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FAILURE MECHANISMS OF LAMINATES TRANSVERSELY LOADED BY BOLT PUSH-THROUGH

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SUMMARY

Stiffened composite panels proposed for fuselage and wing designs utilize a variety of stiffener-to-skin attachment concepts including mechanical fasteners. The attachment concept is an important factor influencing the panel's strength and can govern its performance following local damage. Mechanical fasteners can be an effective method for preventing stiffener-skin separation. One potential failure mode for bolted panels occurs when the bolts pull through the stiffener attachment flange or skin. The resulting loss of support by the skin to the stiffener and by the stiffener to the skin can result in local buckling and subsequent panel collapse.

This paper describes the characteristic failure modes associated with bolt push-through failure and presents the results of a parametric study of the effects that different material systems, boundary conditions, and laminates have on the forces and displacements required to cause damage and bolt push-through failure.

INTRODUCTION

Experience with metals has shown that yielding in the skin is an important feature in suppressing damage propagation and accommodating load redistribution following local damage (ref. 1). By comparison, brittle composites exhibit very little local yielding and therefore may require special design features to accomplish load redistribution following local damage. Current damage-tolerant composite design concepts include the use of "soft" skins, toughened resins, high-strain fibers, and the placement of a ductile adhesive film between the plies (interleaving) of the laminate.

Earlier design conce suggested that a row of bolts would arrest propagating damage in a compression-loaded composite panel (Figure 1(a)). The presence of a row of bolts alone, however, has not been found to be an effective arrestment approach due to the complex failure modes associated with compression failure. Damage arrestment, however, can be achieved through the use of stiffeners attached by fasteners (ref. 2) as shown in Figure 1(b). The thick attachment flanges provide additional bending stiffness which restrain the sublamina buckling deformations, reduces the corresponding interface tension peel stresses and redistributes some of the load into the stiffeners.

The graphite-epoxy hat-stiffened compression panel shown in Figures 2(a) and 2(b) illustrates typical failure modes associated with bolt hole damage: (1) the bolts have pulled through the skin and stiffeners, and (2) the laminate has splintered in the vicinity of the hole. Bolt pull-through is undesirable because it can also lead to skin-stiffener separation and panel failure. It is desirable, therefore, to prevent or delay the bolt pull-through failure mode in order to achieve improved damage tolerance and structural efficiency.

The present paper reports on a study conducted to characterize the response and failure modes of typical composite laminates loaded laterally by a bolt in a countersunk hole. Results are discussed and data are presented in the form of load versus displacement responses and photographs of failed specimens. Photomicrographs of specimen cross-sections are also shown and the micromechanics of laminate failure is discussed.

TESTS AND SPECIMENS

Test Description

The test technique involved loading the head of a bolt located in a countersunk hole which had been drilled in a thick composite laminate. The test section was supported by a fixture with a small diameter circular test section boundary. In a stiffened panel loads are applied to the bolt in tension as the bolt is pulled-through the laminate. For convenience, the current technique used a push-through test method. Deformations of the bolt head during loading were essentially restrained by this test technique. Overall, however, a push through response is not anticipated to be significantly different from a pull-through response. The test fixture and a mounted specimen are shown in Figure 3(a). The bolt was centered in the test section which was secured by four corner bolts in a steel fixture to provide a clamped circular boundary around the test section periphery. Circular boundary diameters of 1 and 2 inches were investigated. Load was transferred to the bolt by the loading probe in the center of the fixture. The guide hole for the probe was chamfered to prevent binding. A cross-section of the test assembly is shown in Figure 3(b). Plate specimens were drilled and countersunk with a series of holes to accommodate the fastener described in Figure 3(c). To accommodate multiple tests, hole spacing in the plate was three times the support boundary diameter. Specimen widths were 3 inches for the 1-inch-diameter boundary and 4 inches for the 2-inch diameter boundary.

The bolt used was a 3/16-inch diameter lightweight groove-proportioned pin manufactured by Huck Manufacturing Company for composite applications. This bolt has a 100° degree flush head and was made of 6AL-4V titanium alloy. A discussion of fasteners designed for composite structure application is presented in reference 3.

Failure loads and displacements for a specific laminate were found to be repeatable over a series of tests. Typically, the first specimen was loaded until the bolt completely penetrated the laminate. A second test specimen was loaded until the first indication of failure on the load-displacement response occurred and then the specimen was unloaded. Loading of a third specimen was stopped at an intermediate response following a subsequent increase in load.

Loading was accomplished by a 120-kip capacity controlled hydraulic loading machine in the displacement-controlled mode. The bolt displacement rate was .05 inches per minute. The crosshead displacement was monitored by a

Direct Current Differential Transformer (D.C.D.T.) and the load-displacement curve was recorded on an x-y recorder.

Composite specimens were inspected for damage by ultrasonic C-scan techniques following testing. Specimens were also cross-sectioned through the center of the hole to study the damage characteristics.

MATERIALS AND LAMINATES

The material systems studied in this investigation included different matrix and fiber combinations. Tests were performed on graphite, DuPont Kevlar and hybrid graphite-tape/Kevlar-Fabric laminates. The graphite/epoxy systems included both brittle and toughened resins. The brittle baseline resins investigated were Narmco 5208 and Hercules 3502. The toughened resins studied included CIBA-Geigy-4 and -2566, and ICI Peek (APC2). The graphite fibers tested were Union Carbide T300, Hercules AS4, and Celanese High Strain Celion (HSC). The Kevlar/epoxy systems used Hercules 3501-6 and 3M Company SP328 resins. Both Kevlar 29 and 49 fibers were studied. The effects of Kevlar fiber transverse stitching and of interleaving a low-modulus adhesive between plies were also studied. Interleaving was accomplished in a 40-ply quasi-isotropic laminate in which a .003-inch thick film of American Cyanamid FM1000 was placed between each ply of AS4/3502. For comparison, two aluminum alloys were tested. The effect of a 1- and 2-inch-diameter boundary condition was investigated for most laminates.

The laminates tested are described in Table I. A total of 12 composite laminates and 2 aluminum alloys were tested ranging in thickness from .244 to .317 inches.

RESULTS AND DISCUSSION

Load-Displacement Response

Brittle Resin Response. Typical load-displacement responses for brittle-resin specimens are presented in Figure 4. The responses are approximately linear to an initial peak where an abrupt drop in load occurs that is followed by a subsequent increase in loading which sometimes, but not always, reaches a peak higher than the first peek.

The T300/5208 and the AS4/3502 specimens (48-ply orthotropic laminates) exhibit very similar reponse characteristics. Increasing the thickness from 48 to 56 plies increased the maximum load capability by approximately 30 percent, however, there was virtually no change in the load and maximum displacement at the first peak. Changing the boundary diameter from 1 to 2 inches-(solid versus dashed curves in Fig. 4) had little effect on the load capabilities.

Kevlar Stitching. Behavior in brittle resins can be improved by the use of Kevlar 49 transverse stitching as shown in Figure 5. Both single and double stitch patterns were studied. The single stitch pattern consisted of rows of stitching at a .25-inch pitch. The double stitch pattern consisted of perpendicular rows of stitching, also spaced at a .25-inch pitch. There are no significant differences for first peak failure loads between the 1- and 2-inch boundary diameters or the single and double stitch patterns.

Examples of failed test specimens are shown in Figure 6. In each photograph the upper specimen was tested with the 2-inch boundary diameter, the lower with the 1-inch-diameter. The hole on the left of each specimen was completely failed (i.e., the bolt continued to be pushed through the hole with decreasing load), testing was stopped at the peak of the subsequent loading for the center hole, and testing was stopped at the initial peak for the hole to the right. Stitching confines fiber breakout on the holes that are completely failed, and suppresses it altogether on the holes where testing was stopped at the subsequent loading peak.

Tough Resins and Interleaving. The load-displacement reponses for toughened laminates tested with 1-inch diameter boundary support are shown in Figure 7. The 48-ply orthotropic AS4/3502 laminate curve is repeated for reference. The T300/CIBA-4 material (48-ply orthotropic laminate) shows minor improvement relative to the brittle AS4/3502 material and improvement on the same order as that measured for T300/5208 laminates with transverse Kevlar stitching. CIBA-4 is an experimental resin which, in previous tests (ref. 4), had shown improved resistance to low-velocity impact damage. The HSC/CIBA-2566 (48-ply quasi-isotropic laminate) material had an initial peak load approximately the same as the initial peak load for the T300/CIBA-4 and a subsequent maximum load substantially higher than the initial peak load.

Peek (APC2) manufactured by Imperial Chemical Industries is a thermoplastic resin which reportedly (ref. 5) has improved damage tolerance characteristics. For the 48-ply quasi-isotropic AS4/Peek (APC2) laminate, the response near the maximum load differs from that observed for the 48-ply orthotropic AS4/3502 laminate. Whereas the AS4/3502 experiences an abrupt drop in load at the initial peak, the AS4/Peek (APC2) material exhibits nonlinear behavior, similar to the yielding characteristic of aluminum. The load continues to increase until an abrupt drop occurs that is followed by additional loading and unloading for which subsequent peaks are lower than the first. Due to the nonlinear response the displacement at maximum load is considerably larger than those at the initial peak for the material systems discussed previously.

Photographs of the front and back surfaces of AS4/Peek (APC2) specimens tested with both the 1- and 2-inch-diameter boundary conditions are shown in Figure 8(a). Loading was stopped for the hole shown with the protruding bolt when the maximum load was reached. Inspection of the back surface reveals fiber breakout has been suppressed. The bolt has been pushed extensively into the laminate for the other two holes shown.

Interleaving the plies of a laminate made from a brittle resin system with a low-modulus adhesive (FM1000) also provided improved behavior. The load-displacement response for these specimens was nearly linear to essentially the same load as the initial failure load for the baseline AS4/3502 laminate. Instead of showing an abrupt drop in load, however, the interleaved laminate exhibited a reduction in the slope of the load-deflection curve and continued to carry additional load up to the maximum which is approximately 20 percent higher than the baseline without interleaving. Minor discontinuities in the load-displacement curve indicate that during the latter load phase irreversible damage is occurring in the laminate. Displacements at maximum load are increased approximately 150 percent compared to the baseline. Photographs of the front and back surfaces of interleaved specimen are shown in Figure 8(b). Loading was terminated for the hole on the left of the figure just following the change in the load-deflection slope. Loading for the center hole was terminated when maximum load was reached. Although a local surface irregularity is evident, fiber breakout was suppressed in contrast to an identical test performed on the baseline laminate without interleaving shown in Figure 6(a). Limited fiber breakout is shown for the hole on the right in which the specimen was loaded significantly beyond the maximum load.

