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INFLUENCE OF INTERFACE PLY ORIENTATION ON FATIGUE DAMAGE OF ADHESIVELY BONDED COMPOSITE JOINTS

W. S. JOHNSON AND S. MALL

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

SUMMARY

An experimental study of cracked-lap-shear specimens was conducted to determine the influence of adherend stacking sequence on debond initiation and damage growth in a composite-to-composite bonded joint. Specimens consisted of quasi-isotropic graphite/epoxy adherends bonded together with either FM-300 or EC 3445 adhesives. The stacking sequence of the adherends was varied such that 0°, 45°, or 90° plies were present at the adherend-adhesive interfaces. Fatigue damage initiated in the adhesive layer in those specimens with 0° and 45° interface plies. Damage initiated in the form of ply cracking in the strap adherend for the specimens with 90° interface plies. The fatigue-damage growth was in the form of delamination within the composite adherends for specimens with the 90° and 45° plies next to the adhesive, while debonding in the adhesive resulted for the specimens with 0° plies next to the adhesive. Those joints with the 0° and 45° plies next to either adhesive had essentially the same fatigue-damage-intiation stress levels. These stress levels were 13 and 71 percent higher, respectively, than those for specimens with 90° plies next to the EC 3445 and FM-300 adhesives.

Key Words: adhesive bonding, composite material, debonding, delamination, stacking sequence, fatigue, fatigue mechanics.

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INTRODUCTION

The weight advantages of composite structures are frequently eroded by using mechanical fasteners. Adhesive bonding may be a desirable alternative to mechanical fasteners in composite structures. To utilize bonded joints efficiently and reliably, a complete understanding of their failure mechanism under different loading conditions is needed. Several studies report on the static strength of adhesively bonded composite joints (e.g., see Ref. 1); however, very little information is available on their fatigue behavior.

In a previous study [2] an experimental program was undertaken to identify and understand the mechanics of the possible modes of fatigue-damage propagation in adhesive joints. It was found that cyclic debond rates correlated better with the sum of the peel-plus-shear energy-release rates than with either mode separately. However, in that study the bonded surfaces of the composites were of 0° orientation only. In actual structures a variety of interfacial fiber orientations would be used. Consequently, the present study was pursued to extend the work in Reference 2 to include interfaces of 45° and 90° plies in addition to those of 0° ply. This investigation focused on fatigue-damage propagation under mixed-mode conditions (i.e., shear and peel modes). Threshold loads for fatigue-damage initiation were also determined. In a previous study by the authors [3], it was shown that the maximum cyclic stress for no debond initiation can be used for bonded systems to determine a no-growth threshold total strain-energy release rate G_{th}. The G_{th} is an important design parameter. The authors have demonstrated a fracture mechanics approach for designing a bonded system utilizing this no-growth threshold G_{th} [3]. For this purpose, the cracked-lap-shear specimens tested in the program were analyzed with the finite-element program GAMNAS [4] to determine the strain-energy release rate for a given geometry, debond length, and applied load. From this analysis and from the experimental data, G_{th} was determined for the debond initiation in the adhesive for the different interface ply orientations.

EXPERIMENTAL PROCEDURE

Test Specimens

The cracked-lap-shear specimen (CLS) shown in Fig. 1 was used in the present study. Two bonded systems were studied: Narmco (T300/5208) graphite/epoxy* adherends bonded with either 3M Co. EC 3445 adhesive or with American Cyanamid Co.* FM-300 adhesive. The properties of the adhesives and of the graphite/epoxy are given in Tables 1 and 2, respectively. The EC 3445 adhesive is a thermosetting paste with a cure temperature of 121°C; specimens were fabricated by conventional secondary bonding procedures. On the other hand, the FM-300 is a modified epoxy adhesive supported with a carrier cloth and has a cure temperature of 177°C; specimens were fabricated by co-cure, whereby adherends were cured and bonded simultaneously. The bonding processes followed the manufacturer's recommended procedures for each adhesive. The nominal adhesive thickness was 0.10 and 0.25 mm for the EC 3445 and FM-300, respectively.

For each adhesive system, three different lay-ups of the adherends were fabricated and tested. The lay-ups are given in Table 3. This arrangement provided three sets of specimens with 0°, 45°, or 90° plies at the adherend-adhesive interface for each adhesive.

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*Use of trade names or manufacturers does not consitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Testing Procedure

The test program consisted of fatigue tests in a closed-loop servo-hydraulic test machine at a frequency of 10 Hz. In all tests, constant-amplitude cyclic loads were applied at a load ratio of 0.1. Friction grips were used, and the grips and load train were considered to be sufficiently stiff to assume fixed-fixed loading conditions on the specimen.

