to stitching. Fiber damage due to the stitching process was evident and may have initiated failure in some specimens. Further research is needed to refine the stitching process to maximize joint failure load.

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