Fatigue Behavior of Bonded Joints in Composite Material Structures

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To date only a few isolated experimental studies of composite-composite adherend bonded joints have been conducted under static and/or constant amplitude cyclic loading. The present research is a systematic, analytical, and experimental program concentrating on those parameters deemed most influential on the fatigue life of adhesive bonded single lap joints. These are over-lap length, orientation of the lamina adjacent to the adhesive, and the effect on the fatigue life of the mean load causing maximum stresses above or below the shear proportional limit of the adhesive material. Results of dynamic screening tests indicate that the proportional limit has a significant influence on the fatigue life of a bonded joint, that up to a 40% load penalty occurs for an angle ply construction vs an all 0° layup and that the absolute magnitude of load withstood by the joint for a given number of cycles increased with overlap length, as one would expect.

I. Introduction

THE application of advanced reinforced composite materials in aerospace structures during the remainder of this century is widely predicted. The joining of structural components by adhesive bonding is extremely desirable, because both bolting and riveting result in the cutting of fibers as well as the introduction of stress concentrations, both of which reduce the structural efficiency. Watson[1] states that, "The next two decades will surely see dramatic advances in structures as compared to those experienced over the last 30 years... Improved titanium alloys and the advanced high strength composites, with more strength per pound than aluminum, will be the principal materials used." Further he writes, "New bonding techniques will gradually replace riveting in many applications, permitting greater design stresses and more efficient distribution of the materials."

Because in aerospace structures, dynamic loads are always present, it is absolutely essential that the fatigue behavior of bonded joints between composite material components be better understood, to have available design principles and rationale to take advantage of the desirable characteristics of composite materials. To date, the few isolated experimental studies of composite-composite or composite-metal adherend bonded joints[2-7] have been conducted under static and/or constant amplitude cyclic loading, and no generally accepted cumulative damage theories have evolved.

The present research is a systematic, analytical, and experimental program of study concentrating on those parameters considered to be the most influential on the static and fatigue life of an adhesive bonded single lap joint. The objectives of the program are to better understand the reasons why certain parameters have such a large influence on the structural integrity of the joint. As a result it is hoped that considerable insight will be gained as to static and fatigue life of more complicated joints such as the double lap and the stepped lap joints. The initial phase of the screening test program is reported on herein.

The objectives of the tests were three-fold: 1) to study the influence of certain geometric variations of the lap joint configuration on the fatigue life of the joint, such as overlap length and the orientation of the laminae of the laminated adherends (particularly the orientation of the lamina immediately adjacent to the adhesive); 2) to discern the relative importance of the shear proportional limit stress on the fatigue behavior of the single lap joint; and 3) to introduce specific introductory comments on the type of failure surfaces observed and why they occurred.

In analyzing the fatigue test results, determination of the stresses in the adhesive and the adherends are found using the closed form analytical routine (Bond 4) developed earlier in this program and reported on in Ref. 8. Recently Sharpe[9] has shown experimentally that this analytical procedure accurately predicts the stress distribution in the adhesive.

Bond 4 enables one to determine accurately the state of stress within both the joint adhesive and the adherends for similar and dissimilar adherends of either isotropic or anisotropic materials. A laminated plate element is the building block for developing the method of analysis. The plate element used included provision for moment, shear and

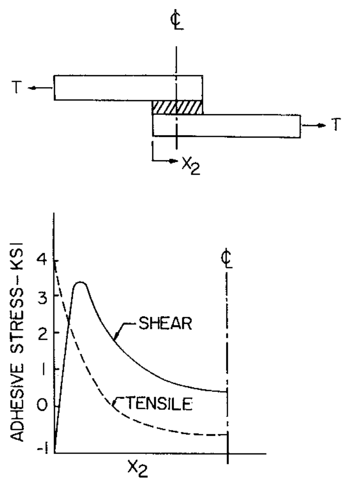

Fig. 1 A typical stress distribution in the adhesive of a single-lap joint.

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axial loads, plus normal distributed loads, and surface shear stresses. To solve the single lap joint problem, required satisfying 26 boundary conditions.