Kevlar and Kevlar/Graphite/Epoxy Hybrid. Kevlar 29 and 49 laminates exhibit low loads at first failure relative to the baseline brittle resin as shown in Figure 9. However, the Kevlar materials are capable of sustaining considerably larger displacements on subsequent loadings and, in the case of Kevlar 49, slightly higher loads. Hybridization of a brittle resin graphite/epoxy system with a Kevlar fabric, such as AS4/3502 and Kevlar 49 (285 Fabric)/5208, reduced both the load and displacement performances relative to the AS4/3502 graphite/epoxy system.

Comparison of Composite Behavior to Aluminum. Two commonly used aluminum alloys, 2024-T4 and 7075-T651, were tested for bolt push-through for a .25-inch-thick plate and typical results are shown in Figure 10. The 7075-T651 aluminum specimens carried greater load but showed a less ductile response than the 2024-T4 specimen. Compared to aluminum, the AS4/Peek (APC2) and AS4/3502/FM1000 laminates show considerably less load carrying capability, but sustain large displacements at peak load that are on the same order as those measured for aluminum. This large displacement capability is recognized in stiffened metallic structures to be an important parameter for permitting load redistribution prior to failure (ref. 1). The failure modes characteristic for the aluminum materials are shown in Figure 11 and will be further discussed in the section on Failure Mode Description.

A summary of load and displacement comparisons are shown on bar graphs in Figures 12 and 13, respectively. The material systems are numbered in accordance with Table I. The data variation is indicated at the end of each bar. Tough resins and interleaving offer minor improvement in load capabilities relative to brittle resin systems. Loads at failure are still 30-70 percent lower than those for aluminum. Overall, changing boundary diameters from 1 to 2 inches does not significantly alter the failure loads. The AS4/Peek (APC2) (System 9) exhibits a displacement at maximum load approximately twice that of the brittle systems (Figure 13). Kevlar, tough resins, and adhesive interleaving have displacement capabilities at maximum load which are higher than those exhibited by brittle resin systems. The displacement at maximum load for the laminate with adhesive interleaving surpasses the displacement capability at failure for the aluminums. Displacement capability without failure may be a

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

more important factor than high load magnitude in permitting load redistribution and preventing collapse of the structure.

Failure Mode Description

Examination of the composite specimen cross-sections indicates three basic mechanisms are involved in bolt push-through failure. These mechanisms include intralaminar transverse shear failure involving fibers oriented approximately parallel to the cross-section, intralaminar failure involving matrix failure of non-parallel oriented plies while excluding failure of fibers oriented parallel to the cross-section, and delamination. These three failure modes were characteristic of all the composite material systems tested including specimens with Kevlar fibers, toughened resins, and adhesive layer interleaving. The suppression or delay of certain failure modes, in particular the matrix dominated ones, was found to be characterstic of material systems with the higher load-displacement responses.

Brittle Resin Laminates. The three characteristic failure modes for bolt push-through are shown for a baseline AS4/3502 48-ply orthotropic laminate in Figure 14(a). Testing of this specimen was terminated following the initial peak load. Transverse shear failure involving inplane fibers as well as matrix failure in nonplanar plies can be seen in the vicinity of the countersink where the concentrated loads are applied through the bolt head (Fig. 14(a)). Further away from the hole boundaries (in regions of high transverse shear) numerous intralaminar fractures have developed which are oriented at approximately 45-degrees to the vertical direction. These matrix failures are in the tension direction of the transformed transverse shear stress. The density of matrix transverse shear failures becomes more numerous in the extended stages of loading, and delaminations develop between plies at the intersection of the matrix transverse shear failure with dissimilar oriented adjacent plies. These three characteristic failure modes were also observed for the failure of Kevlar/epoxy laminates as shown in Figure 14(b).

Kevlar Stitching. The effects of transverse stitching with Kevlar thread in a brittle resin laminate are shown in Figure 15. The transverse shear failure of the fibers and matrix in the vicinity of the countersink (Figure 15, region A) is not as pronounced as in the unstitched case (Figure 14). However, intralaminar shear failure of the matrix in the laminate interior (region B) is still evident. Close examination of the cross-section reveals that in some cases delaminations have been arrested at the intersection with the Kevlar stitching.

Tough Resins and Interleaving. The characteristic failure modes for T300/CIBA-4 at the initial peak load are shown in Figure 16. These modes are similar to those recorded previously for the baseline AS4/3502 system. The principal difference is that transverse shear failures of the fibers and matrix occur at slightly higher loads and displacements, and the failures are less numerous. Extended loading of T300/CIBA-4 causes further intralaminar matrix shear failures in region B and additional interply delaminations as indicated in Figure 17.

The cross-sectional failure characteristics for the AS4/Peek (APC2) material following maximum load is shown in Figure 18. The failure in the vicinity of the bolt head clearly involves the transverse shear failure of the 0° plies as well as matrix failures of angle plies. The matrix transverse shear failure in region B is oriented at approximately 20° to the horizontal axis and propagation by delamination between plies characteristic of brittle resin laminates has not occurred. In addition, very few matrix intralaminar shear failures are observed at this load level.

The failure modes for the brittle resin with low-modulus adhesive interleaving (AS4/3502/FM1000) are shown in Figures 19, 20, and 21. Photomicrographs near the boundary of the countersink (Fig. 19, region A) indicate intralaminar shear failure of the fibers (enlargement C) soon after the specimen is loaded into the nonlinear range. Interleaving almost entirely suppresses the interply delamination failure mode between plies even up to maximum load (Fig. 20). The limited strain capability of the brittle 3502 resin, however, permits intraply delaminations to develop as shown in Figure 21.

Kevlar Laminates. This class of laminates shows essentially the same failure modes as the brittle and first-generation toughened resins; i.e., transverse shear failure of the fibers and matrix near the countersink, intralaminar shear failure in the matrix away from the hole boundary, and interply delamination. Photomicrographs of the failure of a Kevlar 29/3501-6 laminate are shown in Figure 22.

Aluminum Specimens. Failure modes for the two aluminum alloys are shown in Figure 23. Rolling during processing causes the grain structure of 7075-T651 aluminum to be elongated in the roll direction which produces a banded or multi-layered microstructure. This microstructure results in a non-isotropic material that exhibits the stair-step failure pattern shown. With less grain elongation the 2024-T4 aluminum is more isotropic in behavior and failure occurs as a result of the shear-out of a plug approximately the size of the bolt head.

CONCLUDING REMARKS

The strength of transversely-loaded composite bolt holes can be improved through the use of tough resins, high-strain fibers and low-modulus adhesive interleaving. Strengths obtained, however, are 50-75 percent less than those of an equivalent thickness of aluminum. Kevlar/epoxy laminates and laminates with adhesive interleaving exhibited deformations at maximum load which approached or exceeded those of aluminum. The large nonlinear deformation response characteristic of toughened resins and adhesive interleaving is believed to be an important property for accommodating load redistribution following local failure.

Study of the cross-sections of failed specimens indicates three failure modes are characteristic of bolt push-through. In the vicinity of the bolt head a complex stress state exists in which transverse shear stress concentrations are sufficiently high to cause local intralaminar failures of fibers. Although intralaminar matrix failures and delamination may also occur in the vicinity of the bolt head; it is failure of the fiber which distinguishes this region. A second failure mode, matrix intralaminar failure occurs in the interior of the laminate where a more uniform state of transverse shear stress is developed. The matrix intralaminar failures are oriented at 45° to the plane of the laminate and occur only in non-zero angle plies. The failure is due to the tension loads imposed on the matrix by the tension principal stress component of the transverse shear loading.

The third characteristic failure mode is delamination which normally occurs between plies (interply) and often initiates at the intersection of the matrix intralaminar failure with the adjacent ply. The AS4/Peek (APC2) tough resin and adhesive interleaved systems delay the development of matrix intralaminar failure until high loads and displacements are imposed and also suppress the interply delamination mode of progagation. Under extended deformations, however, intraply (within a ply) delaminations were observed to develop in the adhesive interleaved material. Stitching helps to suppress delamination, although it does not suppress the matrix intralaminar failure mode.

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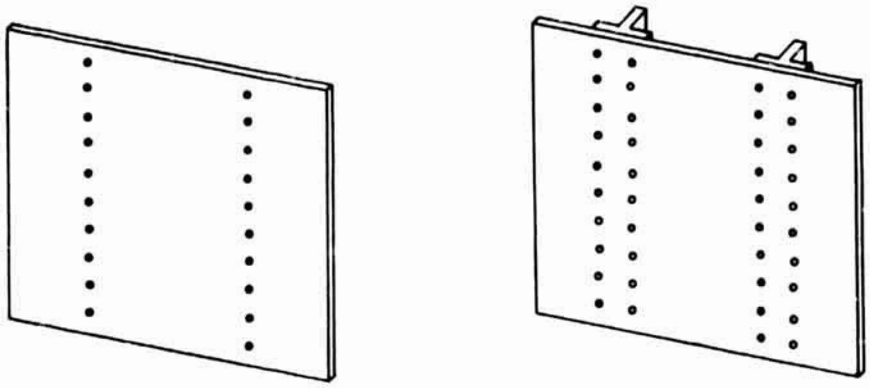
TABLE 1. - Test Specimens.