Tests were conducted on the strap adherend to establish the minimum applied cyclic tensile stress that would cause debond initiation and/or adherend failure for each lay-up. To this end, virgin specimens (i.e., those with no debonding) were tested at a given load range for 1 million cycles, then inspected through dye-enhanced (zinc iodide) radiography. If there was evidence of debond initiation, the test was stopped. Otherwise, the cyclic load level was raised by approximately 10 percent. The specimen was tested for an additional 1-million cycles and then radiographed. These steps were repeated, progressively increasing the load range, until the specimen showed signs of debonding and/or adherend fatigue damage. This procedure allowed for more than one data point to be obtained per specimen. This testing procedure has been successfully employed by the authors to measure the threshold load for debond initiation and propagation in bonded composite joints [3].

FINITE-ELEMENT ANALYSIS

The tested cracked-lap-shear (CLS) specimens were analyzed with the finite-element program GAMNAS [4] to determine the strain-energy release rate for a given geometry, debond length, and applied load. This two-dimensional analysis accounted for the geometric nonlinearity associated with the large rotations in the unsymmetric CLS specimen.

A typical finite-element model of a CLS specimen is shown in Fig. 2. This finite-element model mesh consisted of about 1200 isoparametric 4-node elements and had about 2400 degrees of freedom. Each ply of composite was modeled as a separate layer of elements in the finite-element model, except for the ply at the adhesive interface, which was modeled as two layers. The adhesive thickness was modeled with four layers of elements. A multipoint constraint (indicated in Fig. 2) was applied to the loaded end of the model to prevent rotation (i.e., all the axial displacements along the ends were equal to simulate grip loading of the specimen). Plane-strain conditions were assumed in the analysis. The material properties of composite adherends and adhesives are listed in Tables 1 and 2. The strain-energy release rate was computed with a virtual crack-closure technique. The details of this procedure are given in Ref. 4.

To compute a debond threshold strain-energy release rate, a small debond must be assumed to exist at the location of expected debond initiation, that is, at the end of the lap adherend. For the current computations, a debond length of 1 mm was assumed. This debond length was approximately the minimum size debond that could be found with the X-ray inspection technigue used during the debond initiation tests. Computations using a debond length of 0.5 mm resulted in calculated initiation stresses about 3 percent lower than those for a 1 mm length [3]. Thus, G is not highly sensitive to the finite debond length.

RESULTS AND DISCUSSIONS

Damage Modes

In all specimens with 0° and 45° interface plies, the fatigue damage initiated with cyclic debonding within the adhesive for both EC 3445 and FM-300. Thereafter, in all specimens with 0° interface plies, the debond grew in a cohesive manner within the adhesive region. A detailed investigation of the mechanics of this cyclic debond growth has already been reported [2,5].

For 45° interface plies, the debond grew in a combination of cyclic debonding in the adhesive and intraply failure in the ±45° plies of the strap adherend. The damage continued to grow in this mode for about 5 to 10 mm until it grew through the ±45° plies and reached the 0° ply. Thereafter, fatigue failure grew in the form of cyclic delamination between the -45° and 0° plies. Photographs of these modes are shown in Figs. 3 and 4 for EC 3445 adhesive. Figure 3 shows this failure in a side view while Fig. 4 shows a radiograph in a front view.

For both adhesive systems in all specimens with 90° interface plies, fatigue failure initiated with transverse cracking in the 90° ply of the strap adherend localized at the end of the lap adherend. The fatigue failure then grew as combined delamination and intraply failure between ±45° plies for about 5 to 10 mm until it reached the first 0° ply in the strap adherend. Thereafter, fatigue damage grew in the form of delamination between the -45° and 0° plies. This damage is shown in Figs. 5 and 6 for a typical FM-300 specimen. Figure 5 shows the side view and Fig. 6 shows a radiograph of the front view of the fatigue damage. The damage modes are summarized in Table 4.

Damage Initiation Stress

The minimum cyclic stresses that initiated adhesive debonding or adherend damage within 1 million cycles are plotted in Fig. 7. These test results are also presented in Table 3. Since the number of plies was the same for the specimens with 90° and 45° plies at the interface, the stress levels at damage initiation may be compared. The stress levels for damage initiation in the 90° interface plies are the same for both adhesives, as damage initiated in the strap adherends for these specimens. For EC 3445 specimens, the 45° interface plies allowed a no-damage stress level 13 percent higher than that of the 90° interface plies. For FM-300 specimens, the 45° interface plies allowed a no-damage stress level 71 percent higher than that of the 90° interface plies.

