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EFFECT OF ADHESIVE INTERLEAVING AND DISCONTINUOUS PLIES ON FAILURE OF COMPOSITE LAMINATES SUBJECT TO TRANSVERSE NORMAL LOADS

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EFFECT OF ADHESIVE INTERLEAVING AND DISCONTINUOUS PLIES ON FAILURE OF COMPOSITE LAMINATES SUBJECT TO TRANSVERSE NORMAL LOADS

by

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Abstract

Results of a series of tests to determine the effects of adhesive interleaving and discontinuous plies (plies with end-to-end gaps) on the displacements, failure loads and failure modes of graphite-epoxy laminates subjected to transverse normal loads are presented. Adhesive interleaving can be used to contain local damage within a group of plies, i.e., to arrest crack propagation on the interlaminar level, and it can increase the amount of normal displacement the laminate can withstand before failure. However, the addition of adhesive interleaving to a laminate does not significantly increase its load carrying capability. A few discontinuous plies in a laminate can reduce the normal displacement and load at failure by 10 to 40 percent compared to a laminate with no discontinuous plies, but the presence of the ply discontinuities does not generally change the failure location or the failure mode of the laminate.

Introduction

Laminated composites have failure mechanisms which are not characteristic of homogeneous isotropic materials. These unique failure mechanisms must be understood to use composite materials safely and efficiently in structural components. Laminated composites are weaker in the transverse direction and are more brittle than isotropic materials. This transverse weakness makes laminated composites more sensitive to transverse stresses and makes transverse shearing and delamination more likely to cause failure in composites than in isotropic structures. Defects in composite laminates, such as broken fibers, broken plies or end-to-end gaps within a ply, are sometimes unavoidable when laminates are constructed from unidirectional tapes of finite width and length. Such end-to-end ply gaps or ply discontinuities may cause a reduction in the load carrying capability of the laminated structure.

This report presents the results of a series of tests that were conducted to study the use of adhesive interleaving as a way of relieving some of the problems associated with the use of brittle materials and the presense of high transverse shear stresses. Adhesive interleaving is the inclusion of thin layers of adhesive in selected locations in a laminate. This report also presents the results of tests with laminates with end-to-end ply gaps (ply discontinuities) in some of the 0° plies that were used to study the problem of broken plies or of gaps in plies formed in the manufacturing process between sections of graphite-epoxy tape.

Test Specimens and Procedure

The test specimens used in this study are 1 inch wide, 4 inches long and approximately .25 inches thick. Specimens of several stacking sequences, shown in Table 1, were tested. They were made from AS4-3502 unidirectional graphite-epoxy pre-impregnated tape. A ply of graphite-epoxy is approximately .0052 inches thick. All specimens were cut from panels of stacking sequences A-E in Table 1. Specimens F-J were made by rotating the panels containing laminates A-E by 90°. Some of the specimens were manufactured with adhesive interleaving (specimens B, D, E, G, I and J) to study the effects of including thin layers of adhesive in the laminate on the normal displacement, the failure load and the failure mode. The specimens with adhesive interleaving also contained layers of FM1000 adhesive film that is approximately .003 inches thick per layer. Half of the specimens of types A-E were manufactured with initial ply discontinuities in the form of end-to-end ply gaps at specified locations in the 0° plies. Each gap was located halfway along the length of the specimen (see figures 1a and 1b) in all 0° plies. This gap could be positioned for testing in a region of the specimen subjected to high tensile stresses or in a region of the specimen subject to high shear stresses.

A transverse normal load was applied through the multi-span-beam shear test procedure described in references 1 and 2 and shown in figures 1c and 1d. Five cylindrical rollers of .5 inch diameter are positioned such that line loads across the width of the specimen are applied at the locations of contact between the rollers and the test specimen (see figure 1a). Adjacent rollers are positioned such that line loads are one inch apart, producing a span-to-depth ratio of approximately 4. This load distribution causes some sections of the specimen to be subjected to high shear stresses and some to be subjected to high longitudinal tensile stresses when a transverse normal load is applied, i.e., the top rollers are pressed toward the bottom rollers. The regions of the specimen directly opposite the two top rollers and opposite the center bottom roller are subjected to a high longitudinal tensile stress due to bending. The parts of the specimen between rollers are subjected to high shear stresses. In the multi-span-beam shear test, the transverse normal displacement δ and the applied load P are recorded as the load is slowly increased. A detailed study of the resulting failure events is accomplished by observing the test and photographing the specimen through a microscope during the test. Most tests were stopped and the load maintained at the first failure event while photographs were taken to record the initial failure mode. The photographs were taken while the specimen was still loaded because the cracks in the plies and between plies close and become undetectable when the load is removed. After photographing the initial failure mode, load application can be resumed to study the progression of failure.

Results and Discussion

A comparison of loads, normal displacements and failure mechanisms for specimens with and without interleaving is made. The effect of these gaps was evaluated based on the load and displacement at initial failure (first reduction in the specimen's load carrying ability) and the failure mechanism for specimens with and without adhesive interleaving.

Effects of adhesive interleaving

The most noticable effect of including adhesive layers in a laminate can be seen in the load-displacement curves for the specimens, e.g., figure 2. For brittle graphite-epoxy laminates (such as specimens A and C) these curves are mostly linear up to the first failure event. For these laminates the formation of the first crack in any ply signifies both the first failure event and final failure. Laminates containing adhesive layers do not always behave the same way as laminates without adhesive layers when the load approaches or exceeds the load corresponding to the initial failure of the laminate without interleaving. Cracks may sometimes form in a specimen with interleaving while the load and displacement continue to increase. An example of this difference in the load-displacement curves for laminates with and without interleaving is shown in figure 2. The load-displacement curves for laminates with (specimen D) and without (specimen C) interleaving are shown by the solid and dashed lines, respecively. The failure loads for the specimens shown (C and D) are about the same, but the transverse normal displacement at final failure of the specimen with interleaving is more than double the displacement of the laminate without interleaving. Transverse normal displacements at failure and failure loads are shown in Table 2 for these specimen.

For specimens without end-to-end ply gaps, adding thin adhesive layers to a laminate has little effect on the failure load, but can have a significant effect on the transverse normal displacement at failure. It appears that, in general, the more layers of adhesive there are in a laminate, the more displacement there is at failure. The results indicate that if adhesive layers are placed on both sides of $\pm 45^{\circ}$ plies or 90° plies, the increase in displacement is more significant than if they are placed on both sides of 0° plies. Specimens E and J have the same percentage of 90° plies and 0° plies but their displacements differ by 30%. In specimen E the 90° plies are surrounded by adhesive layers while in specimen J the 0° plies are surrounded by adhesive. Surrounding 90° plies by adhesive layers increases the normal displacement at failure more than surrounding 0^{o} plies by adhesive layers.

If a laminate is primarily made of $\pm 45^{o}$ plies, several adhesive layers are needed to affect the normal displacement at failure. For example, a $[(\pm 45)_{12}/0/(\mp 45)_{12}]_T$ laminate (specimen A) behaves the same way as a $[(\pm 45)_{12}/FM1000/0/FM1000/(\mp 45)_{12}]_T$ laminate (specimen B) behaves. These laminates fail due to high shear stresses approximately 12 plies from top or bottom (in the middle of a group of $\pm 45^{o}$ plies). The first failure event is the formation of an intraply crack in one or more of the $\pm 45^{o}$ plies. This crack is not perpendicular to the ply, but crosses the ply at approximately 45 degrees. This crack is caused by high shear stresses. Usually an interply delamination which starts at the ends of the intraply crack occurs immediately after the crack forms. This failure mode is shown in figure 3 for a specimen with adhesive interleaving (specimen B). The failure is in a region of the specimen subject to high shear stresses in laminates A and B. These specimens have essentially the same loads and displacements at failure. These loads and displacements are shown in Table 2.