System	Material	Laminate	Nominal Thickness, Inch
1	T300/5208	$[(\pm45/0_2)_2/\pm45/0/90]_{2S}$	0.244
2	AS4/3502	$[(\pm45/0_2)_2/\pm45/0/90]_{2S}$	0.257
3	T300/5208 (Kevlar Stitch)	$[(\pm45/0_2)_2/\pm45/0/90]_{2S}$	0.312
4	AS4/3502	$[(\pm45/\pm45)_2/+45/0_2/-45_2/0_2/+45_2/0_2/-45_2/0_2/+45_2/90_2/-45]_S$	0.298
5	Kevlar 29/3501-6	$[(\pm45/0_2)_2/\pm45/0/90]_{2S}$	0.246
6	Kevlar 49/3501-6	$[(\pm45/0_2)_2/\pm45/0/90]_{2S}$	0.256
7	Kevlar 49/SP328	$[(\pm45/\mp45)_2/90_2\pm45/\mp45/\pm45/\mp45]_S$	0.312
8	T300/CIBA-4	$[(\pm45/0_2)_2/\pm45/0/90]_{2S}$	0.317
9	AS4/PEEK (APC2)	$[+45/0/-45/90]_{6S}$	0.254
10	HSCelion/CIBA-2566	$[+45/0/-45/90]_{6S}$	0.265
11	AS4/3502/FM1000	$[+45/0/-45/90]_{5S}$@	0.309
12	Aluminum 2024-T4		0.251
13	Aluminum 7075-T651		0.256
14	AS4/3502 (0, 90) Kevlar 285 Fabric/ 5208 (±45)	$[(\pm45/0_2)_2/\pm45/0/90]_{2S}$	0.246

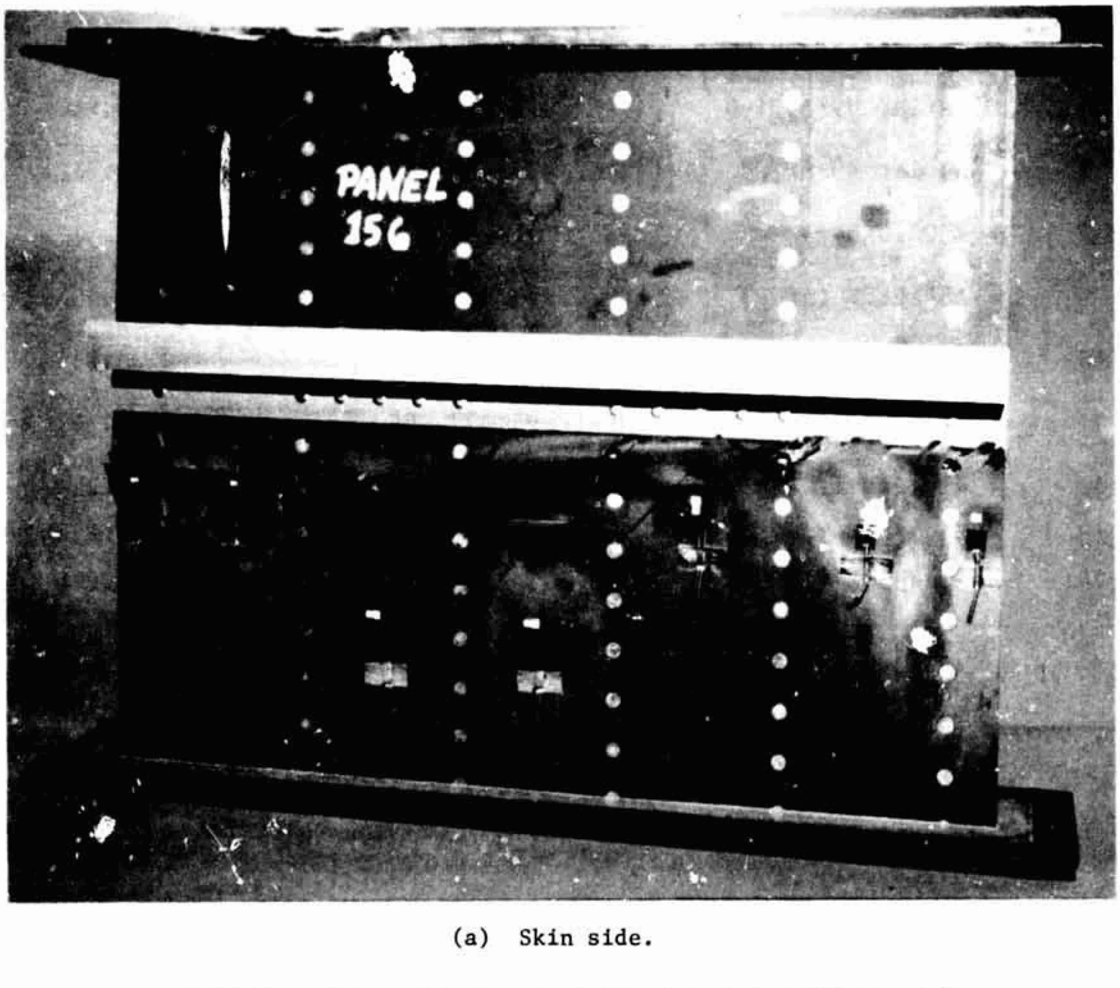
@ Laminate has a layer of FM1000 adhesive (.003-in. thick) between each ply.



(a) Unstiffened with row of bolts. Damage propagation not arrested.

(b) Stiffened, propagation arrested.

FIGURE 1. Damage containment concepts for compression loaded panels.



(a) Skin side.

FIGURE 2. Failure modes associated with bolt pull-through.

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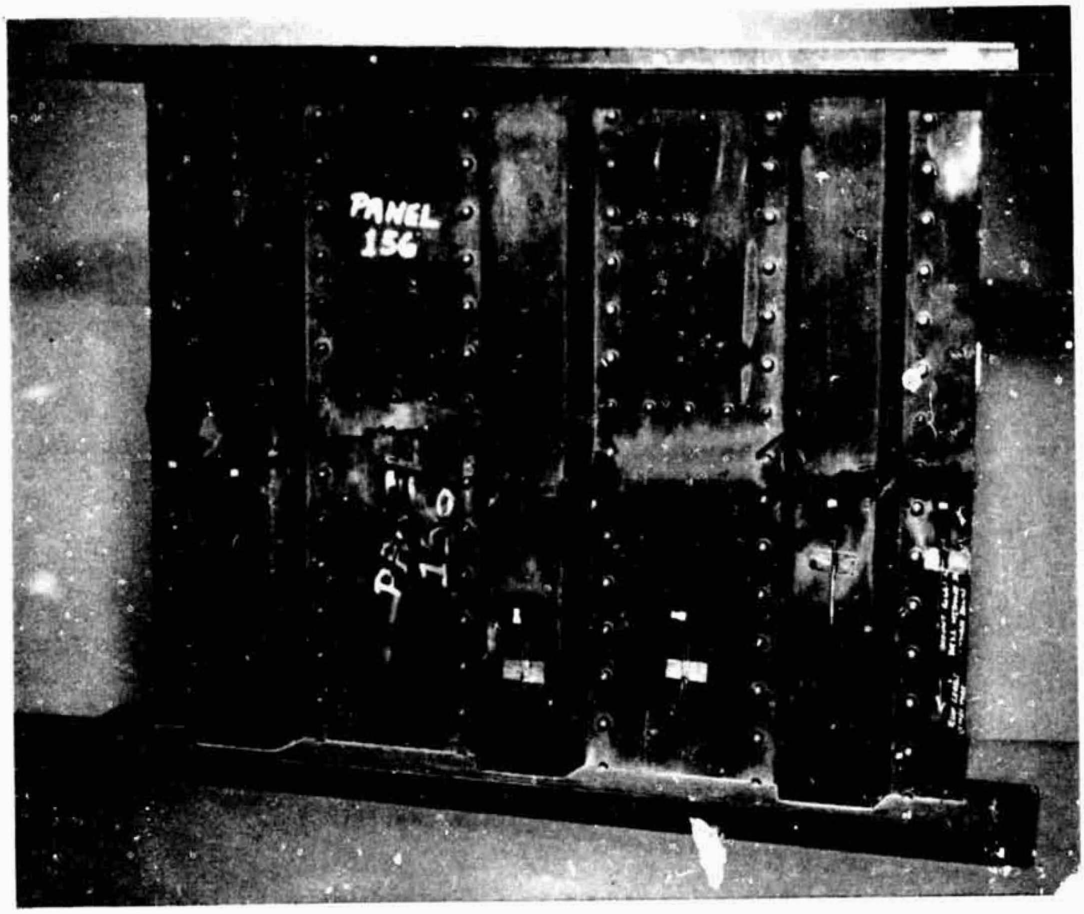
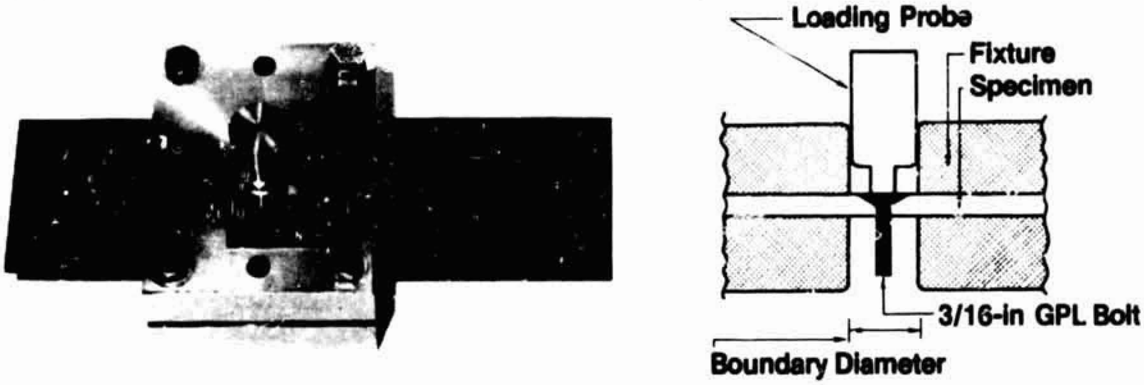


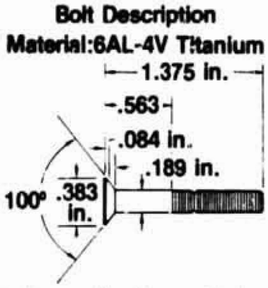
(b) Stiffener side.

FIGURE 2. Concluded.