Since the specimens with 0° interface plies had a different geometry (i.e., different number of plies in the adherends) from the 90° and 45° interface ply specimens, they cannot be compared on a stress basis. In this case the strain-energy release rates were calculated, as previously explained, based upon the minimum cyclic stress at damage initiation for both the 45° and 0° specimens (values shown in Fig. 7 and Table 3). This approach resulted in a threshold total strain-energy release rate, G_{th}, equal to 38 J/m^2 and 42 J/m^2 for bonded systems with EC 3445 having 0° ply and 45° ply at the adhesive-adherend interface, respectively. For FM-300 the values of G_{th} were 87 J/m^2 and 96 J/m^2 for 0° and 45° plies, respectively. This variation in G_{th} obtained from specimens with 0° or 45° plies at the interface (for both adhesive systems) was within the observed experimental scatter band. Therefore, joints with 0° or 45° plies at the interface had practically equal strain-energy release rate thresholds. This is expected since the fatigue failure mechanism was the same for both cases. Further, the same is expected for all joints with any ply orientation at the interface as long as cyclic debonding in the adhesive is the cause of fatigue-damage initiation.

The effect of the interface ply orientation on the resulting G value of the adhesive was less than 3 percent. The stiffness and thickness of the total adherend was the primary factor. Therefore, essentially the same minimum cyclic stress for damage initiation would be expected for 0° or 45° interface plies if the same specimen geometry was used (i.e., the same number of plies in a quasi-isotropic laminate).

Apparently the strength of the 90° ply was so low that ply cracks developed below that stress required to create G_{th} in the adhesive. The static strength of a 90° T300/5208 lamina is listed as approximately 40 MPa in ref. [6], while the strength of a 0° lamina is approximately 1455 MPa. These strength values indicate how relatively easy it is to initiate damage in a 90° ply compared with a 0° ply. Once damage started in the strap adherend, the damage propagated in the form of ply cracking, intraply damage, and delamination until a 0° ply was reached. At that point the damage continued to spread by delamination between the 0° ply and the adjacent ply closest to the adhesive bond line, once again illustrating it is difficult for damage to grow past a 0° ply.

The debond initiation threshold values, G_{th}, obtained in the present study are very close to the values of total strain-energy release rate associated with the debond growth rate of 10^{-6} mm/cycle obtained previously [2]. Thus, the G_{th} assocciated with a low crack growth rate (i.e., corresponding to 10^{-6} mm/cycle) can be used to predict or assess the durability of bonded joints in composite structures where fatigue would occur by debond initiation (as in the case of 0° or 45° interface plies).

CONCLUSIONS

An experimental study of a cracked-lap-shear specimen subjected to constant-amplitude cyclic loading was undertaken to investigate the fatigue failure mechanism of simple composite-to-composite bonded joints. Two bond systems were studied--graphite/epoxy adherends bonded with EC 3445 adhesive in a secondary bonding procedure and the adherends bonded with FM-300 adhesive in a co-cure bonding procedure. With each bond system, specimens with three different quasi-isotropic lay-ups were tested, providing 0°, 45°, or 90° plies at the adherend-adhesive interface. The present study led to the following conclusions:

1. In both bond systems, fatigue damage initiated as cyclic debonding in specimens with 0° or 45° plies at the adherend-adhesive interface. However, in specimens with a 90° ply at adherend-adhesive interface, damage occurred due to ply cracking in the 90° lamina.
2. Fatigue damage grew in the form of cyclic debonding within the adhesive for specimens with a 0° ply at the interface. For specimens in both bond systems with 45° or 90° plies at the adherend-adhesive interface, fatigue damage grew in the form of intraply damage in the strap adherend until it reached the first 0° ply, and thereafter it grew as a cyclic delamination.
3. Joints with adherend lay-ups that result in damage initiation in the adhesive (e.g., 0° and 45° interface plies) resulted in allowable stress levels for no damage 13 and 71 percent higher than those joints with 90° interface plies for EC 3445 and FM-300 adhesives, respectively.
4. The total strain-energy release rate threshold, G_{th}, was practically the same for specimens with 0° or 45° fibers next to the adhesive. This is to be expected because damage started in the adhesive in both cases. This indicates that G_{th} is an adhesive material property that may be applied to different joint geometries and adherend lay-ups.

These results are significant because they indicate that 0° fibers do not have to be in the direction of maximum stress to achieve a maximum no-damage threshold stress level. This assumes that a safe-life design is used based on maximum design stress levels below those required to cause G_{th} in the adhesive at an assumed initial defect [3]. Care must be exercised to assure that 90° (or near 90°) plies are not adjacent to the bond line in the direction of principal stress, or else delamination in the composite adherend will result unless lower design stress levels are used.

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Table 1.- Adhesive material properties [2].

	Modulus, GPa		Poisson's Ratio
	E	G	ν
EC 3445 (3M Company)	1.81	0.65	0.4
FM-300 (American Cyanamid Company)	2.32	0.83	0.4

Table 2.- Graphite/epoxy[a] adherend material properties.

Modulus,[b] GPa			Poisson's Ratio[b]	
E_1	E_2	G_{12}	ν_{12}	ν_{23}
131.0	13.0	6.4	0.34	0.34

[a]T300/5208 (NARMCO), fiber volume fraction is 0.63.
[b]The subscripts 1, 2, and 3 correspond to the longitudinal, transverse, and thickness directions, respectively, of a unidirectional ply.