If more adhesive layers are included, the transverse normal displacements may be increased by over 200% compared to the specimen without interleaving. The load-displacement curves for two similar laminates are shown in figure 2. The primary difference between these laminates is that one has interleaving while the other does not. The stacking sequences of the laminates shown are $[(\pm 45/0_2)_2(\pm 45/0/90)]_{2S}$ (specimen C) and $[(\pm 45/FM1000/0_2/FM1000)_2 \pm 45]_{2S}$ (specimen D). These stacking sequences were chosen to obtain approximately the same total thickness in the two laminates instead of making the thickness of the one with interleaving greater than the thickness of the one without interleaving by the thickness of the interleaved layers. The stiffnesses of these laminates are not the same, specimen C is approximately 30% stiffer than specimen D, however, the difference in stiffness alone is not enough to account for the difference of a factor of 2 in transverse normal displacements at failure. The mode of failure and the maximum load are the same in these two laminates but interleaving does affect the normal displacement at failure and the failure load. The laminate with interleaving fails at a normal displacement of .076 inches while the one without interleaving fails at a displacement of .032 inches. Intraply cracks begin to form in the laminate with interleaving at a load of approximately 5950 lb, but the specimen is capable of deformation without losing load-carrying ability up to a load of 6725 lb. The load-deflection curve changes from linear to non-linear when the cracks begin to appear. The specimen without interleaving fails when the first crack appears. The adhesive layers can deform more than the graphite-epoxy plies because the epoxy is brittle and the adhesive interleaving is more compliant. The graphite-epoxy plies break when the adhesive layers cannot deform enough to relieve the stresses induced by the applied load. When no adhesive layers are present, the graphite-epoxy plies must carry all the stresses and the plies break at a smaller transverse normal displacement since they cannot deform as much as adhesive layers can. The adhesive layers can deform in shear which reduces the shear stress in the epoxy and allows a larger displacement before failure.

Laminates with many 90° plies (such as specimens E, I, and J) may fail due to longitudinal tension stresses. However, interleaving prevents the tension stress induced cracks from continuing into adjoining plies. The first failure event in a tension stress induced failure is the formation of an intraply crack in a 90° or 45° ply directly opposite a roller. Tension stress induced cracks are perpendicular to the ply, as shown in figure 4 for specimen I, and can cross more than one ply for each failure event. The cracks progress in the transverse direction (from one ply to the next) until they reach a layer of adhesive, and then they stop growing. Adhesive interleaving contains the local damage to within a group of plies, i.e., arrests crack propagation on an interlaminar level. The laminate shown in figure 4 has adhesive layers between every 2 to 4 plies. The initial cracks go through two 90° plies but do not proceed into the neighboring adhesive layers.

Effects of end-to-end ply gaps

In many cases the significance of an end-to-end ply gap at one lengthwise position in a 0° ply is dependent upon the location of the gap relative to the applied load, i.e., whether it is in a region of the specimen which is subjected to high shear stress or to high longitudinal tensile stress. In virtually all cases where the gap is placed in a region of high longitudinal tensile stress, (i.e., directly opposite a roller), the first noticable change in the specimen under loading is that the gap widens or becomes larger, as shown in figure 5 for specimen C. However, this widening does not necessarily lead to a failure at the location of the gap. In cases where there are many ±45° or 90° plies together, the first failure is in the region of high shear stress in the 90° and ±45° plies even though the gaps are in a region of high tensile stress. The specimens with gaps fail in the same failure location and mode as specimens without gaps even though the gaps are in a region of high tensile stress. In these cases the gap reduces the maximum load by less than 5% and has little effect on the transverse normal displacement at failure. But if the groups of 90° and $\pm 45^{\circ}$ plies are separated by 0° plies containing gaps, the presence of the gaps may reduce the failure load and displacement by up to 20% compared to the laminate with no gaps. These results are shown in Table 3. Specimen E failed due to longitudinal tension stress at approximately the same load and the same displacement with or without gaps, no matter where the gaps were located relative to the test fixture.

If the gaps are located in a region of the specimen subjected to high shear stresses, once again, the first noticable effect on the specimen as the load is applied is that the gaps widen, as shown in figure 6 for specimen D. The presence of the gaps decreases the load carrying ability of the specimen by as much as 10% when compared to a specimen with no gaps, with or without adhesive interleaving. If no adhesive interleaving is present, the gaps may cause the transverse normal displacement at failure to decrease by as much as 10% compared to a specimen without adhesive interleaving and without gaps. If adhesive interleaving is present (as in figure 6) in the specimen containing gaps, the displacement may be decreased by 0 to 20% compared to a specimen with interleaving but without gaps. However, the failure mode does not change in either case, the first failure mode is still intraply cracking in the $\pm 45^{\circ}$ or 90° plies because of high shear stresses due to bending. Adhesive interleaving does not increase the displacement at failure in specimens with gaps as much as in specimens without gaps. The delaminations seen in figure 6 are in groups of $\pm 45^{\circ}$ plies and have propagated from a failure in another part of the specimen. The failure due to high shear stress is not affected by the gaps.

Successive Failures

For specimens in which the first failure event is due to high longitudinal tensile stresses, successive failure events are also due to high longitudinal tensile stresses. The first failure is in one of the outer most 90° and $\pm 45^{\circ}$ plies and the subsequent failure events are in the same plies or in 90° or $\pm 45^{\circ}$plies near the ply with the first failure event. Specimen E, with interleaving and many intraply cracks caused by high longitudinal tensile stresses, is shown in figure 7. All of the intraply cracks are in $\pm 45^{\circ}$ or 90° plies and none continue past the interleaving or cause interply delamination. When the load is increased, eventually there is a major interply delamination and several of the outer plies separate from the rest of the specimen as shown in figure 8 for specimen J. The outer most plies, of stacking sequence -45/90, separated from the rest of the laminates.

For specimens which first failed due to high shear stresses, the initial intraply crack caused interply delamination and then continued into adjoining $\pm 45^{\circ}$ and 90° plies but usually not into 0° plies or into adhesive layers. This phenomenon can be seen in figures 9 and 10 for specimens B and D, respectively. This intraply cracking is frequently accompanied by interply delaminations between the weaker ($\pm 45^{\circ}$ and 90°) plies. Intraply cracks do not propagate into adhesive interleaving and interply delamination rarely occurs next to an adhesive layer. In all cases except specimen D, subsequent failures occurred right after the first failure and the load carrying capability was reduced after the first failure. Specimen D continued to carry load after the first intraply crack appeared until several more cracks formed.

Concluding Remarks

The effects of adhesive interleaving (the inclusion of thin layers of adhesive in a laminate) and of end-to-end ply gaps on the failure of graphite-epxoy laminates subjected to transverse normal loads were studied experimentally. Interleaving has the most significant effect on transverse normal displacement when used to separate large groups of $\pm 45^{\circ}$ and 90° plies into smaller groups. While including adhesive interleaving does not increase the load carrying ability of a laminate subjected to high transverse normal load, it can significantly increase the amount of transverse normal displacement at failure. Interleaving contains damage to within one group of plies because intraply cracking which easily can propagate from one ply to another does not grow into the adhesive layers.

Discontinuities in the form of end-to-end ply gaps in 0° plies reduce the maximum load and the maximum transverse normal displacement of a laminate at failure. The results of the study indicate that the gaps reduce the load and deflection most when the stacking sequence of the specimen tested contains no more than four $+45^{\circ}$, -45°, or 90° plies located next to each other. In this case the effect on laminate failure is a reduction in failure load by as much as 20% and a reduction in displacement at failure by as much as 40% compared to laminates without gaps. There is more of an effect on the failure load and displacement at failure when the gaps are located in specimen regions subjected to high longitudinal tensile stresses than in specimen regions subjected to high shear stresses. This generalization is true for specimens with or without adhesive interleaving.

References

1. Jegley, Dawn C.; and Williams, Jerry G.: Multispan-Beam Shear Test for Composite Laminates. NASA Tech Brief LAR-13605, April 1988.

2. Post, Daniel; Czarnek, Robert; Joh, Duksung; and Wood, Judy: Deformation Measurements of Composite Multi-Span Beam Shear Specimens by Moire Interferometry. NASA CR 3844, November 1984.