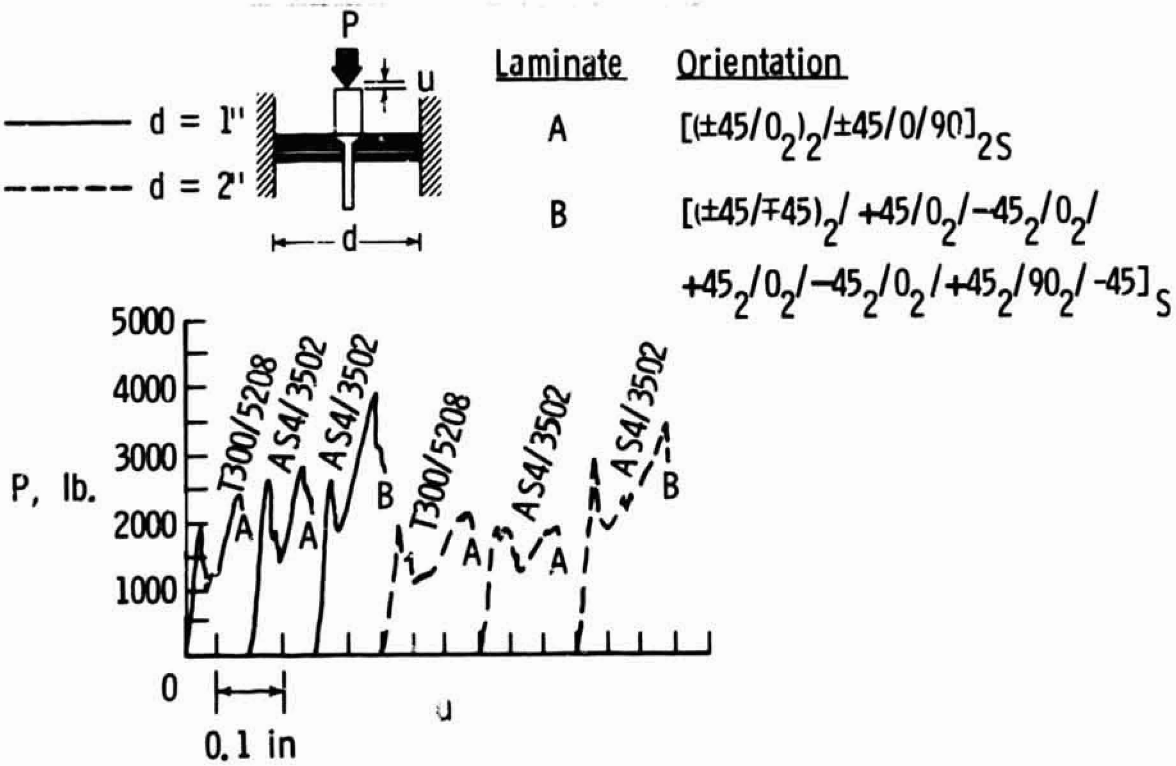
(a) Fixture, mounted specimen, and bolt.

(b) Cross-section of fixture.



(c) Bolt description (material: 6AL-4V titanium).

FIGURE 3. Bolt push-through test fixture.



Laminate	Orientation
A	$[(\pm45/0_2)_2/\pm45/0/90]_{2S}$
B	$[(\pm45/\mp45)_2/+45/0_2/-45_2/0_2/+45_2/0_2/-45_2/0_2/+45_2/90_2/-45]_S$

FIGURE 4. Bolt push-through load-displacement responses for brittle resin laminates.

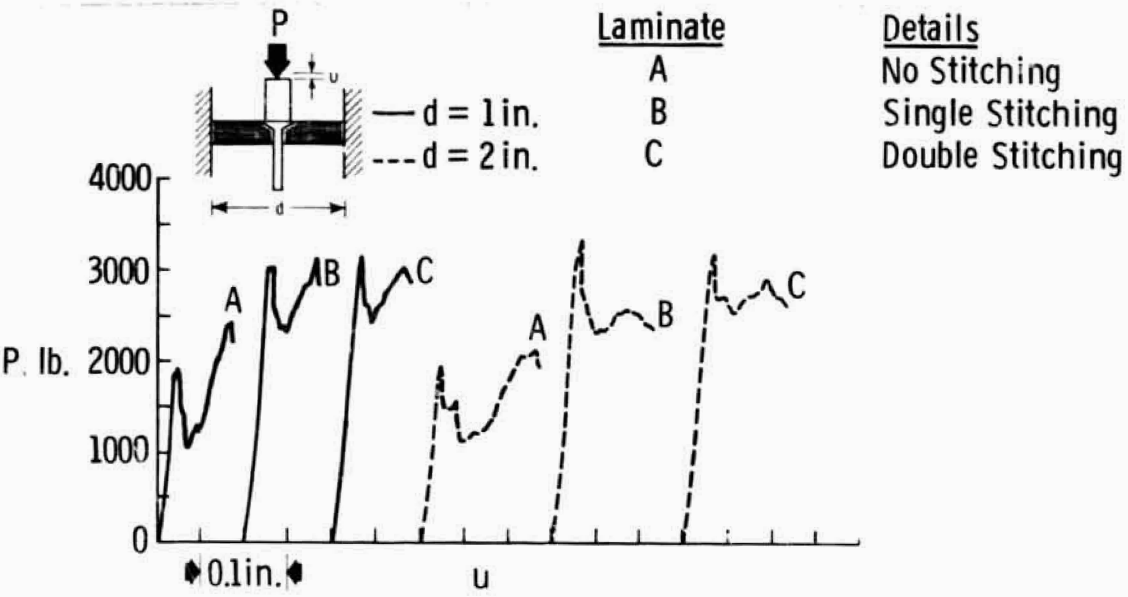
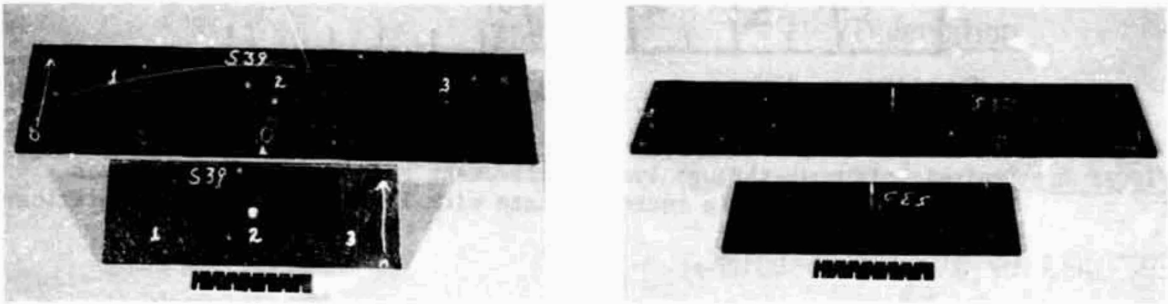
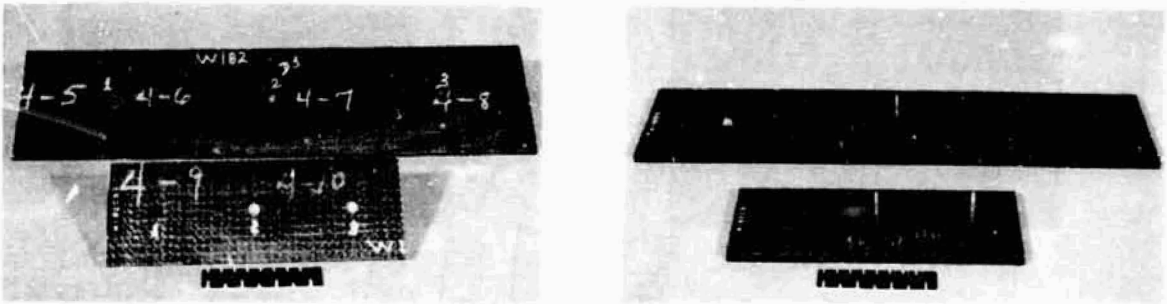


FIGURE 5. Effects of Kevlar 49 stitching on a $[(\pm45/0_2)_2/\pm45/0/90]_{2S}$ T300/5208 laminate bolt push-through response.



(a) T300/5208



(b) T300/5208 stitched

FIGURE 6. Failed specimens: $[(\pm45/0_2)_2/\pm45/0/90]_{2S}$ T300/5208.