Table 3.- TEST RESULTS

Adhesive	Ply at Interface	Lay-up Strap / Lay-up Lap	Number of Test Specimens	Average Minimum Cyclic Stress, MPa
EC 3445	0°*	$[0/\pm45/90]_s/[0/\pm45/90]_{2s}$	4	78
	45°	$[\pm45/0/90]_{2s}/[\pm45/0/90]_{2s}$	4	70
	90°	$[90/\pm45/0]_{2s}/[90/\pm45/0]_{2s}$	4	62
FM-300	0°*	$[0/\pm45/90]_{2s}/[0/\pm45/90]_s$	3	123
	45°	$[\pm45/0/90]_{2s}/[\pm45/0/90]_{2s}$	4	106
	90°	$[90/\pm45/0]_{2s}/[90/\pm45/0]_{2s}$	4	62

*previous paper [2]

TABLE 4.- DAMAGE MODES FOR EC 3445 AND FM-300 ADHESIVES IN CRACKED-LAP-SHEAR SPECIMENS

Interface orientation	Initiation	Early growth	Later growth
0°	Adhesive debonding	Within adhesive	Within adhesive
45°		Combination of in-adhesive and between ±45° plies	Delamination between −45° and 0° plies
90°	Cracks in 90° ply in strap adherend	Delamination and ply cracking in 90° and ±45° plies.	

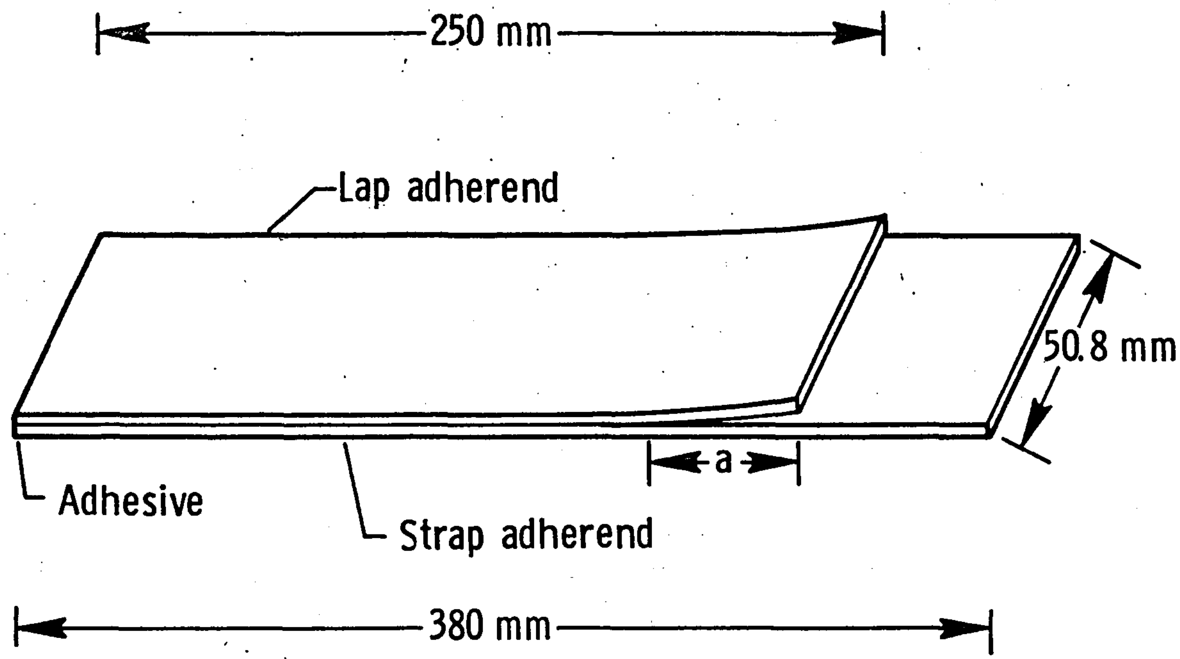

Figure 1. - Cracked-lap-shear specimen.