Table 1. Test Specimen Stacking Sequence

Specimen Designation	Stacking Sequence[a]	Thickness,[b] inches
A	$[(\pm 45)_{12}/0/(\mp 45)_{12}]_T$	.266
B	$[(\pm 45)_{12}/F/0/F/(\mp 45)_{12}]_T$	.266
C	$[(\pm 45/0_2)_2(\pm 45/0/90)]_{2s}$	.257
D	$[(\pm 45/F/0_2/F)_2/\pm 45]_{2s}$	.254
E	$[(45/0/-45/F/90/F)_4/45/0/F/-45/F/90)]_s$	.263
F	$[(\mp 45)_{12}/90/(\pm 45)_{12}]_T$	.263
G	$[(\mp 45)_{12}/F/90/F/(\pm 45)_{12}]_T$	.268
H	$[(\mp 45/90_2)_2(\mp 45/90/0)]_{2s}$	.255
I	$[(\mp 45/F/90_2/F)_2/\mp 45]_{2s}$	.258
J	$[(-45/90/45/F/0/F)_4/-45/90/F/45/F/0)]_s$	.263

[a] F represents one layer of FM1000 adhesive of .003 in. nominal thickness all other plies are graphite-epoxy layers of AS4-3502

[b] average of several specimens

Table 2. Failure of Specimen without gaps

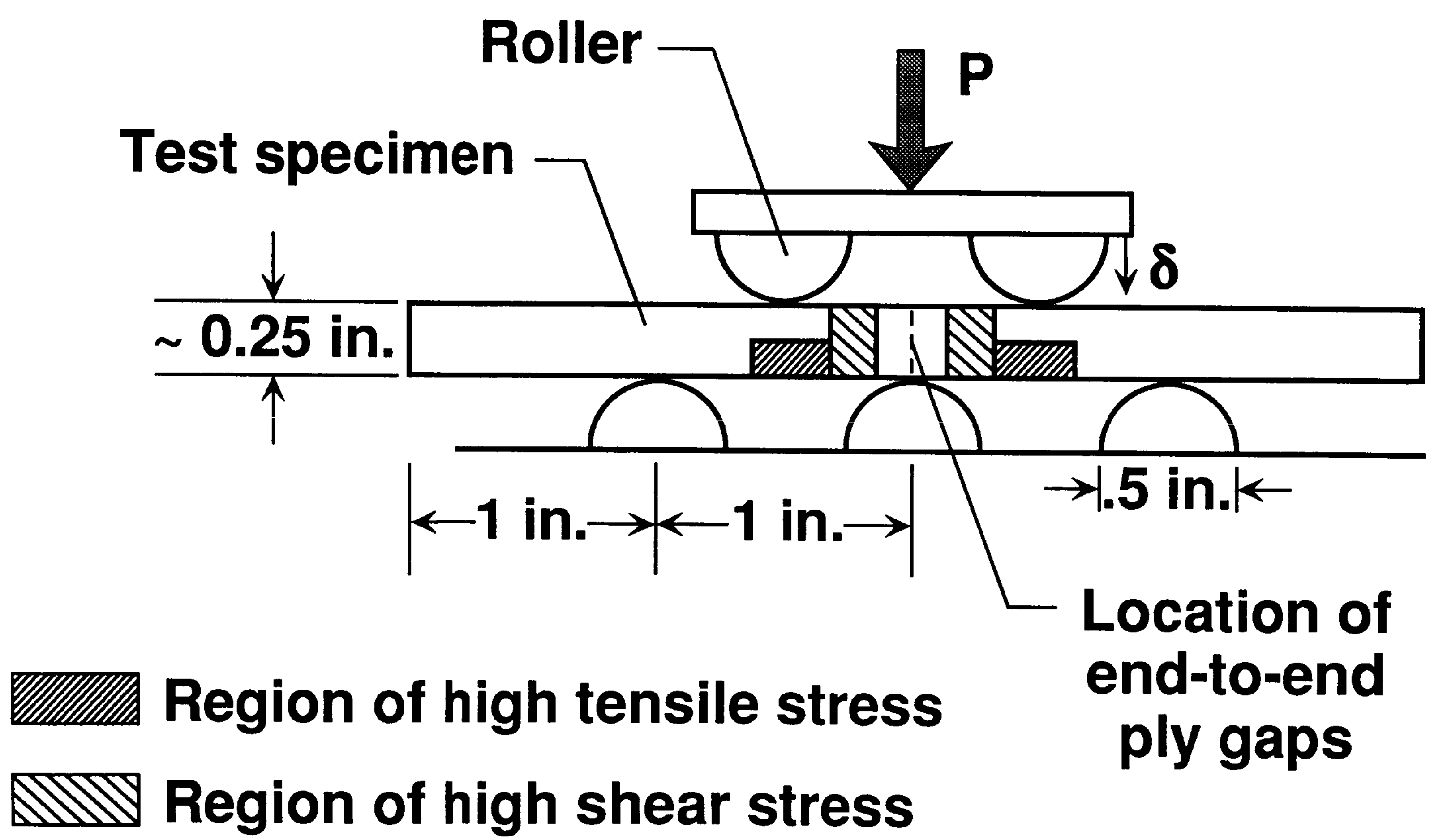
Specimen Designation	Load[a] P, lb	Displacement[b] δ, in	Failure Mode	Number of Specimens Tested
A	6317	.033	SHEAR	3
B[a]	6290	.036	SHEAR	2
C	6675	.032	SHEAR	2
D[a]	6725	.076	SHEAR	2
E[a]	7000	.066	TENSION	3
F	5600	.023	SHEAR	2
G[a]	6125	.032	SHEAR	2
H	4660	.026	SHEAR	2
I[a]	5650	.041	TENSION	2
J[a]	6362	.042	TENSION	2

[a]contains adhesive film
[b]average of specimens tested

Table 3. Failure of Specimen with gaps

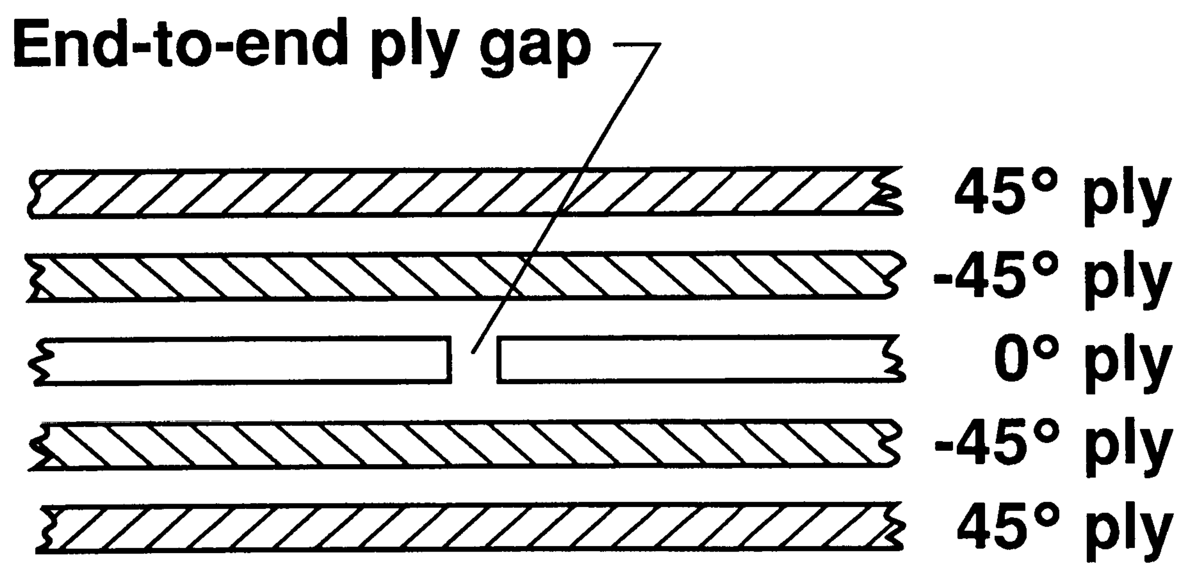
Specimen Designation	Gaps in high shear stress region		Gaps in high tensile stress region		
	Load[b] P, lb	Displacement[b] δ, in	Load[b] P, lb	Displacement[b] δ, in	Failure Mode
A	5625	.030	6050	.030	SHEAR
B[a]	5790	.036	6000	.036	SHEAR
C	5862	.028	5375	.025	SHEAR
D[a]	6575	.060	6200	.051	SHEAR
E[a]	7100	.064	7100	.068	TENSION

[a]contains adhesive film
[b]average of specimens tested



(a) Sketch of specimen in test fixture.