With the inclusion of transverse shear deformation and normal strain effects an accurate shear stress deformation and normal strain effects an accurate shear stress distribution in the adhesive is obtained for the first time; namely, the shear stress goes to zero at the edge of the lap, reaches a maximum a short distance away from the edge and diminishes somewhat further into the joint interior. Transverse normal stresses in the adhesive do reach a maximum at the edge of the lap. The typical adhesive stress distribution is shown in Fig. 1.

Both the static and fatigue specimens are composed of 1002-S glass pre-preg tape adherends, seven plies thick.The adhesive is Hysol EA951 nylon-epoxy, selected for its low moduli, high ductility, and high ultimate tensile, and shear strength. The specimens are 9 in. long and 1 in. wide. The adherends tested to date have been identical, each being 0.063 in. thick. The ultimate strength of the 1002-S glass in the filament direction was tested to be 230,000 psi. Lap lengths varied from 0.30 to 0.60 in. Adherend ply orientations are all 0° and 45°/0°/45°/0° repeated patterns. The ratio of lap length to adherend thickness varied from 4.3 to 8.7

II. Static Tests of Bonded Joints

The static test specimen is shown in Fig. 2. The all 0° adherend static tests were conducted at a loading of 0.05 in./min. The 45°/0°/-45°/0° specimens were tested at a loading rate of 0.02 in./min. All static tests were run at 72°F and approximately 30% relative humidity.

The all 0° adherend specimens failed in the adhesive in a combination adhesion-cohesion manner. The angle ply adherend specimens failed either in an adhesive or cohesive manner except for the 0660109 specimens. This group appeared to be approximately 50% stronger than its counterparts, failing primarily in the resin of the 45° ply adjacent to the adhesive. This group of test pieces was inadvertently run at a strain rate of 0.05 in./min, and the EA951 being strain rate sensitive, has an ultimate shear strength of approximately 6100 psi vs 4400 psi for a strain rate of 0.02 in./min.

The results of all static tests are summarized in Table 1. The average results within each subgroup are given and show consistency. Based on the results summarized in Table 1 the influence of overlap length (L/t ratio) and ply orientation on the ultimate load capability of the joint can be discerned.

The effect of joint strength vs overlap length is presented in Fig. 3. In general the joint strength increased with the length of overlap (L/t ratio) up to the upper overlap length tested of 0.610 in. It is felt that for larger overlaps this trend would continue, possibly at a reduced rate, until a configuration was reached in which failure occurs in the adherends. This has been substantiated in Ref. 3 and by Bond 4 analytical predictions[8] which indicate that increasing the overlap length reduces the peak adhesive stresses for (L/t) ratios less than 10.

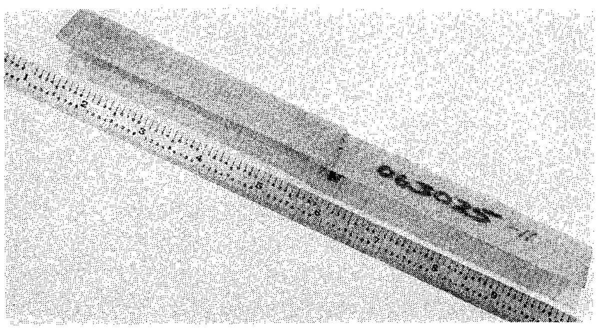

Fig. 2 Single lap joint static test and fatigue specimen.

Table 1 Summary of single lap joint static test results

Spec. no.	t/adhesive (in.)	Overlap (in.)	Width ≅1.000 in. Ult. load (lb)	Avg. Adhesive shear stress (psi) ($\tau = P/A$)
All 0° ply orientation				
063025-2	0.0020	0.310	1750	5630
−9	0.0010	0.310	1750	5630
			Avg. 1750	Avg. 5630
063045-2	0.0040	0.360	1760	4890
−9	0.0020	0.340	1910	5620
			Avg. 1835	Avg. 5255
066029-2	0.0010	0.610	3000	4920
−9	0.0010	0.610	2900	4740
			Avg. 2950	Avg. 4830
066049-2	0.0040	0.610	2675	4370
−9	0.0030	0.600	3250	5410
			Avg. 2962	Avg. 4890
45°/0°/−45°/0° ply orientation				
x063025-4	0.0005	0.300	1275	4231
−7	0.0010	0.315	1185	3940
−15	0.0010	0.315	1115	3740
			Avg. 1191	Avg. 3970
0630105-3	0.0050	0.301	1042	3480
−8	0.0040	0.300	996	3310
−16	0.0030	0.298	1047	3520
			Avg. 1028	Avg. 3436
x066029-4	0.0005	0.604	2061	3390
−8	0.0005	0.600	2204	3640
−11	0.0005	0.600	2076	3410
			Avg. 2113	Avg. 3480
0660109-7	0.0020	0.601	3152	5190
−10	0.0020	0.600	3085	5100
−13	0.0030	0.601	2942	5150
			Avg. 3059	Avg. 5146