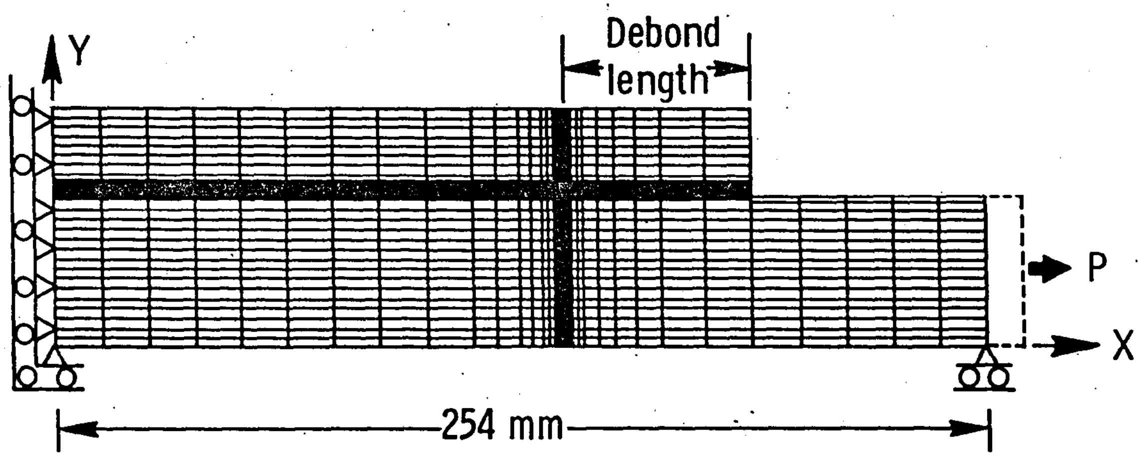

Figure 2. - Typical finite element mesh (Y coordinates are magnified 20X).

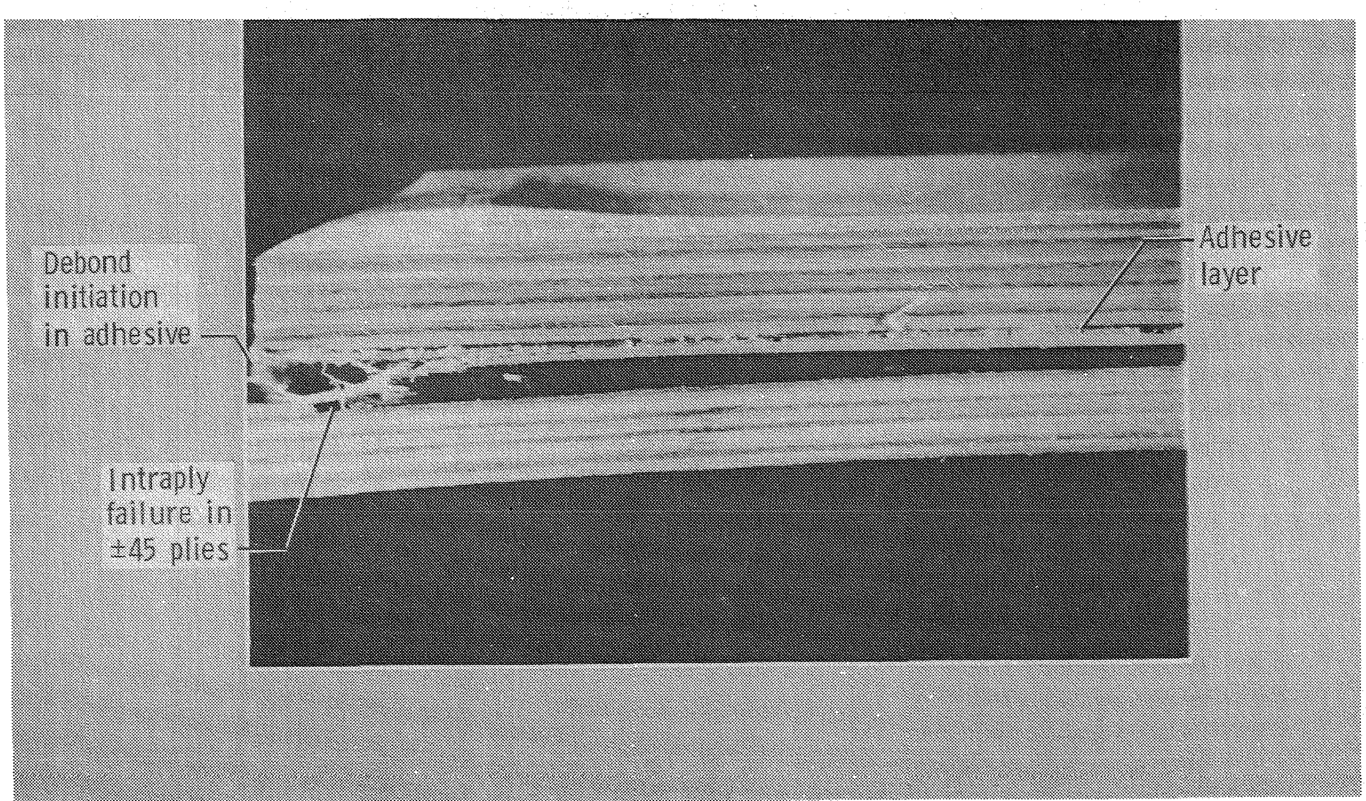

Figure 3. - Edge view of fatigue damage in the EC 3445 adhesive CLS specimen with $[\pm 45/0/90]_{2s}$ layup.