Figure 1. Multi-Span-Beam Shear Test.



(b) End-to-end ply gap in a $[\pm 45/0/\mp 45]_T$ laminate.

Figure 1. Multi-Span-Beam Shear Test.

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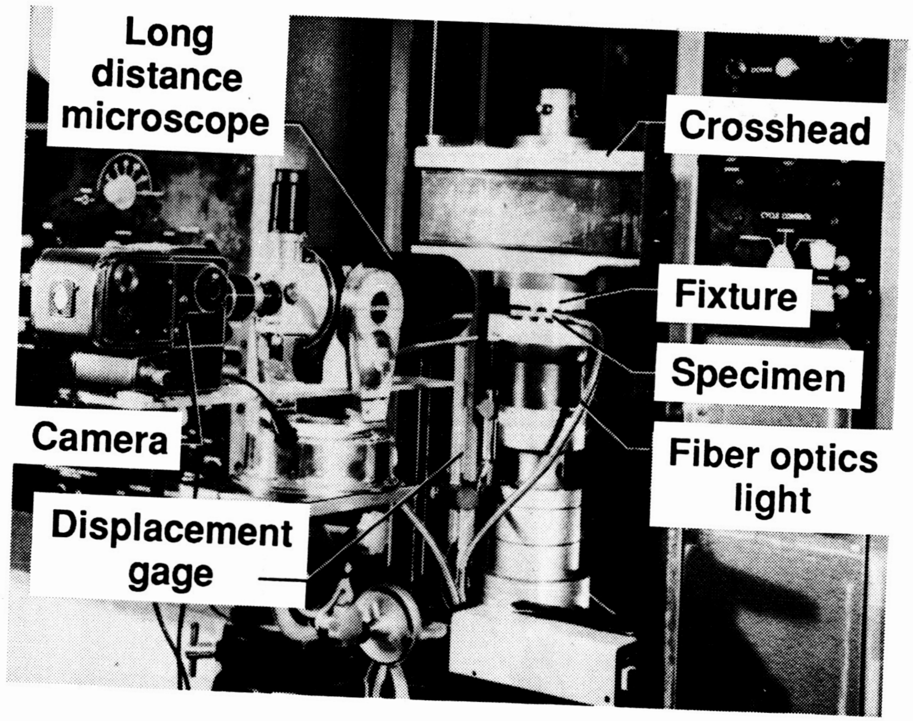
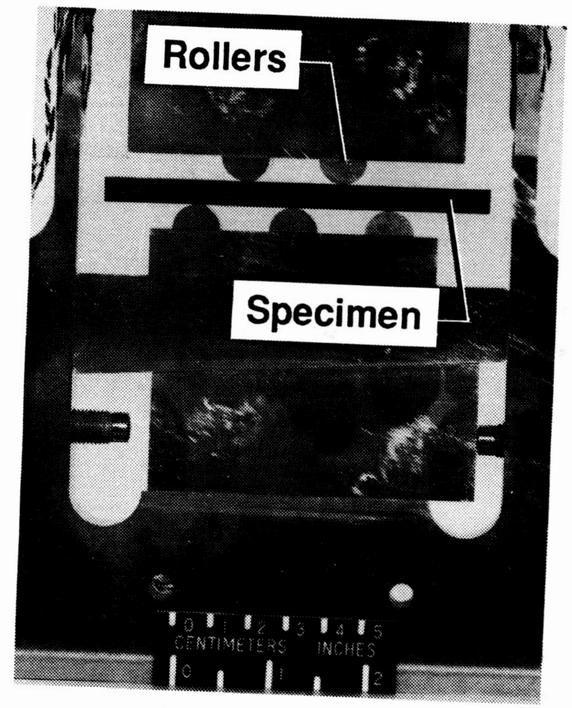


(c) Test set up.



(d) Test fixture.

Figure 1. Multi-Span-Beam Shear Test.

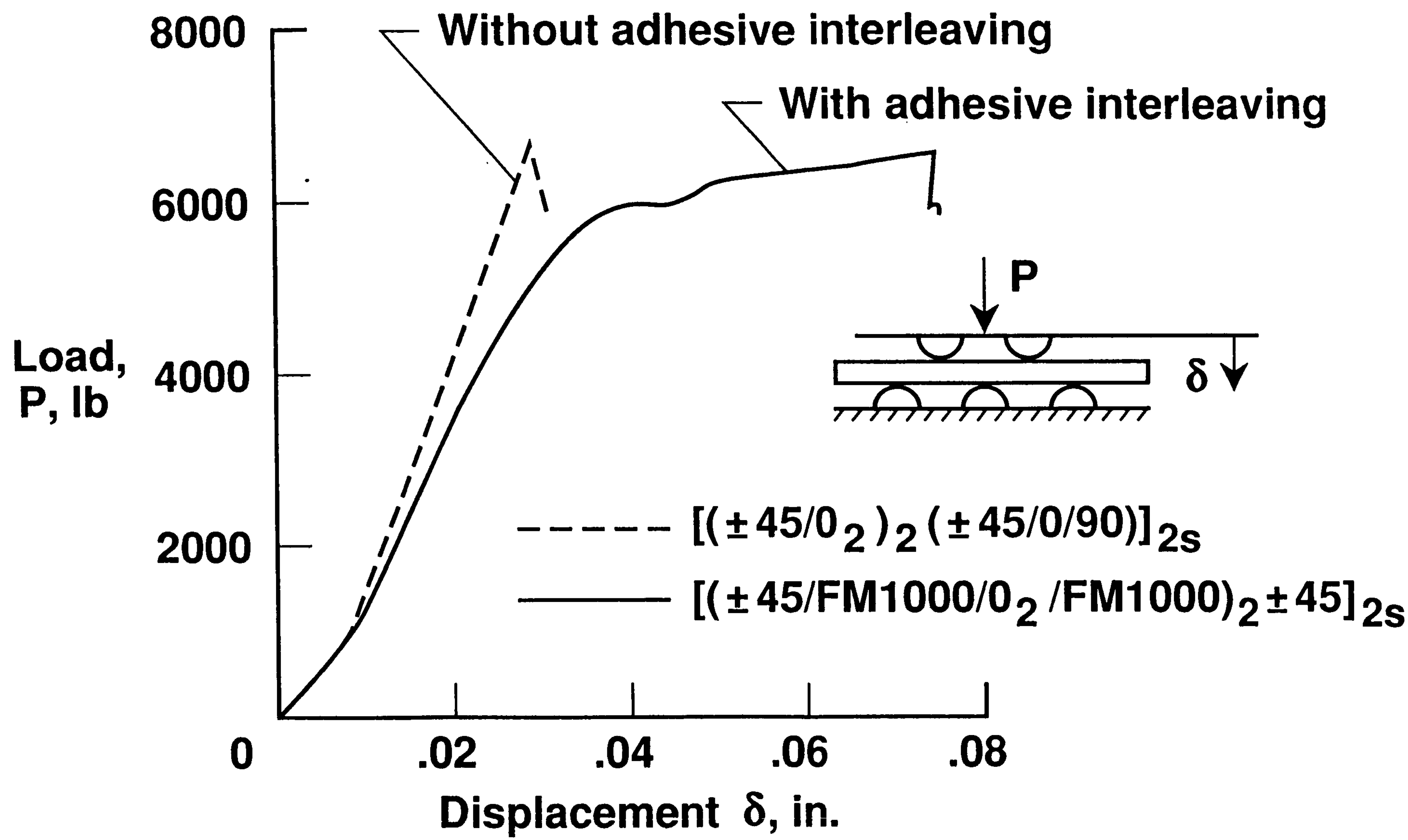


Figure 2. Load-displacement curves for specimens with and without adhesive interleaving.