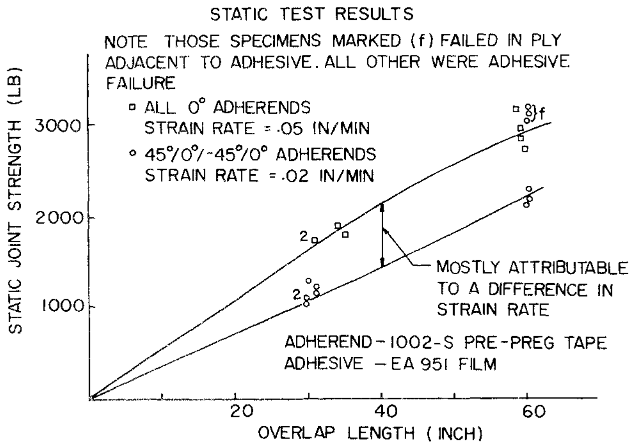

Fig. 3 Bonded joint strength vs overlap length.

The influence of ply orientation within the adherend and/or the orientation of the ply adjacent to the adhesive is not readily discernable. Its effect on static joint strength is considered to be minor over the range of overlap lengths tested. The difference between the curves of Fig. 3 is attributed to the difference in strain rates at which the all 0° and 45°/0°/-45°/0° specimens were tested, namely, the higher the strain rate, the higher the ultimate strength of the adhesive which is known to be strain rate sensitive.[3]

III. Fatigue Tests of Bonded Joints

A total of 57 lap joint fatigue tests have been run. Twenty-nine are of all 0° construction while the 28 angle ply specimens had a 45°/0°/-45°/0° ply orientation pattern. All tests were run at 75°F at 15 cps and for a constant amplitude loading (stress ratio = + 0.10 tension). The range of relative humidity values for the tests varied between 15 and 40%. References 3 and 10 show that such a humidity variation would have a negligible effect on the fatigue response of the adhesive and adherend materials respectively, for the period of time associated with the tests.

All 0° Adherend Fatigue Test Results

The results of the all 0° ply adherend tests are summarized in Table 2. The overlap lengths varied from 0.300 in. to 0.625 in. The adhesive thicknesses were between 1 and 3 mils with the majority of the thicknesses being approximately 2 mils. Therefore, any effort to discern a correlation between adhesive thickness and fatigue life was not possible.

One of the primary objectives of the test program was to determine the influence of the shear proportional limit stress of the adhesive on the fatigue life of the joint. This was obtained using the test piece shown in Fig. 4. The test is described in detail in Ref. 10. A plot of the typical results for the EA951 adhesive is shown in Fig. 5.

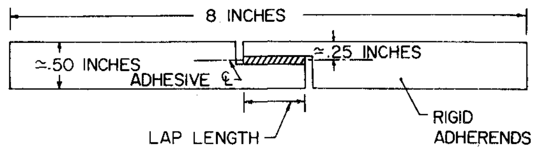

Fig. 4 Shear property test piece.

Fatigue runout for the tests (i.e., the number of cycles at which the test is stopped) was defined to be 4.0×10^6 cycles. Based on this criteria, fatigue runout was achieved at a mean load of 247 lb for the 0.30 in. overlap specimens, at 275 lb for the 0.36 in. overlap specimens, and at 330 lb for the 0.62 in. overlap specimens.