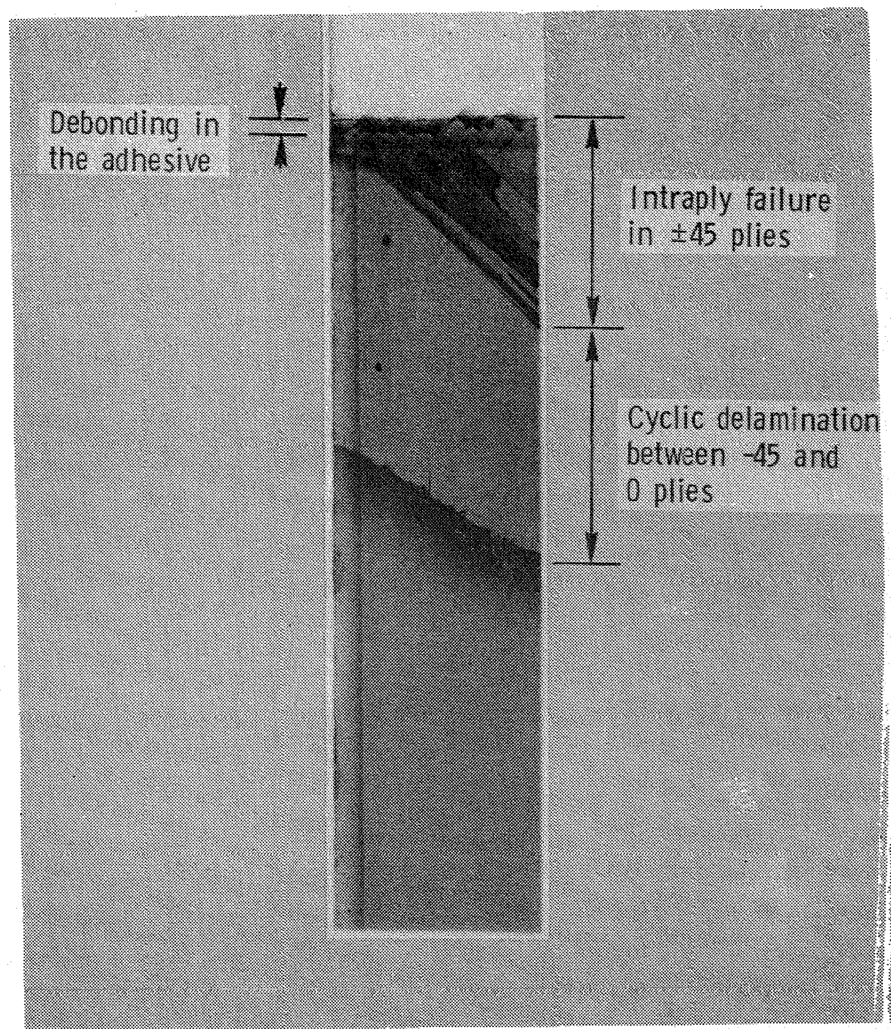

Figure 4. - Radiograph showing fatigue damage in the EC 3445 adhesive CLS specimen with $[\pm45/0/90]_{2s}$ layup.