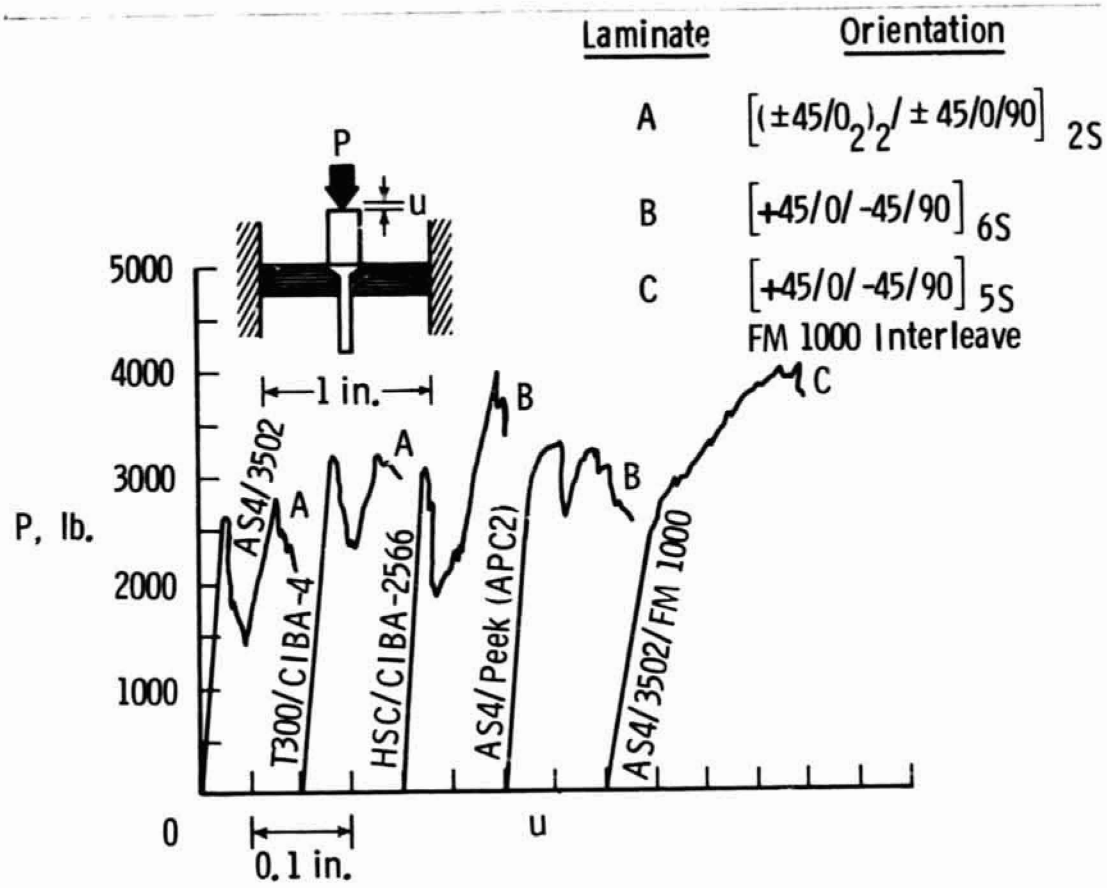
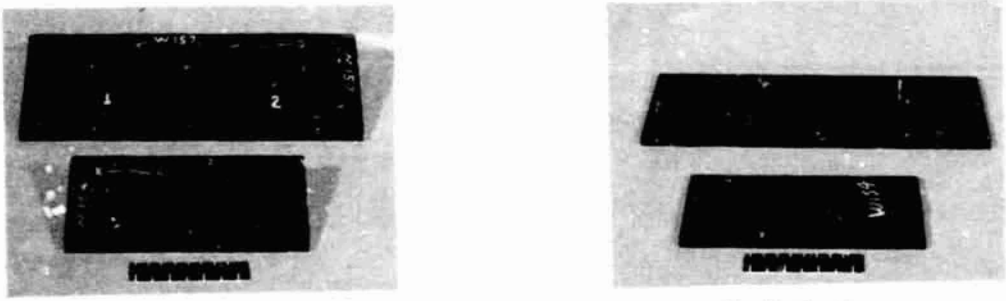


FIGURE 7. Typical bolt push-through load-displacement responses for tough resin laminates and a brittle resin laminate with low-modulus adhesive interleave.

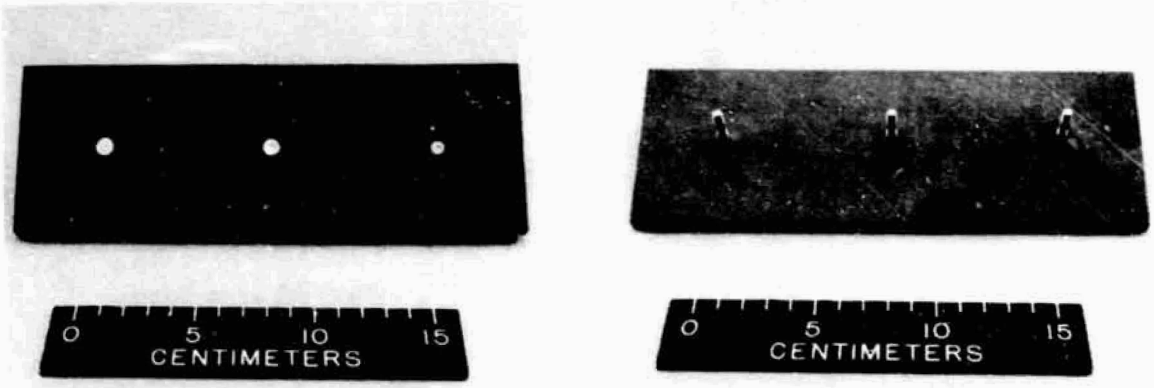


Front Surface

Back Surface

(a) AS4/PEEK (APC2), $[+45/0/-45/90]_{6S}$

FIGURE 8. Failed specimens.



Front Surface

Back Surface

(b) AS4/3502/FM1000 interleave, $[+45/0/-45/90]_{5S}$.

FIGURE 8. Concluded.

Laminate	Orientation
A	$[(\pm45/0_2)_2/\pm45/0/90]_{2S}$
B	$[(\pm45/\mp45)_2/90_2/\pm45/\mp45/\pm45/\mp\overline{45}]_S$
C	$[+45/0/-45/90]_{2S}$: (0, 90) AS4/3502 (±45) Kevlar 285 Fabric/5208

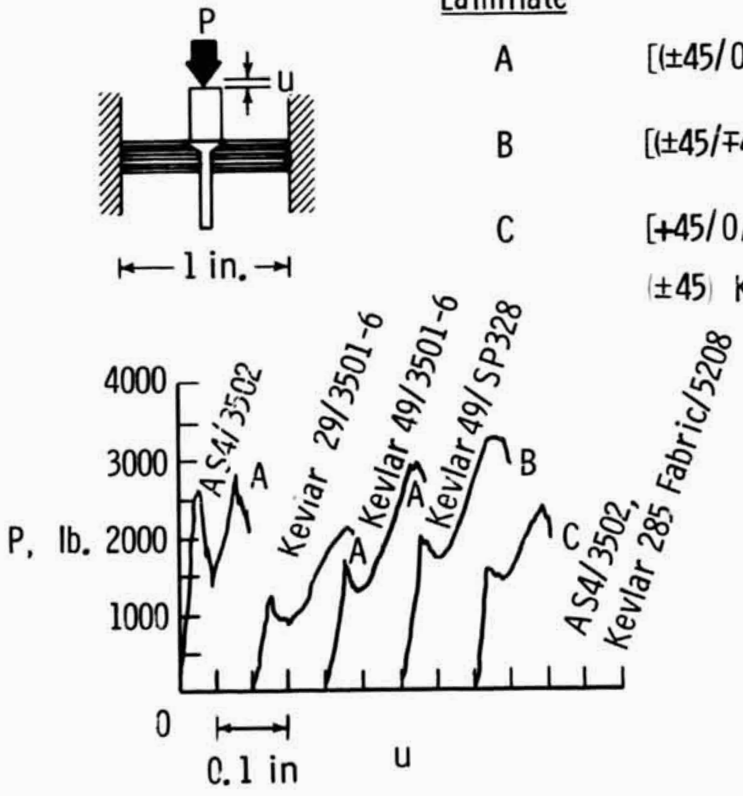


FIGURE 9. Typical bolt-through load-displacement responses for Kevlar and Kevlar/graphite laminates.

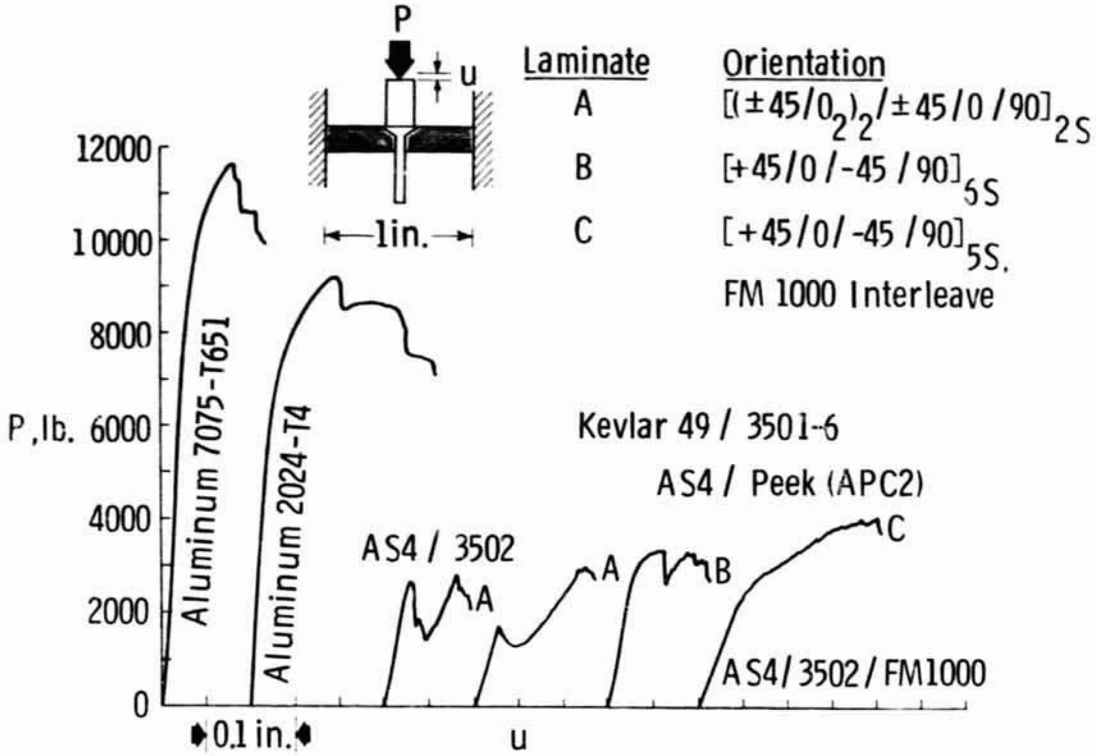
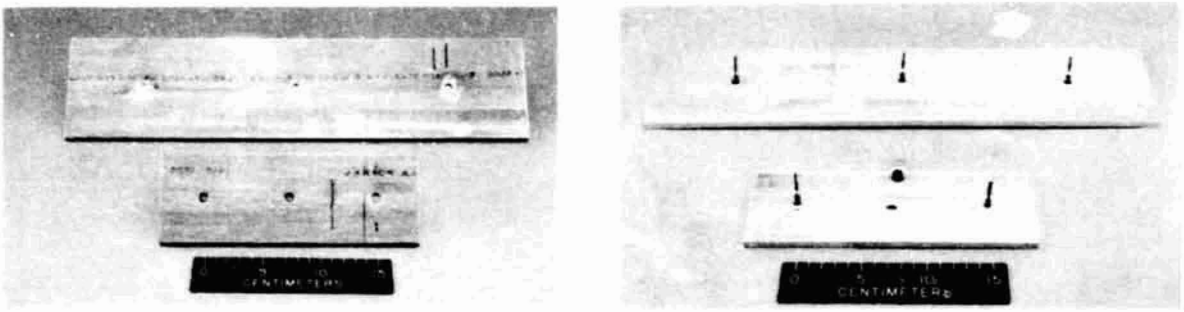


FIGURE 10. Comparison of aluminum bolt push-through response with selected composite laminate responses.