The Bond 4 analysis[8] was then used to determine the maximum shear stress in the joint corresponding to the mean loads at run-out stated previously. These peak stresses are compared with the shear proportional limit stresses of the adhesive from Ref. 11. The results are tabulated in Table 3. The correlation is good. In essence it strongly indicates that if the peak shear stress in the adhesive at mean load remains below the shear proportional limit stress of the adhesive, a marked increase in fatigue life of the joint can be achieved, assuming an adhesive failure is the critical mode of failure in the construction. In this series of tests, in which 100 lb load increments were used, an increase in life of the joint of 5 times or more was achieved if the specimen was loaded below the proportional limit shear stress of the adhesive. Moreover, this 100 lb load increment is believed to be the main reason for the discrepancy in the data of Table 3. Smaller load increments would reveal more closely that load which just achieves runout, and the peak shear stress associated with that load would more closely duplicate the calculated peak stress.

Table 2 Summary of fatigue test results—all 0° adherends

Spec. no.	Overlap (in.)	t_{adh} (in)	Mean ± alt load (lb)	Max[a] load (% of ult. load)	Cycles × 10^6	Type failure
063025-1	0.310	0.0018	55±45	5.7	4.740	Test stopped
-3	0.310	0.0020	165±135	17.2	4.781	" "
-4	0.310	0.0020	220±180	23.0	1.000	" "
			275±225	28.5	1.152	" "
-5	0.300	0.0018	330±270	34.4	0.838	Band evident cohes-adh
-6	0.310	0.0015	330±270	34.4	0.288	Band evident cohes-adh
-7	0.300	0.0010	330±270	34.4	0.518	Band evident cohes-adh
-8	0.300	0.0012	275±225	28.5	2.301	Band evident cohes-adh
-10	0.310	0.0012	247±202	25.7	4.530	Test stopped
-11	0.300	0.0015	247±202	25.7	6.144	Test stopped
063045-1	0.370	0.0040	330±270	32.7	1.580	Adh-bands starting
-3	0.370	0.0030	330±270	32.7	0.897	Cohes-adh bands starting
-4	0.360	0.0025	330±270	32.7	2.901	Cohes-adh bands starting
-5	0.360	0.0025	275±225	27.3	4.753	Adh-no bands
-6	0.360	0.0020	275±225	27.3	4.689	Test stopped
-7	0.350	0.0020	275±225	27.3	5.044	Cohes-adh-bands starting
066029-1	0.600	0.0025	550±450	34.0	0.116	Cohes-adh-bands evident
-3	0.625	0.0020	550±450	34.0	0.129	Cohes-adh-bands evident
-4	0.625	0.0025	495±405	30.5	0.303	Cohes-adh-bands evident on ends
-5	0.625	0.0020	330±270	20.4	4.102	Test stopped
-6	0.620	0.0020	330±270	20.4	4.009	" "
-7	0.610	0.0015	330±270	20.4	4.133	" "
-8	0.610	0.0015	385±315	27.0	3.327	Cohes-adh-bands evident on ends
-10	0.610	0.0017	385±315	27.0		Cohes-adh-bands evident on ends
066049-3	0.620	0.0022	440±360	30.5	0.439	Cohes-adh-bands evident on ends
-4	0.620	0.0025	385±315	23.6	1.294	Cohes-adh-bands evident on ends
-5	0.610	0.0030	385±315	23.6	1.052	Cohes-adh-bands faintly evident on ends
-6	0.620	0.0025	330±270	20.2	4.616	Test stopped
-7	0.610	0.0025	330±270	20.2	1.306	Failure due inadvertent Mach. overload (Adh)
-8	0.610	0.0020	330±270	20.2	4.033	Test stopped

Adherend - 1002-S, pre-preg tape
Adhesive - EA951 film
All Spec. ≈ 0.95 in. wide
R = ×0.10 (tension)

[a] Based on static test results of Table 1.