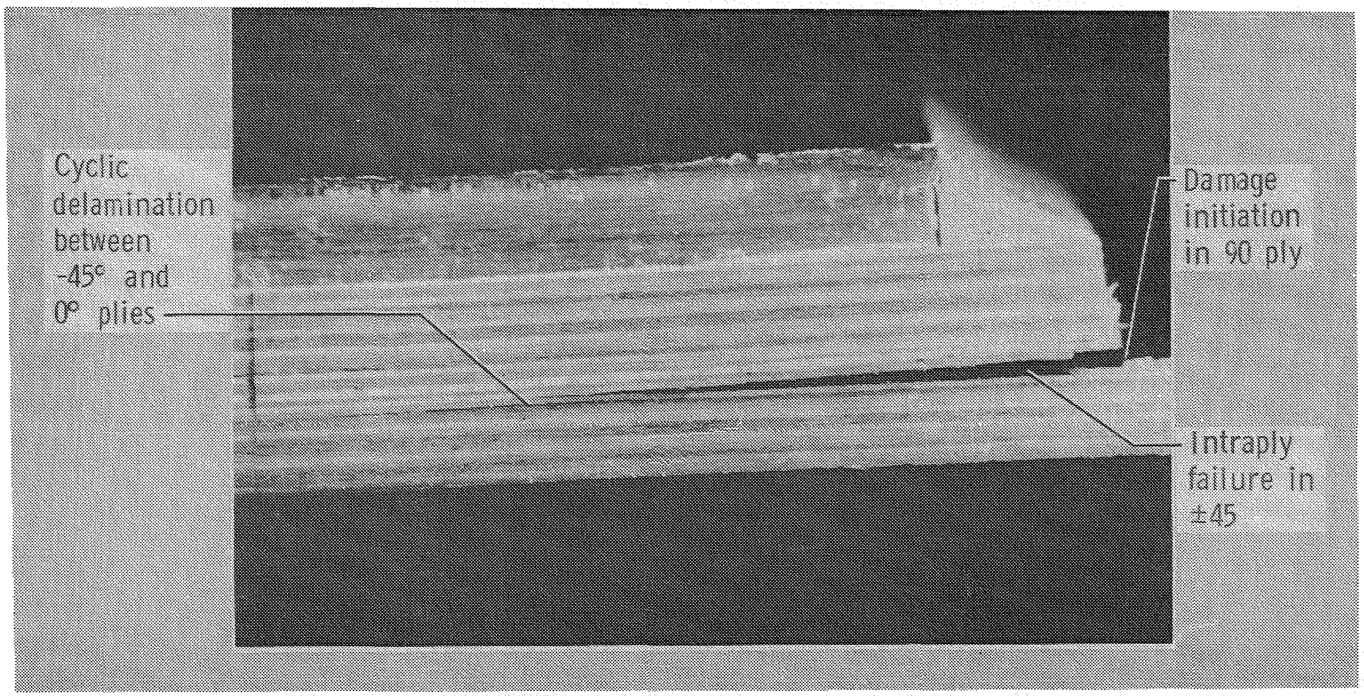

Figure 5. - Edge view of fatigue damage in the FM-300 adhesive CLS specimen with $[90/\pm45/0]_{2s}$ layup.

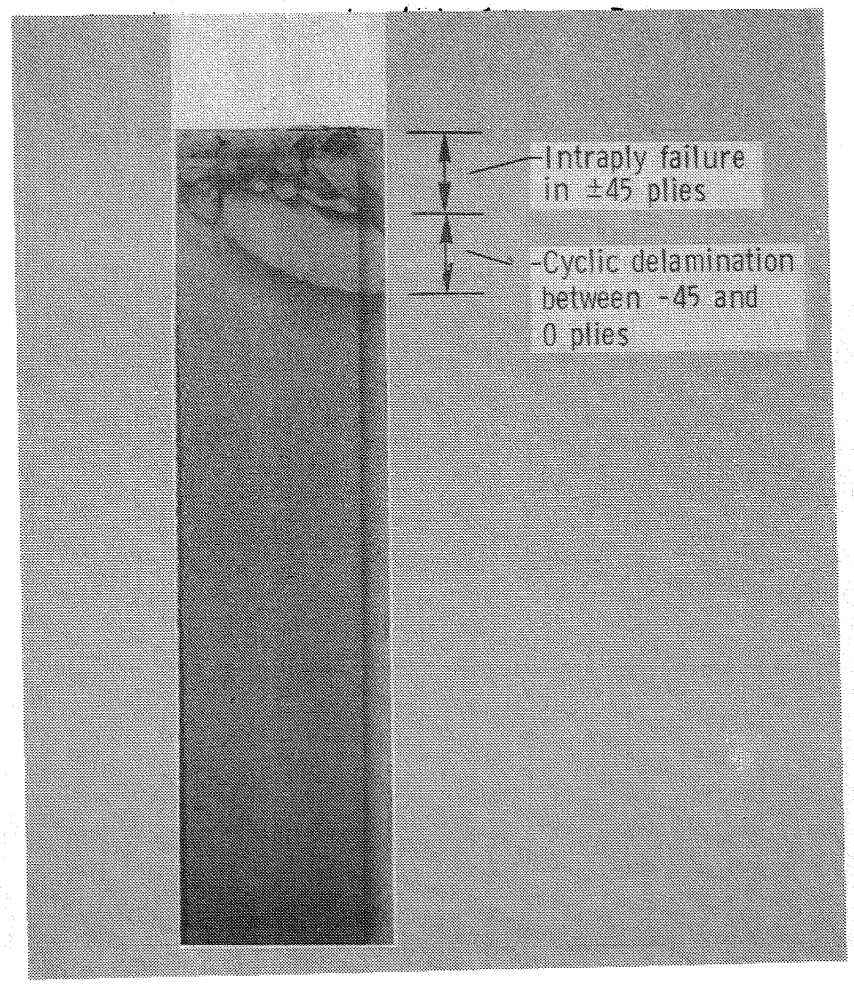

Figure 6. - Radiograph showing fatigue damage in the FM-300 adhesive CLS specimen with $[90/\pm45/0]_{2s}$ layup.