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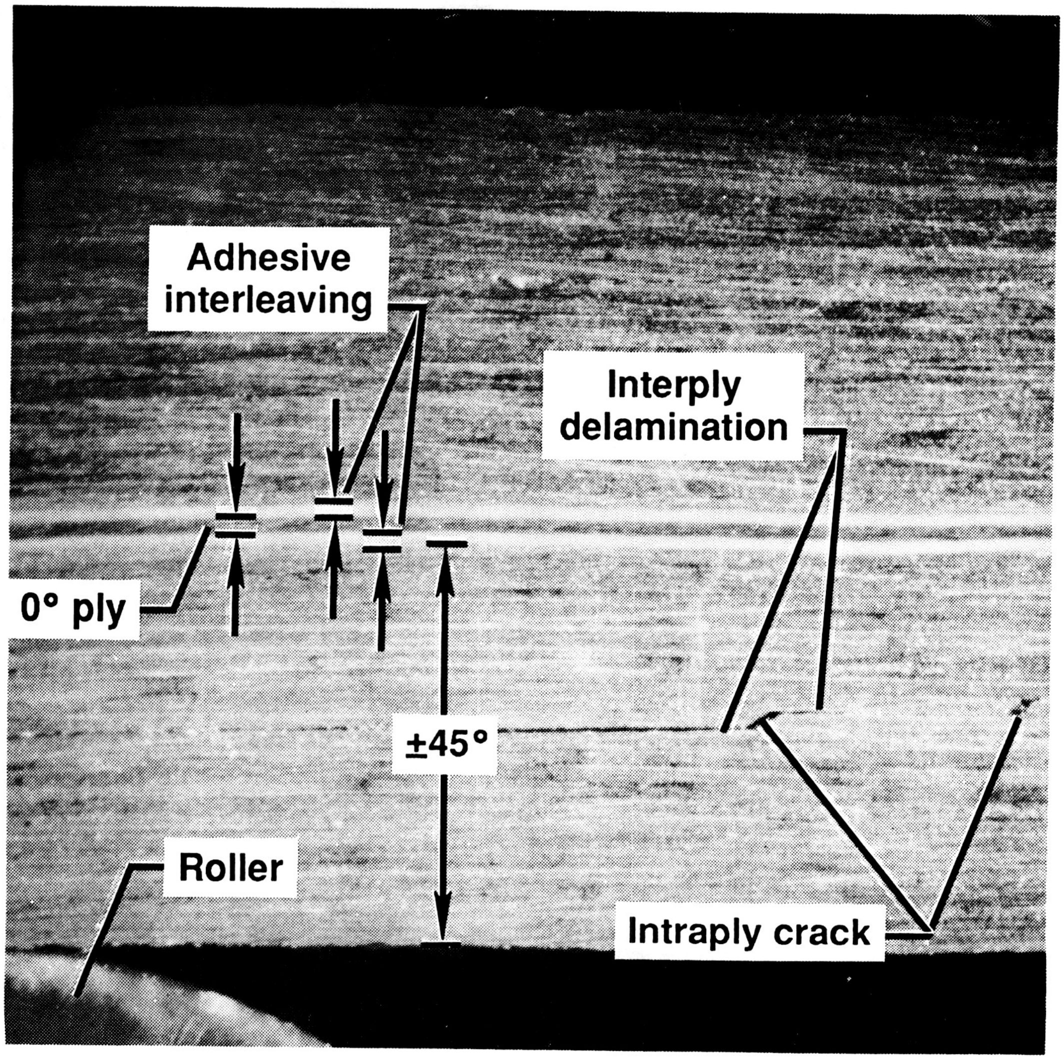

Figure 3. Failure in 45° ply due to high shear stress in specimen B.

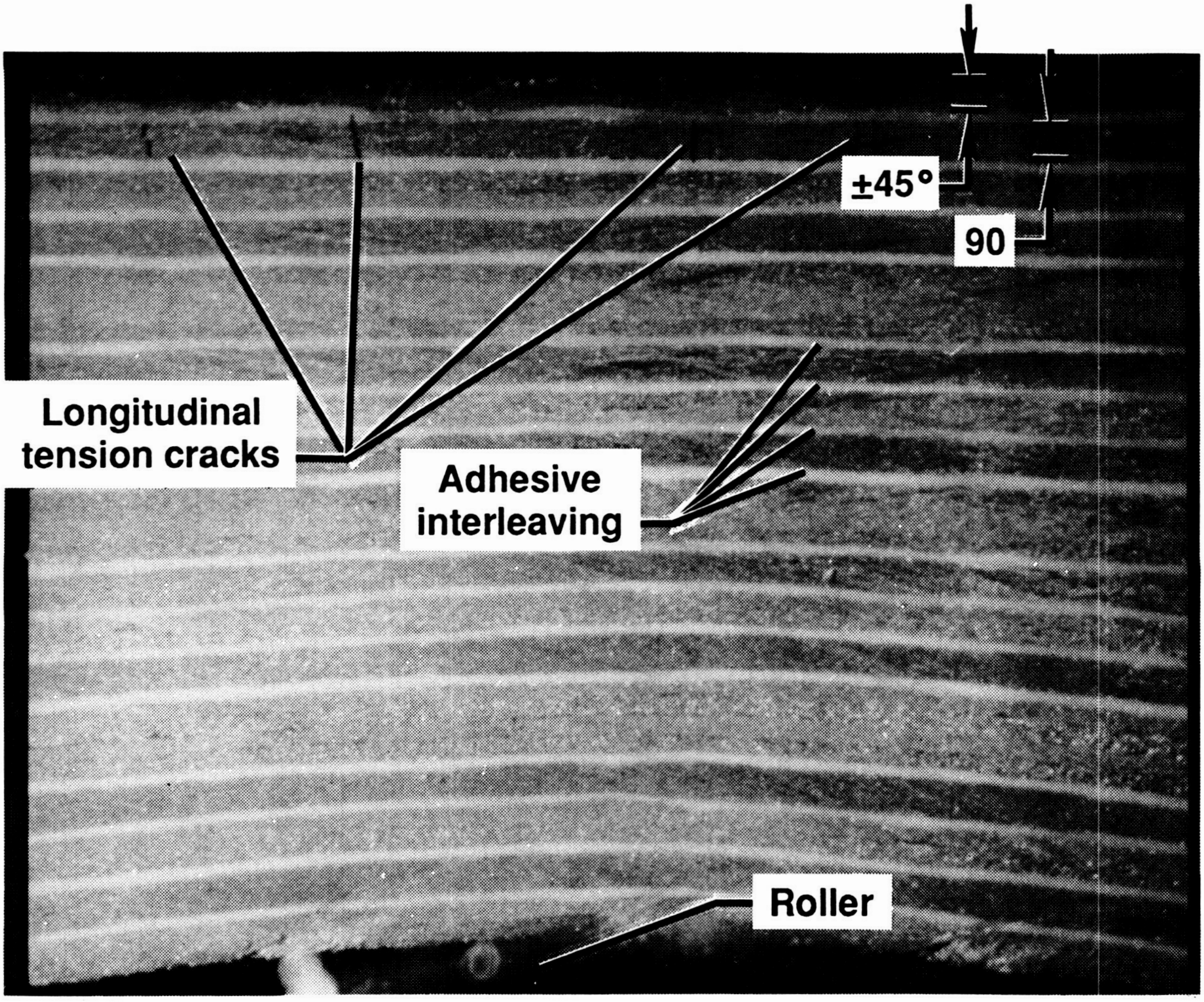

Figure 4. Longitudinal tension stress induced failures in 90° ply in specimen I.