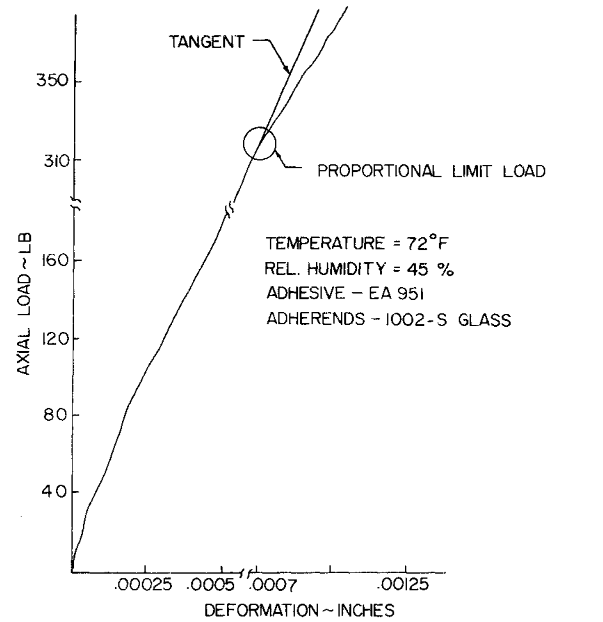

Fig. 5 Adhesive shear load deformation data.

Table 3 Maximum shear stress at runout and shear proportional limit stress

Spec. no.	Max shear[a] proport. limit stress (psi)	Max shear[b] stress for mean load at runout (psi)
063025	1015	930
063045	990	1017
066029	590	731
066049	590	731

[a]From shear test results, Ref. 11. [b]From Bond 4 analysis.

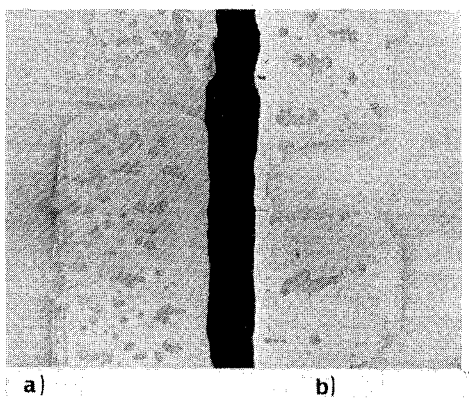

Fig. 6 Failure surfaces: a) static, b) fatigue.

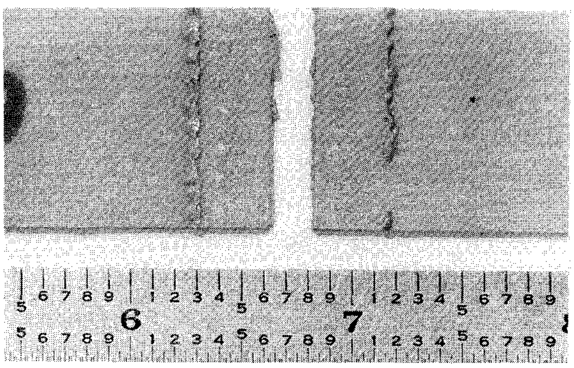

Fig. 7 Fatigue bonds of all zero degree adherend failure surface.

Moreover, for those specimens in which runout was attained, anywhere from 50 to 99% of the static strength of the joint, based on the results of Table 1, remained as determined through statically testing these specimens to failure. This in turn suggests that a much longer life for those parts which achieved runout could have been attained if the fatigue testing had continued past 4×10^6 cycles.

It is hypothesized that this significant increase in fatigue life associated with stressing only below the proportional limit stress of the adhesive at mean load is primarily due to the retention of a primarily elastic stress field which experiences very little plastic flow. This in turn usually means a slower propagation of cracks within the adhesive to the critical crack length whereby failure suddenly occurs.

Of those specimens which exhibited failure prior to four million cycles, all exhibited an adhesive-cohesive failure as shown in Fig. 6. Typically, the failed surfaces displayed distinct bands as shown in Fig. 7. The bands were harder to discern in the thicker adhesives and in numerous instances were uneven in width over the width of the joint. The bands at each end of the joint were similar to each other, were smooth, and displayed a cohesive failure while the center region displayed a failure surface analogous to that of a statically failed specimen. It is assumed that the smooth nature of the outer bands was due to the minute motion of the adhesive after cracking had occurred yet no one cycle striations were evident. Further it is believed the cracks initiated from the ends of the overlap, moving inward until the net section of the remaining adhesive, which was uncracked, could not withstand the applied load in a static manner. Such growth of the bands is believed realistic as small initial smooth bands are evident emanating from the ends of the overlap of those specimens in which runout was attained and which were then statically tested to failure.