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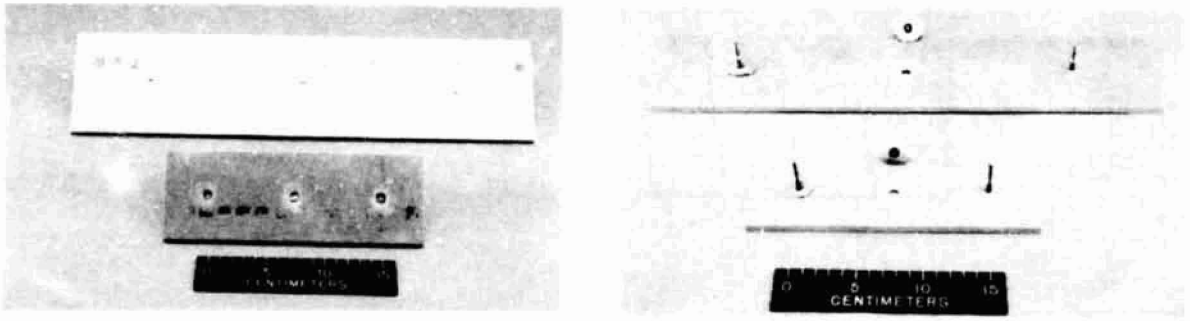

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FIGURE 11. Failed aluminum specimens.

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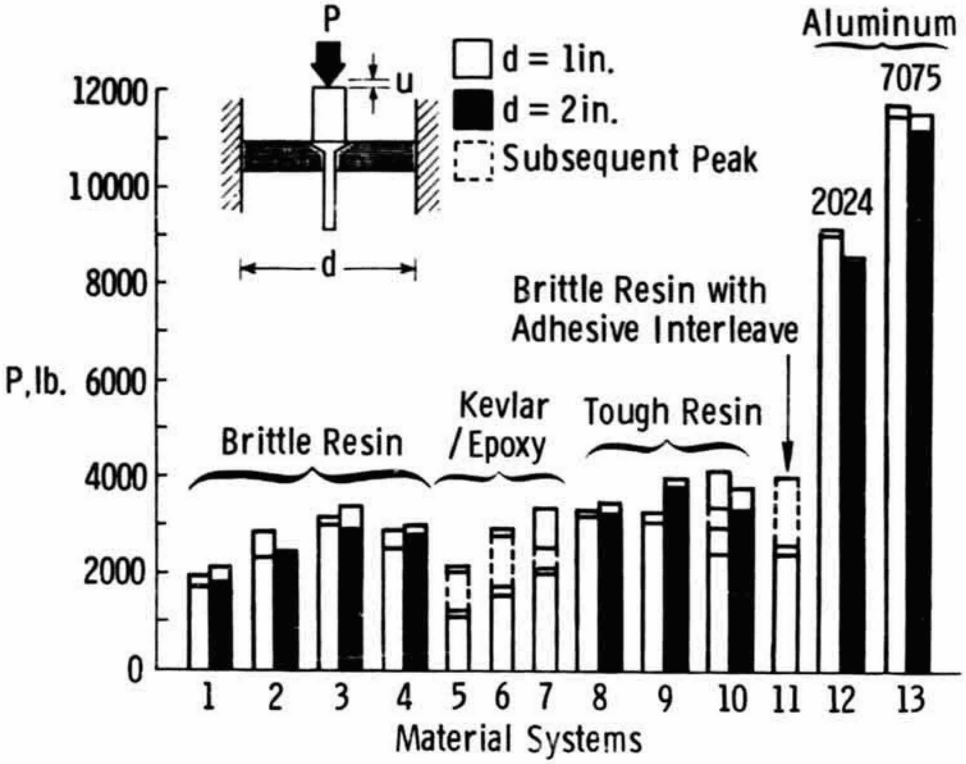


FIGURE 12. Comparisons of bolt push-through loads at failure.

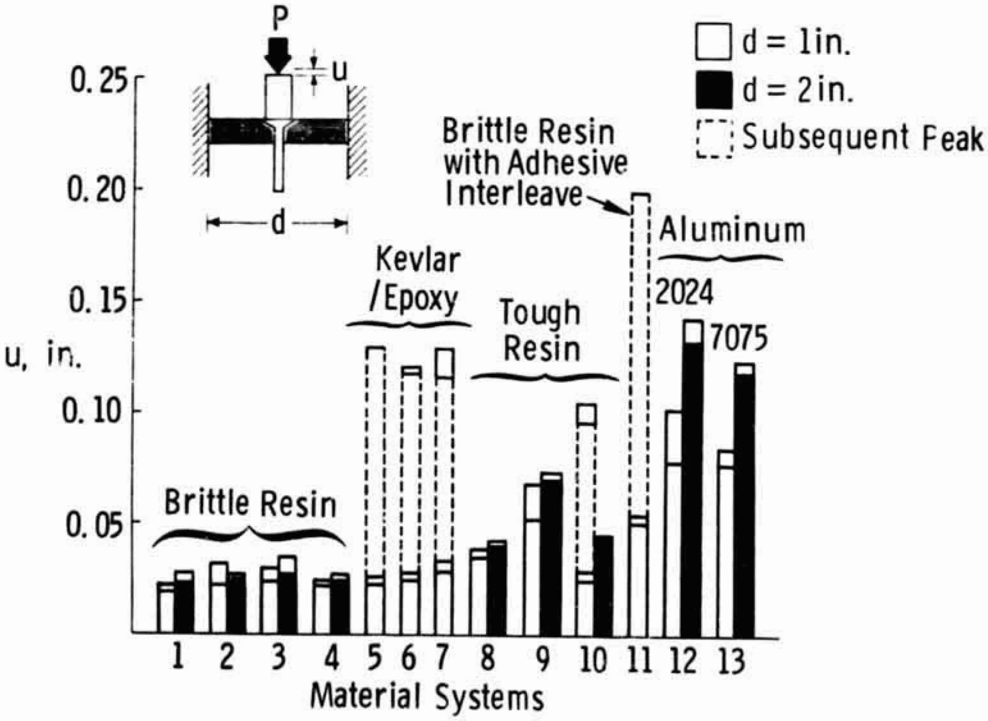
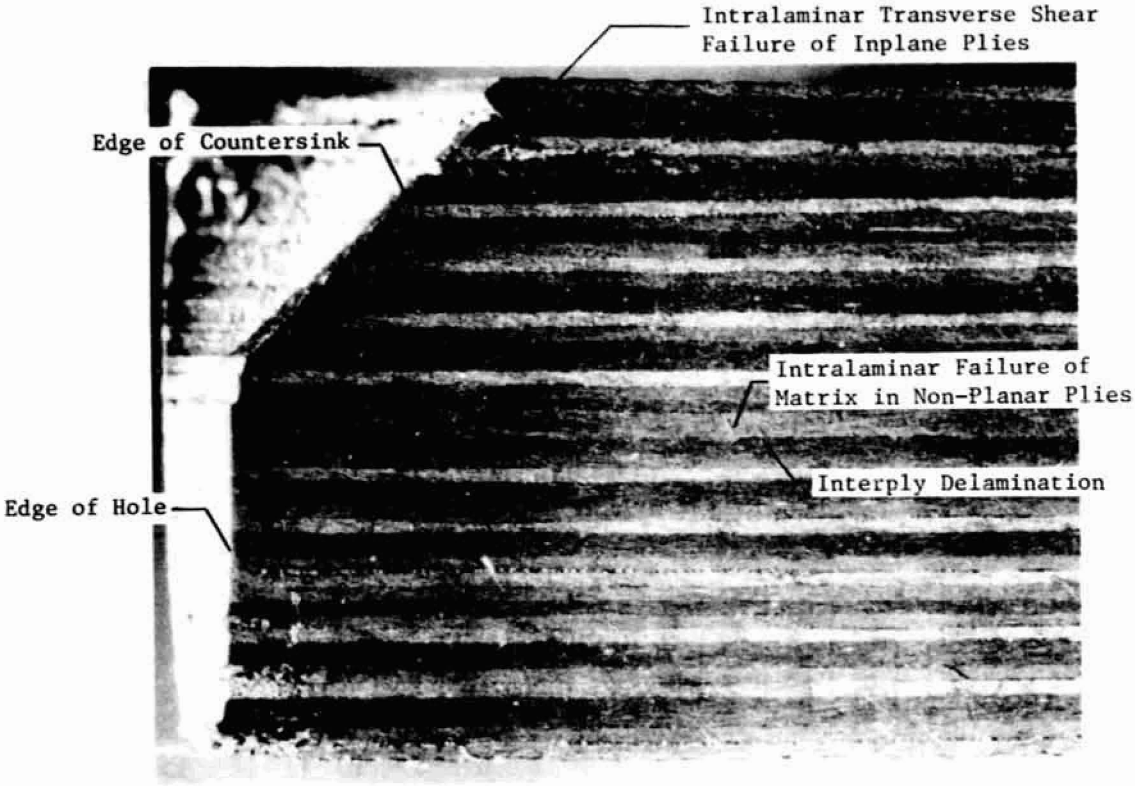
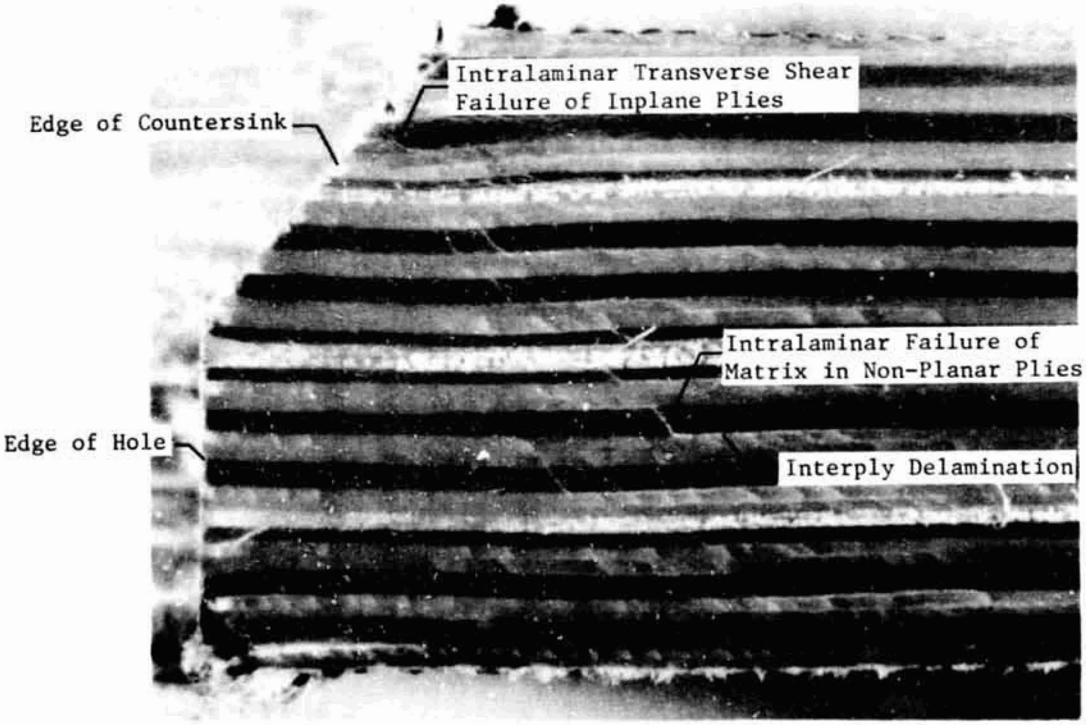