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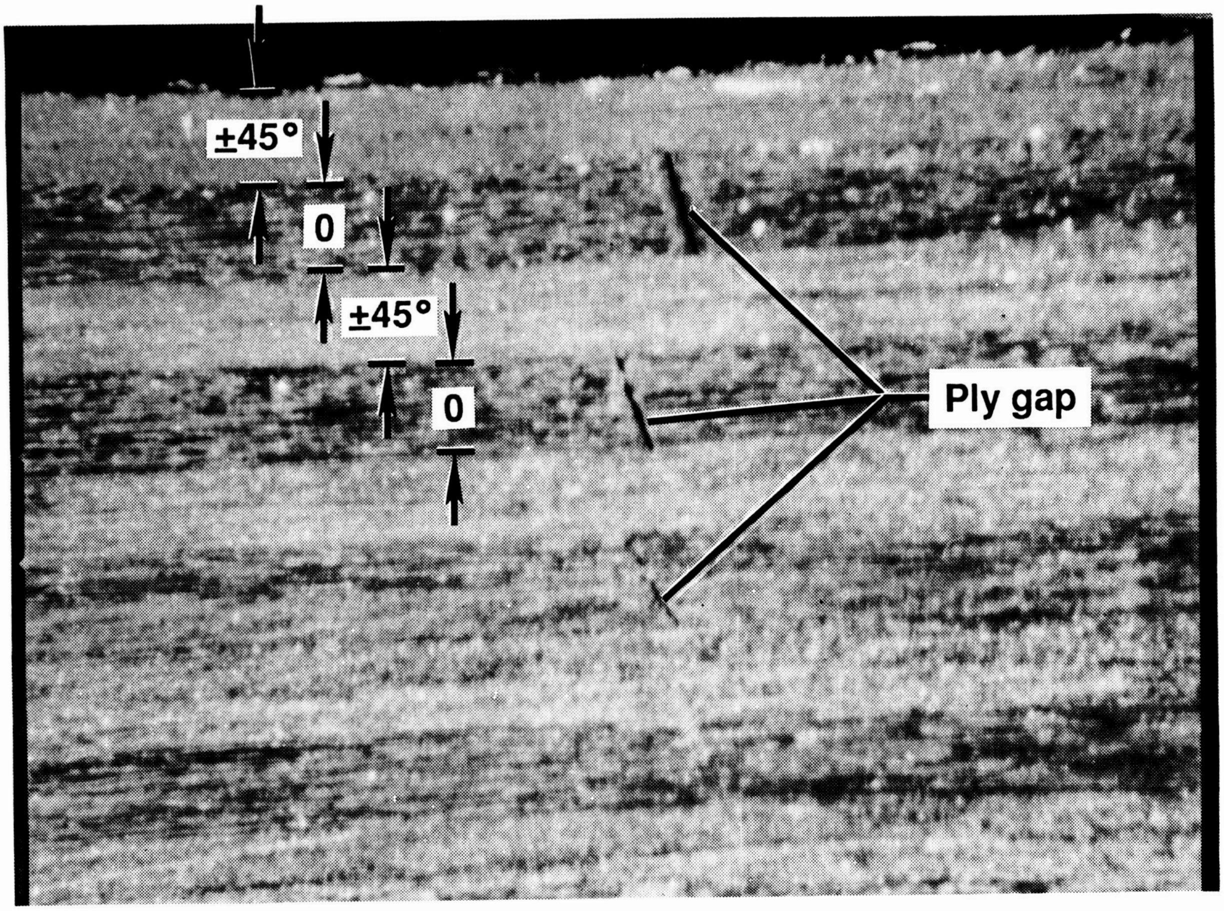

Figure 5. End-to-end ply gaps in 0° plies in specimen C.

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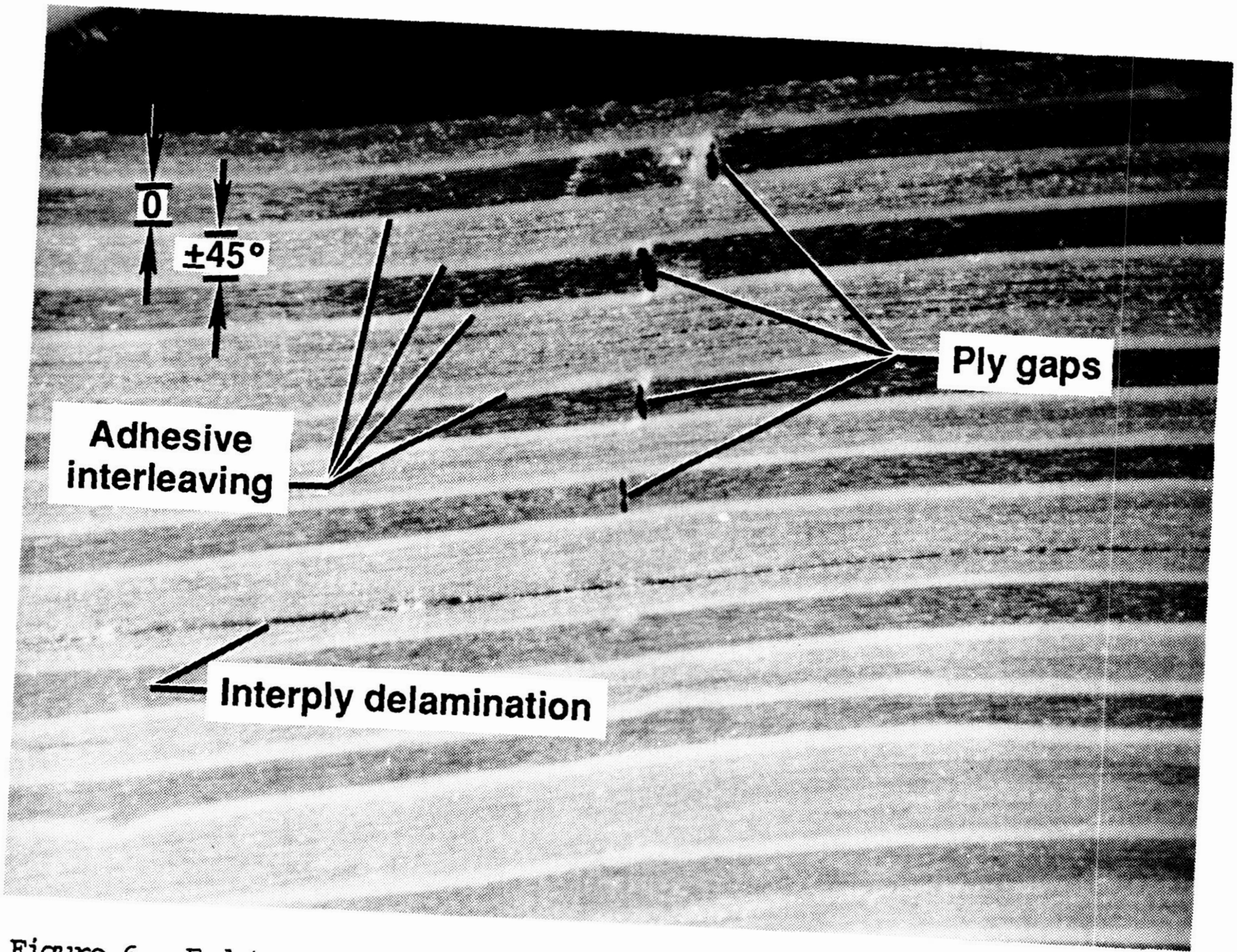

Figure 6. End-to-end ply gaps in region of high shear stress in specimen D.