The overall mode of failure in fatigue can be hypothesized as follows. Initially a crack forms at the end of the overlap due to an initial flaw in the adhesive which is propagated by the peak stresses at the end of the overlap due to an initial flaw in the adhesive which is propagated by the peak stresses at the end of the joint. The growth of this flaw is much more rapid if the threshold stress (i.e., proportional limit shear stress) level in the adhesive has been attained. As the crack grows, the effective length of the joint is reduced, the peak tensile and shear stresses moving inward just ahead of the crack. This effectively alters the geometry of the joint. Therefore, the original part must withstand the increased peak stresses brought about by the shorter overlap length. Eventually, the ultimate strength of the adhesive is reached and a sudden failure is observed.

Angle-Ply (45°/0°/-45°/0°) Fatigue Test Results

Analogous to the all uni-directional fiberglass adherends, the objectives of this section were to study the influence on fatigue life of certain parametric variables. These were overlap length, and the influence of the 45°/0°/-45°/0° lamina orientation of the adherends. In addition, the influence of the adhesive proportional limit stress and the types of failures observed were also of interest. A summary of the fatigue test results is tabulated in Table 4. Fatigue runout (i.e., 4.0×10^6 cycles) for the x063025 specimens was at a mean load of 165 lbs. Specimens 0630105, x066029, and 0660109 achieved runout at 165 lbs, 200 lbs, and 275 lbs respectively.

The general appearance of the fatigue failure surfaces differs from their static test counterparts. Figure 8 displays the fatigue and static failure surfaces observed for the bulk of the specimens. The static failure mode is in the adhesive, and is seen to have been raised up. This indicates a tearing away by normal stresses of the adhesive from the adherend. The fatigue failure mode also displays this raising up of the adhesive. However, the actual fatigue failure is believed to be the result of resin degradation in the 45° ply adjacent to the

Table 4 Summary of fatigue test results-45°/o°/−45°/0° adherends

Spec. no.	Overlap (in.)	t adh (in.)	Mean ± alt load (lb)	Max[a] load (% of ult. (load)	Cycles × 10^6	Type failure
x603025-1	0.300	0.0005	220 ± 180	34.5	0.107	Bands forming cross-ply failed
-2	0.300	0.0010	220 ± 180	34.5	0.676	Bands forming cross-ply failed
-3	0.300	0.0005	220 ± 180	34.5	0.513	Bands forming cross-ply failed
-5	0.300	0.0005	165 ± 135	26.0	6.267	Runout
-6	0.315	0.0005	165 ± 135	26.0	4.168	Runout
-8	0.315	0.0010	165 ± 135	26.0	4.246	Runout
0630105-1	0.300	0.0040	220 ± 180	39.0	3.632	Cross-ply failed, adh raised
-2	0.301	0.0040	275 ± 225	48.5	0.194	Cross-ply failed, adh raised
-4	0.301	0.0030	220 ± 180	39.0	0.551	Cross-ply failed, adh raised
-5	0.300	0.0040	220 ± 180	39.0	0.576	Adhesive failure, adh raised
-6	0.300	0.0050	275 ± 225	48.5	0.141	Cross-ply failed, adh raised
-7	0.300	0.0040	275 ± 225	48.5	0.123	Cross-ply failed, adh raised
-9	0.300	0.0040	165 ± 135	29.4	5.020	Runout
-10	0.300	0.0040	165 ± 135	29.4	4.120	Runout
x066029-1	0.586	0.0010	330 ± 270	28.5	0.055	Bands formed, cross-ply failed
-2	0.586	0.0010	275 ± 225	23.6	0.298	Bands formed, cross-ply failed
-3	0.591	0.0005	192 ± 158	16.6	6.176	Runout
x066029-5	0.604	0.0005	220 ± 180	19.0	4.092	Runout
-6	0.604	0.0005	220 ± 180	19.0	2.800	Bands formed, cross-ply failed
-7	0.600	0.0010	275 ± 225	23.6	0.526	Bands formed, cross-ply failed
0660109-1	0.601	0.0030	330 ± 270	19.6	1.318	Resin in cross-ply layer adj to adh failed, no bands
-2	0.601	0.0030	330 ± 270	19.6	2.002	Resin in cross-ply layer adj to adh failed, no bands
-3	0.601	0.0020	330 ± 270	19.6	1.453	Resin in cross-ply layer adj to adh failed, no bands
-4	0.601	0.0020	275 ± 225	16.3	4.164	Runout
-5	0.601	0.0020	275 ± 225	16.3	4.164	Runout
-5	0.601	0.0020	275 ± 225	16.3	4.281	Runout
-6	0.601	0.0010	275 ± 225	16.3	4.393	Runout