FIGURE 13. Comparisons of bolt push-through displacements at failure.



(a) Graphite/Epoxy



(b) Kevlar/Epoxy

FIGURE 14. Cross-section illustrating typical failure modes for laminates transversely loaded by bolt push-through.

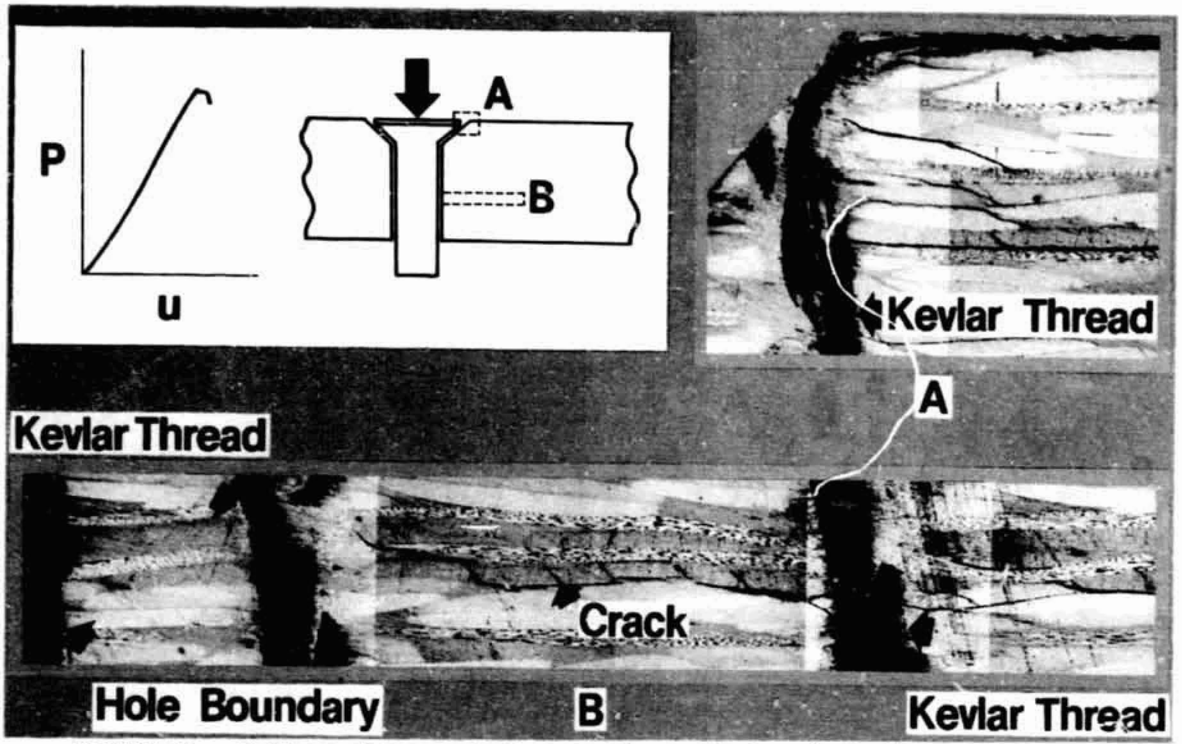


FIGURE 15. Failure characteristics at the initial peak load for $[(\pm45/0_2)_2/\pm45/0/90]_{2S}$, T300/5208, Kevlar 49 stitched laminate.

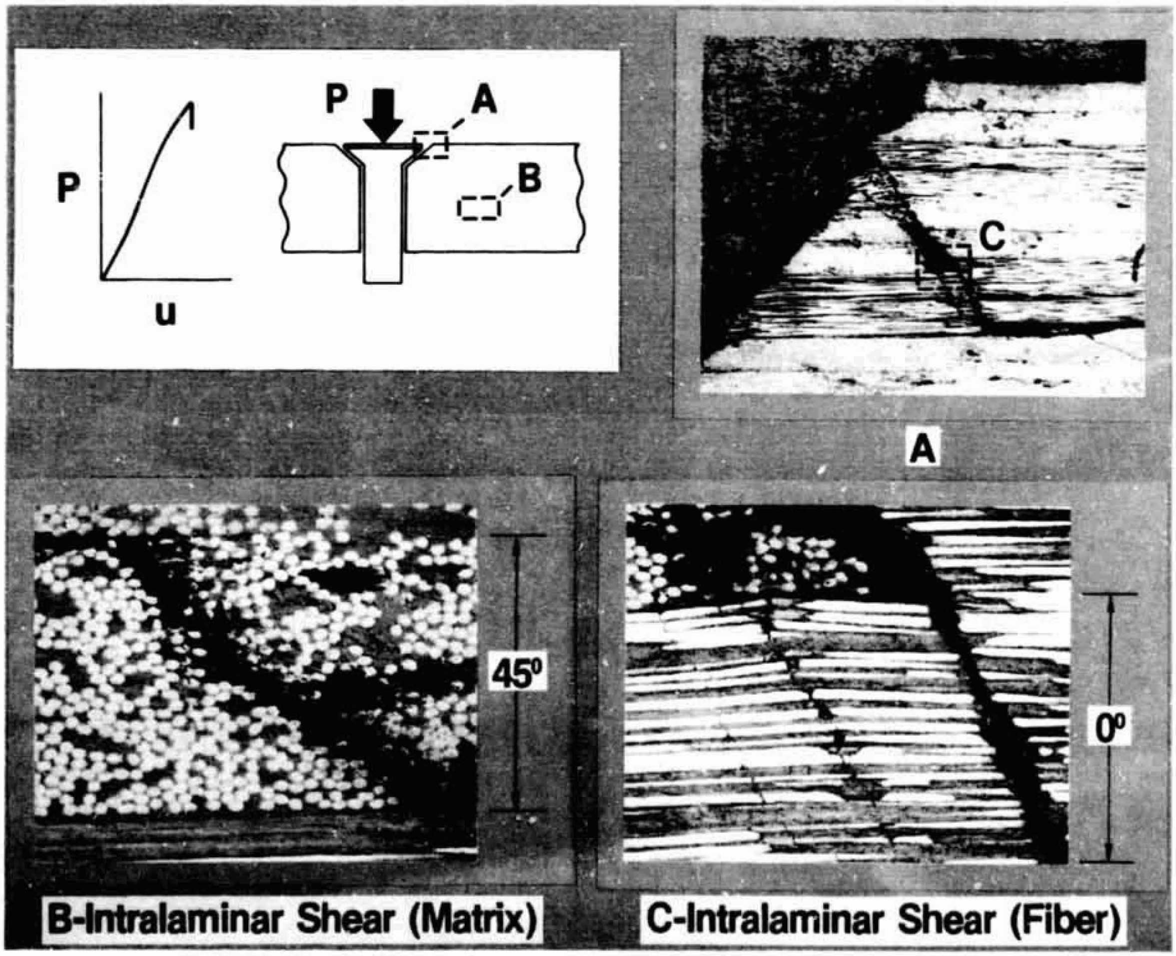


FIGURE 16. Failure characteristics at initial peak load for $[(\pm45/0_2)_2/\pm45/0/90]_{2S}$, T300/CIBA-4 laminate. One-inch diameter boundary support.