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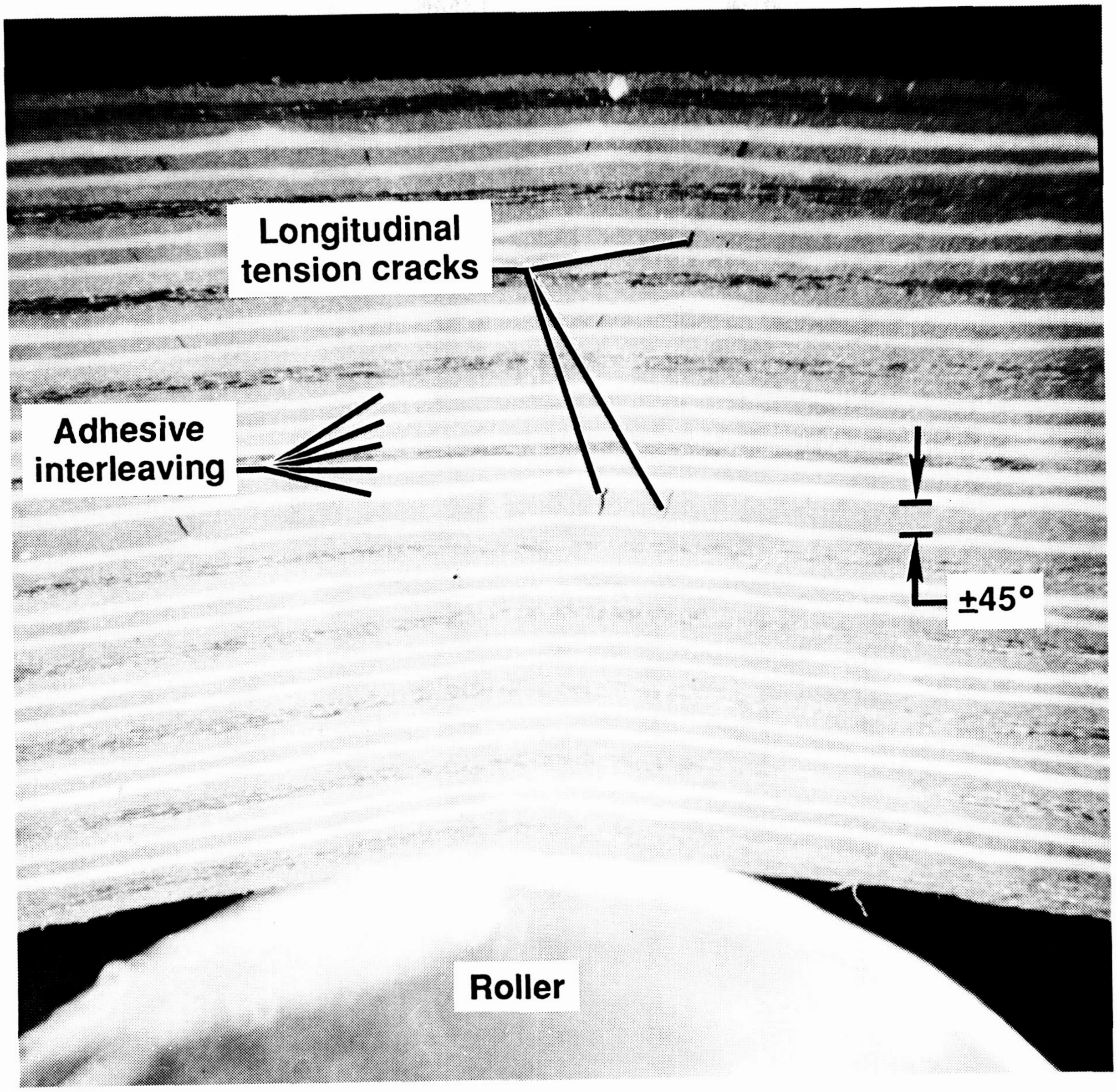

Figure 7. Longitudinal tension stress induced failures in $\pm 45^{\circ}$ and 90° plies in specimen E.

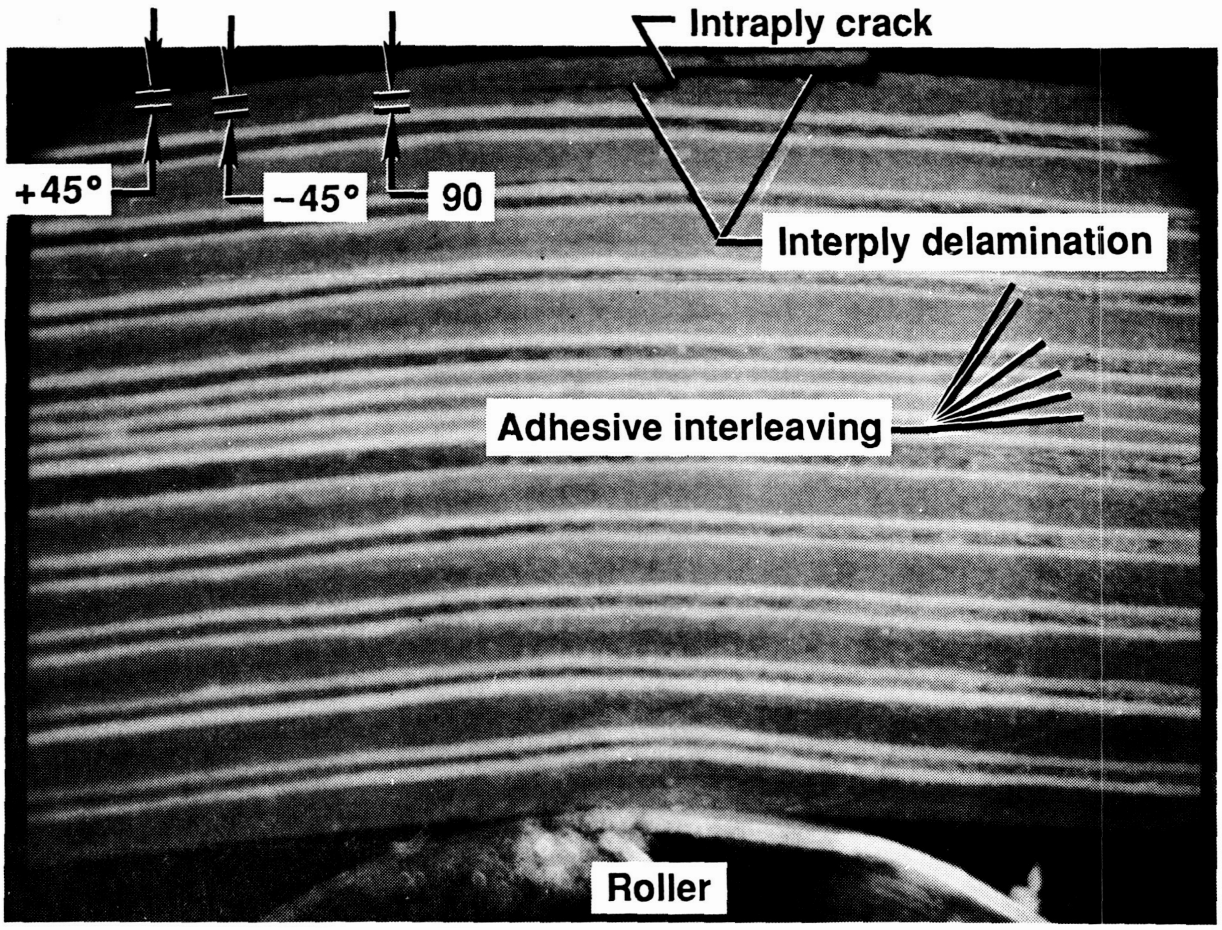

Figure 8. Final failure due to interply delamination of outer most plies in specimen J.