Adherend—1002-S pre-preg tape
Adhesive—EA951 film
All Spec ≃ 1.0 in. wide
$R = +.10$ (tension)

[a] Based on static test results of Table 1.

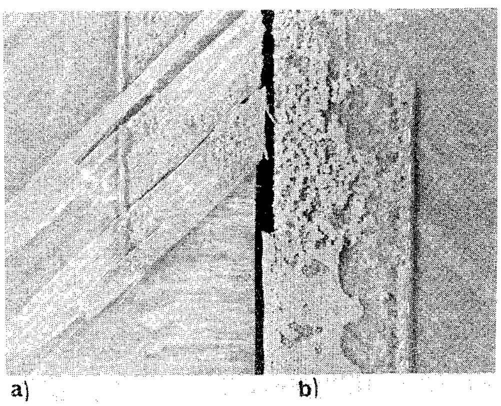

Fig. 8 Failure surfaces: a) fatigue, b) static.

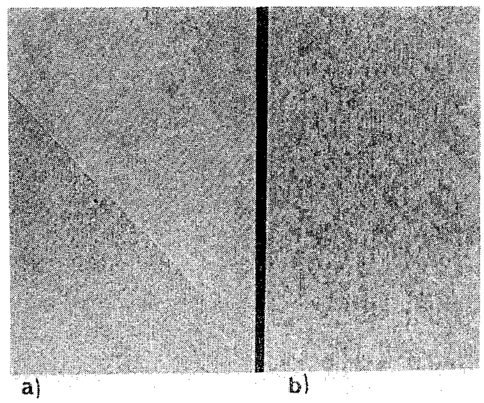

Fig. 9 Failure surfaces: a) static, b) fatigue.

adhesive. This is thought to be the result of high interlaminar shear and normal stresses in the resin.

Figure 9 compares the static and fatigue failure surfaces of specimen x066029. This set of test pieces behaved most closely to the all zero degree adherend specimens. Failure was in the adhesive when tested to static failure. Moreover, the fatigue specimens failed almost simultaneously in the adhesive, where the bands were evident, and in the 45° ply adjacent to the adhesive.

In summary, the ply orientation effect is definitely a factor in the type of fatigue failure observed. Whereas the all zero degree adherend specimens failed in the adhesive, displaying definite bands attirbuted to the growth of cracks in the adhesive and related to the shear proportional limit shear stress of the adhesive, the 45°/0°/-45° /0° specimens failed the 45° ply adjacent to the adhesive. Finally, in referring back to Table 4 it is readily discernable that the mean load increased as the length of overlap increased.

IV. Design Considerations

In an effort to discern a possible fatigue methodology from the fatigue results presented, Fig. 10 was developed. The results of the 0° and the 45°/0°/-45°/0° fatigue tests are plotted vs the maximum fatigue load (mean + alternating load) as a percent of the static load. Looking at the best fit curves for the data it becomes apparent that regardless of the type of ply orientation pattern used and the associated mode of fatigue failure observed, the data seems to suggest that the fatigue life of a joint for a given load level is a specific percent of its static capability.

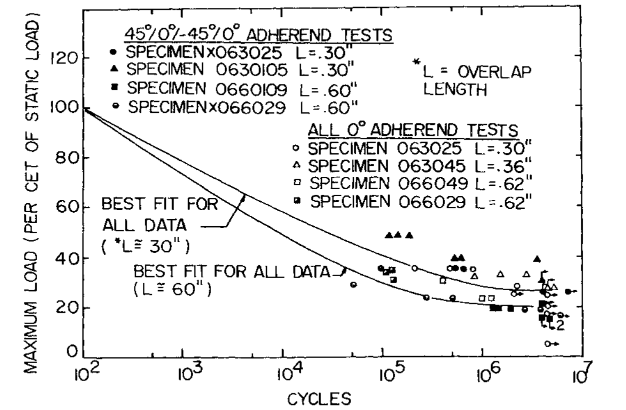

Fig. 10 Maximum design fatigue load for single lap joint vs cycles to failure.