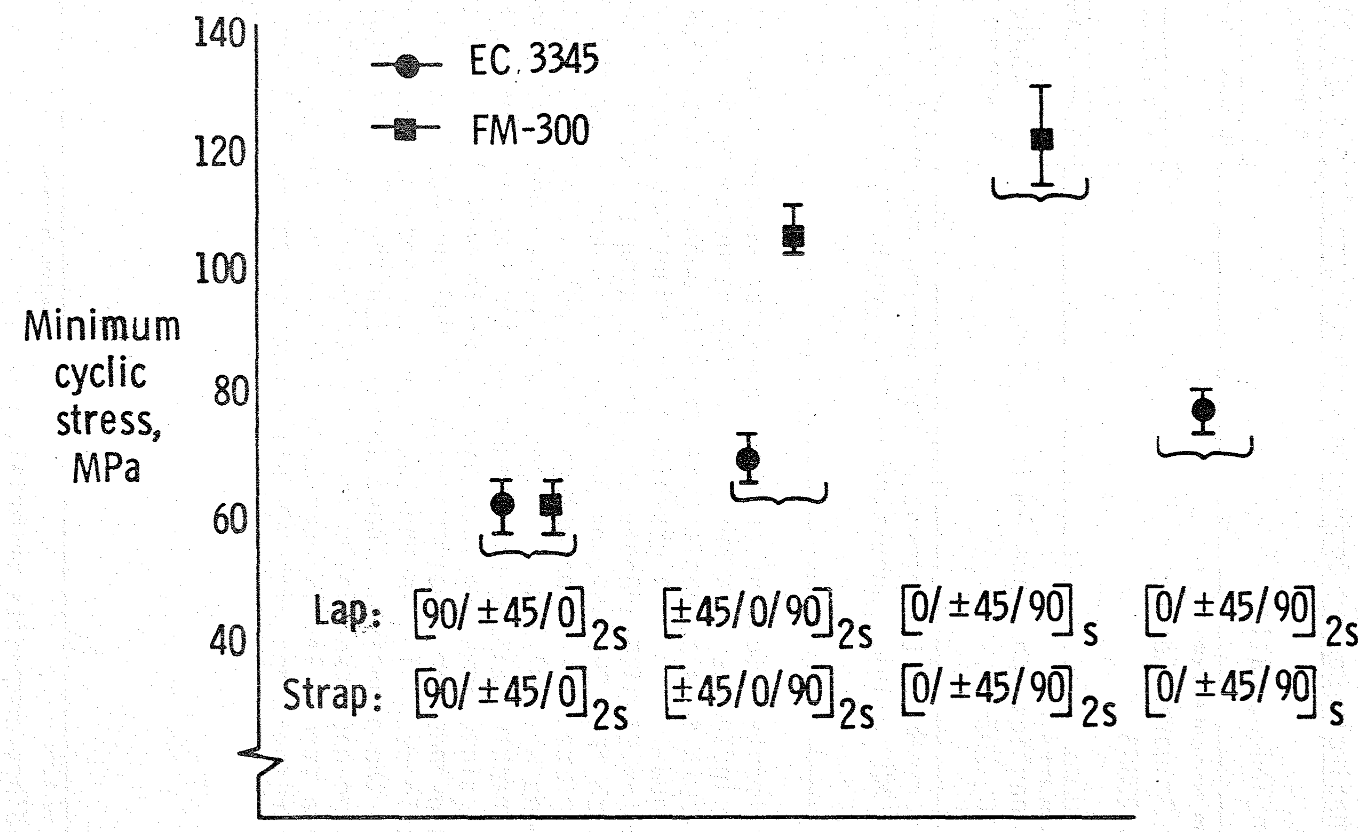

Figure 7. - Minimum cyclic stress for damage initiation in CLS specimens with various layups. (R = 0.1)

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15. Supplementary Notes * S. Mall, Department of Engineering Mechanics, University of Missouri, Rolla, MO 65401. Submitted to ASTM Journal of Composites Technology and Research.

16. Abstract

An experimental study of cracked-lap-shear specimens was conducted to determine the influence of adherend stacking sequence on debond initiation and damage growth in a composite-to-composite bonded joint. Specimens consisted of quasi-isotropic graphite/epoxy adherends bonded together with either FM-300 or EC 3445 adhesives. The stacking sequence of the adherends was varied such that 0°, 45°, or 90° plies were present at the adherend-adhesive interfaces. Fatigue damage initiated in the adhesive layer in those specimens with 0° and 45° interface plies. Damage initiated in the form of ply cracking in the strap adherend for the specimens with 90° interface plies. The fatigue-damage growth was in the form of delamination within the composite adherends for specimens with the 90° and 45° plies next to the adhesive, while debonding in the adhesive resulted for the specimens with 0° plies next to the adhesive. Those joints with the 0° and 45° plies next to either adhesive has essentially the same fatigue-damage-initiation stress levels. These stress levels were 13 and 71 percent higher, respectively, than those for specimens with 90° plies next to the EC 3445 and FM-300 adhesives.

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