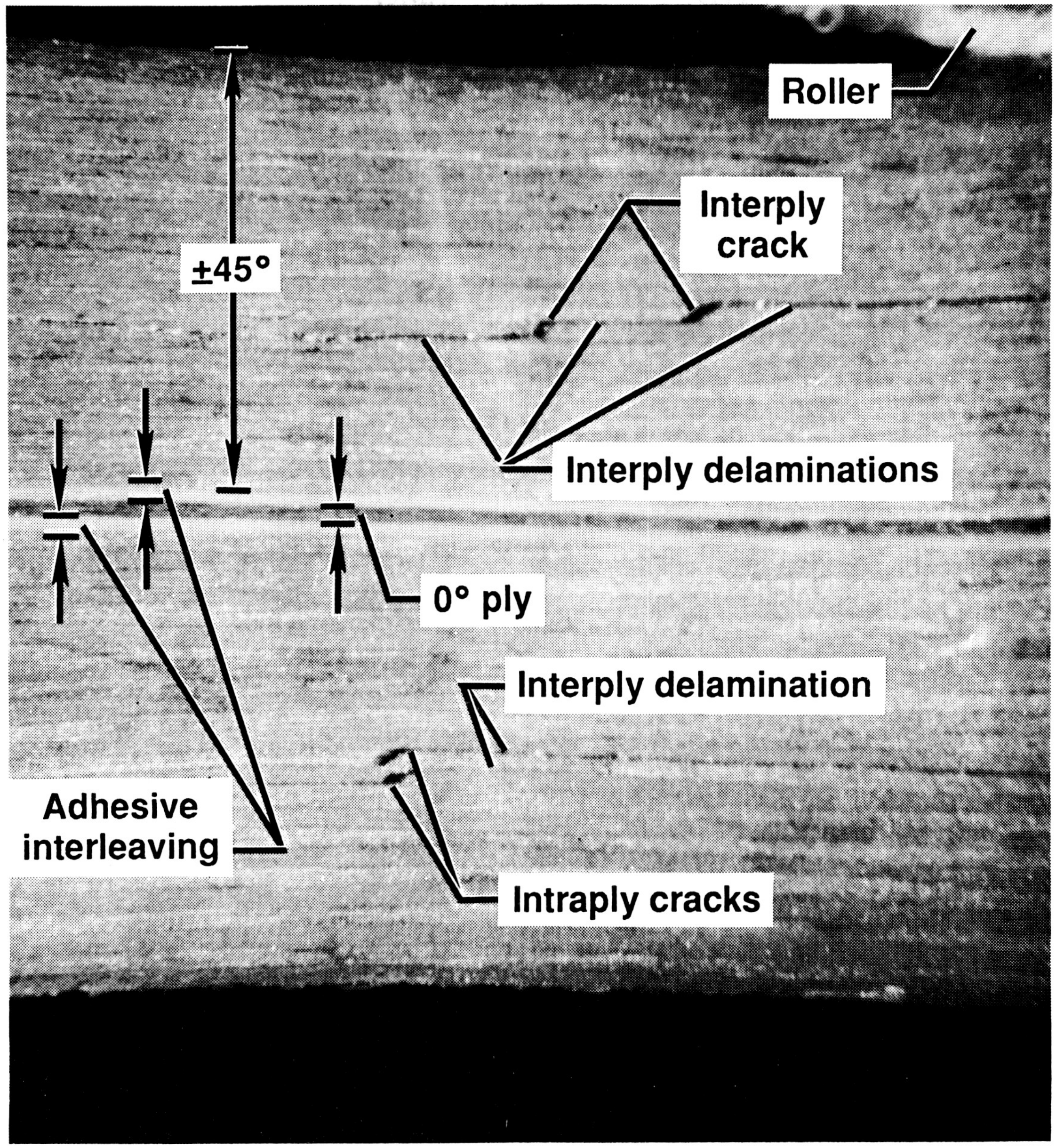

Figure 9. Intraply cracks propagating in 45° plies and interply delaminations in specimen B.

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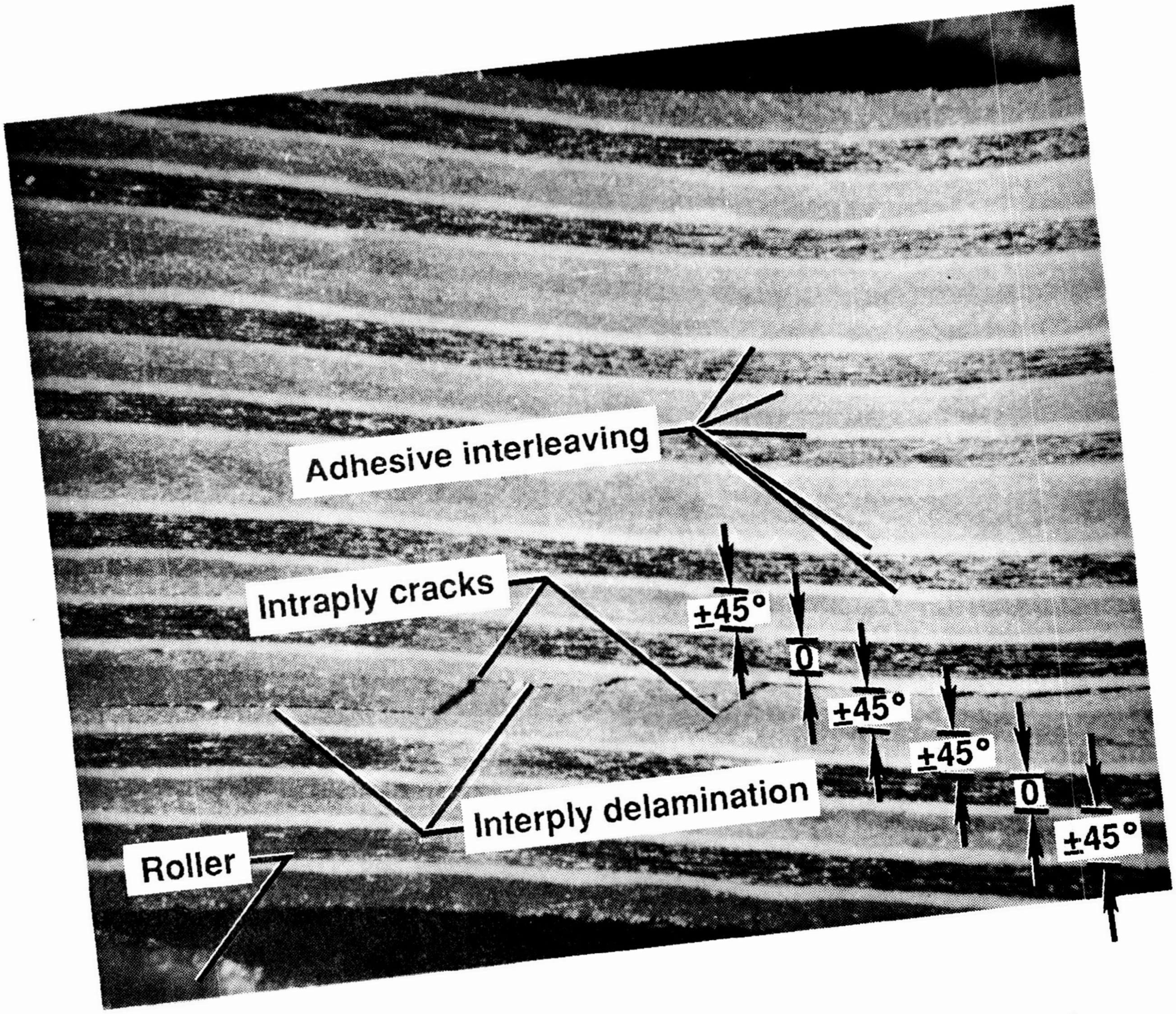

Figure 10. Intraply crack propagation in 45° and 90° plies in specimen D.

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15. Supplementary Notes

16. Abstract

Results of a series of tests to determine the effects of adhesive interleaving and discontinuous plies (plies with end-to-end gaps) on the displacements, failure loads and failure modes of graphite-epoxy laminates subjected to transverse normal loads are presented. Adhesive interleaving can be used to contain local damage within a group of plies, i.e., to arrest crack propagation on the interlaminate level, and it can increase the amount of normal displacement the laminate can withstand before failure. However, the addition of adhesive interleaving to a laminate does not significantly increase its load carrying capability. A few discontinuous plies in a laminate can reduce the normal displacement and load at failure by 10 to 40 percent compared to a laminate with no discontinuous plies, but the presence of the ply discontinuities does not generally change the failure location or the failure mode of the laminate.

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