Table 5 Comparison of the stresses in a 0° and 45° ply adjacent to the adhesive[b] (load held constant)

Specimen[a]	τ_{12}(psi)	σ_2(psi)	σ_3(psi)	Type failure
All 0° adherend	0.0	3123.0	500.0	Adhesive
45°/0°/−45°/0°	3505.0	9515.0	654.0	45° ply adjacent to adhesive

[a]The specimens were identical except for the ply orientation-tensile allowable 1002-S Resin 6100 psi.

[b]Stresses are at .005" from loaded edge of overlap. Stresses refer to axes defined in Fig. 1.

The curves would further suggest that this percentage may be a function of overlap length. Yet, this is not to suggest that an angle ply pattern is as efficient in absolute load carrying ability as the 0° adherend specimens. In fact, inspection of Tables 2 and 4 show a 20-40% reduction in load carrying capability for a given number of cycles for a 45°/0°/45°/0° adherend system vs an all 0° adherend one with an overlap length of 0.60 in.

It is hypothesized eariler that premature degradation of the 45° ply adjacent to the adhesive was due to a severe stress state in the resin of the adherend material. To resolve this, the differences in the peak stresses experienced by a 45° ply adjacent to the adhesive vs a zero degree ply adjacent to the adhesive was investigated. The Bond 4 analysis program of Ref. 8 was used and the results are summarized in Table 5, where the applied load is in the 1 direction.

The peak adhesive shear stresses can be shown to be within 15% of each other. Therefore, the reason for the failure of the 45° ply adjacent to the adhesive can readily be discerned from Table 5. Significant increases in the interlaminar shear stress (τ_{12}) and the in plane stress perpendicular to the load (σ_2) clearly specify the severe state of stress the resin in the 45° ply must withstand under a fatigue loading condition. Obviously, it is unable to perform this task as well as the adhesive is.

V. Conclusions

The following conclusions are drawn from the test results for the range of geometries tested.

Static Tests

1) The static joint strength increased with increased lap length. 2) Strain rate is extremely important for the Hysol EA951 adhesive. Increased strain rate increases the ultimate shear strength of the adhesive. 3) Ply orientation overall, or of the ply immediately adjacent to the adhesive, has a minor effect on static joint strength.

Fatigue Tests

1)Comparing the fatigue results with the material test data for the 0° specimens would suggest that if the peak shear stress in the adhesive at mean load is kept below the shear proportional limit stress, the fatigue life of the joint is markedly increased. This suggests that the proportional limit shear stress may in fact represent a threshold level, above which rapid deterioration of the adhesive occurs. In these tests, in which 100 lb load increments were used, increases in life of the joint by factors of five or more were seen if one stayed below this threshold level.

2) For those specimens in which runout (4×10^6 cycles) was attained, the residual static strength was between 50-99% of the static test results of Table 1.

3) A 20-40% penalty in the ultimate load levels associated with runout is experienced in the angle ply construction compared to the uni-ply construction.

4) For a fatigue life of 4×10^6 cycles, a maximum design load corresponding to 26% of static load was attained for a lap length of 0.30", and 20% for a lap length of 0.60", independent of the ply orientation (see Tables 2 and 4.)

5) Failure of the adhesive in fatigue was due to a static type failure in the uncracked material, once a critical crack length was reached.

6) Failure in the 45° ply adjacent to the adhesive, in the angle ply construction, was due to excessive interlaminar and normal stresses in the resin of the ply. This construction should be avoided for this loading condition. This was substantiated analytically by methods developed in Ref. 8.

7) The ideas presented here are based on screening tests. Therefore, much additional work is needed to justify them conclusively.

VI. General

The program is continuing, wherein testing will include effects of elevated temperature, dissimilar composite-composite and composite-metal adherends, and the effect of adding short length high modulus fibers to the adhesive. Tests using Kevlar 49 epoxy adherends are also underway at this time.

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