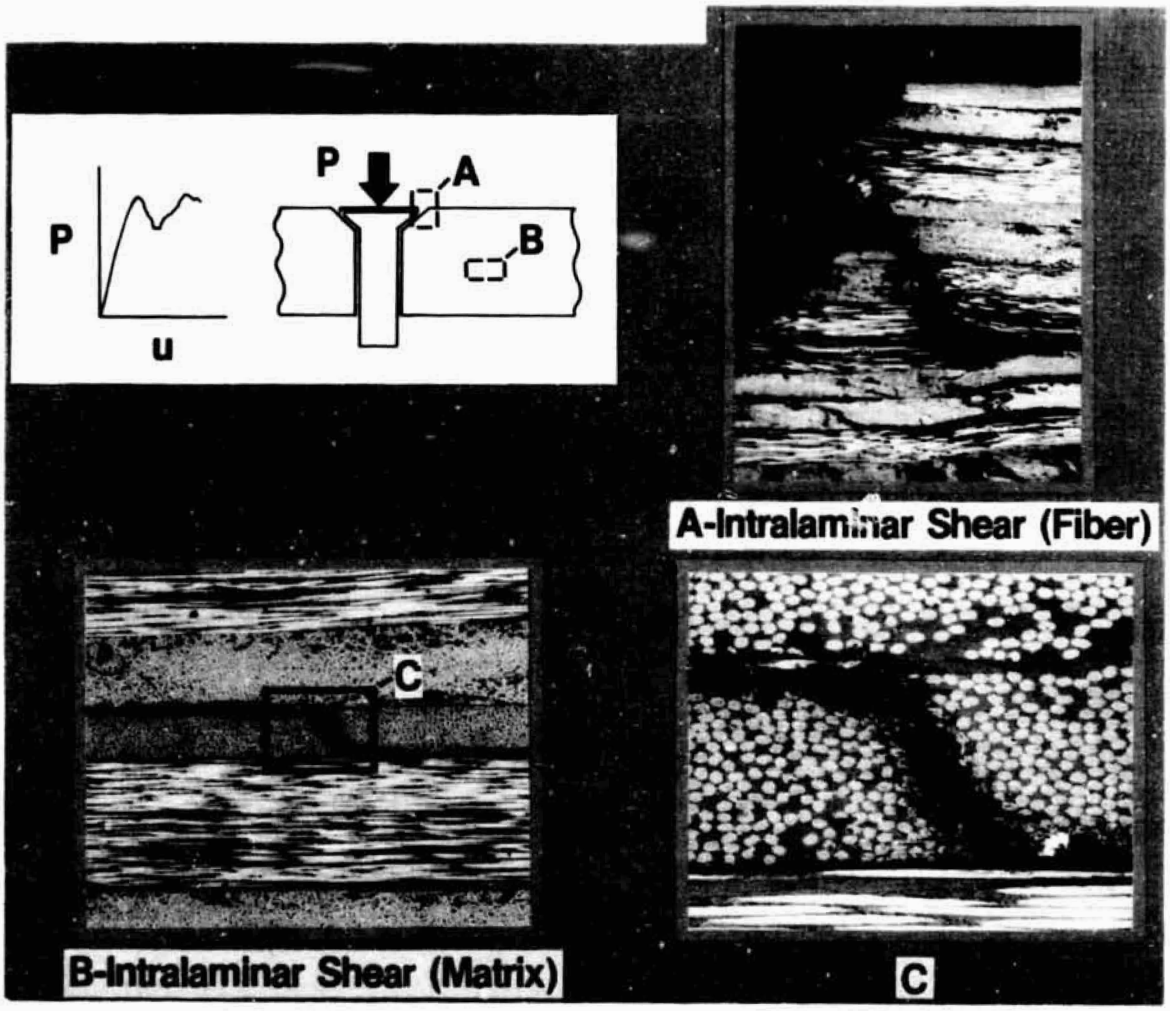


FIGURE 17. Failure characteristics at extended loading for $[(\pm 45/0_2)_2/\pm 45/0/90]_{2S}$, T300/CIBA-4 laminate. One-inch-diameter boundary support.

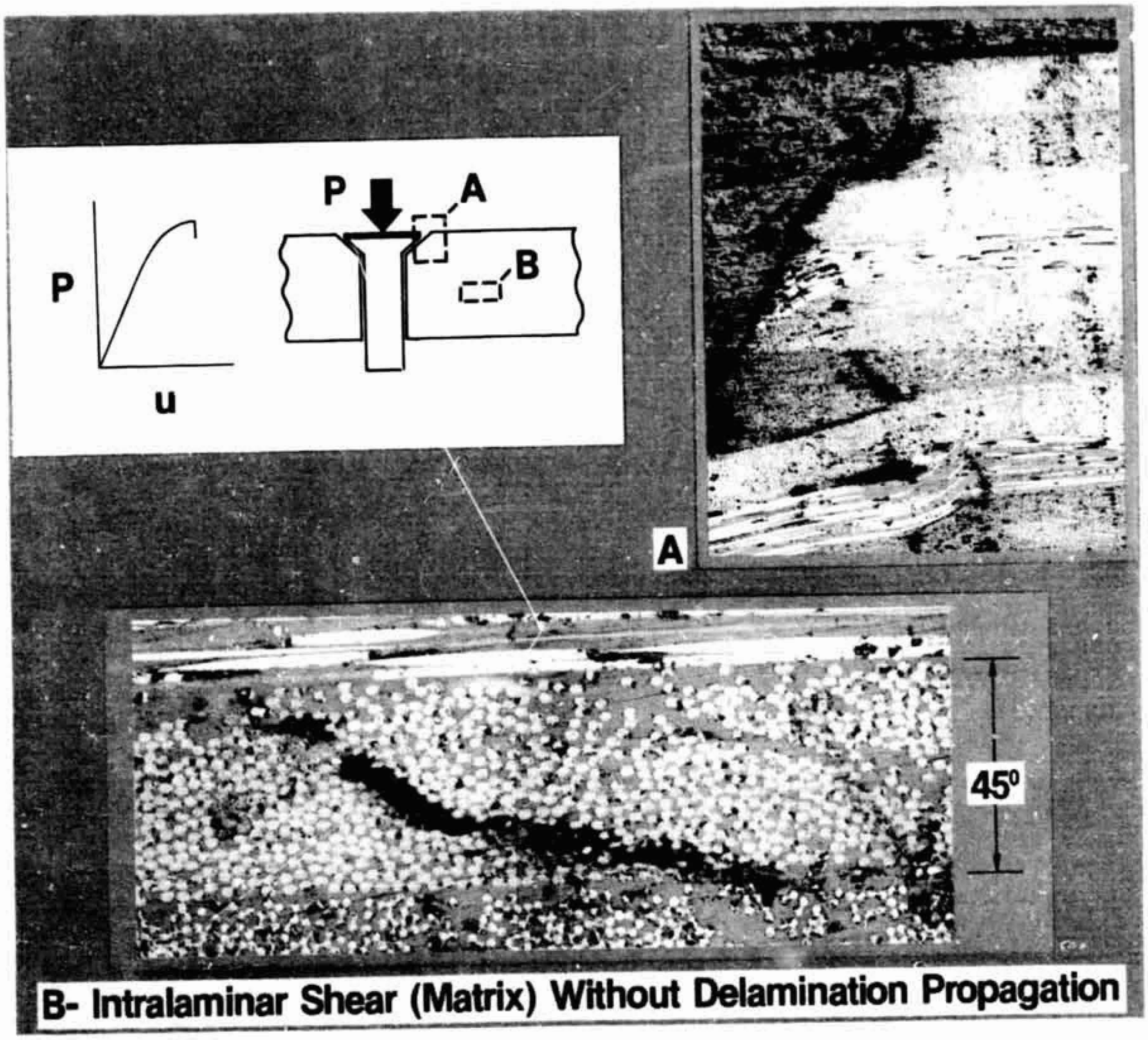


FIGURE 18. Failure characteristics at maximum load for $[+45/0/-45/90]_{6S}$, AS4/PEEK (APC2) laminate.

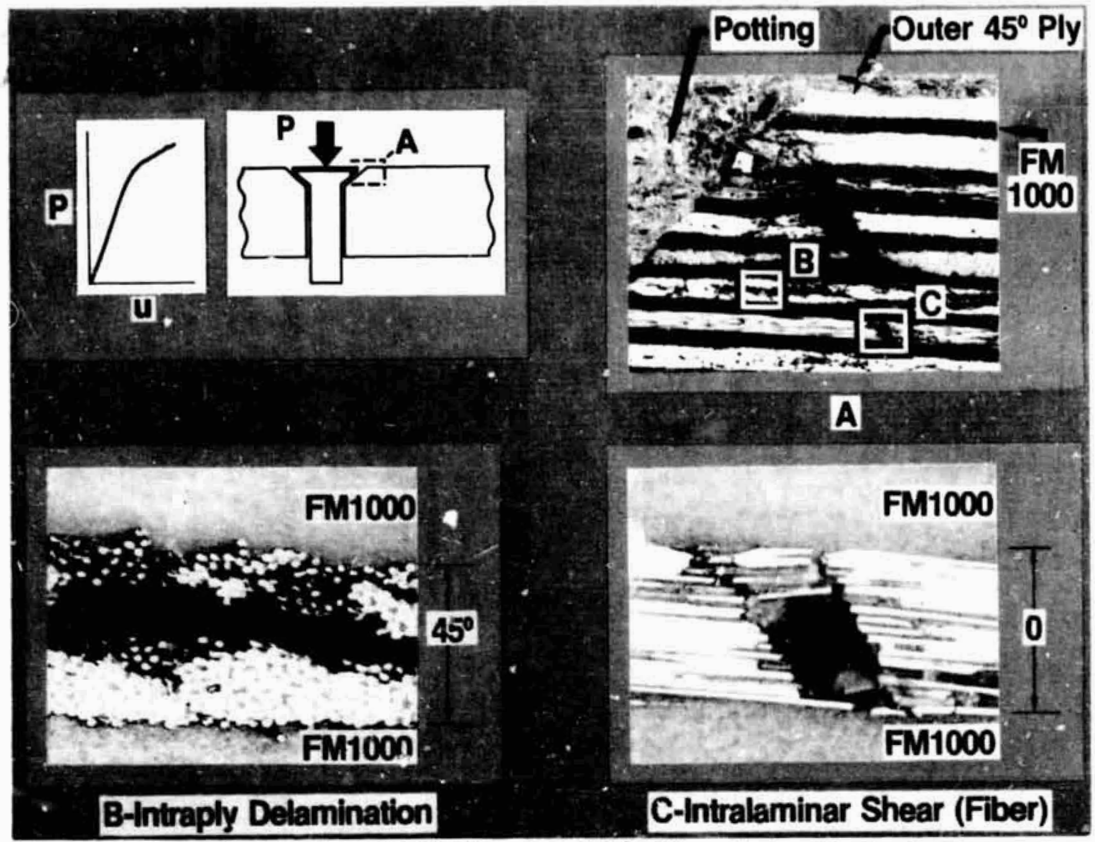


FIGURE 19. Failure characteristics for AS4/3502 orthotropic laminate with FM1000 interleave for applied load less than typical maximum capability.

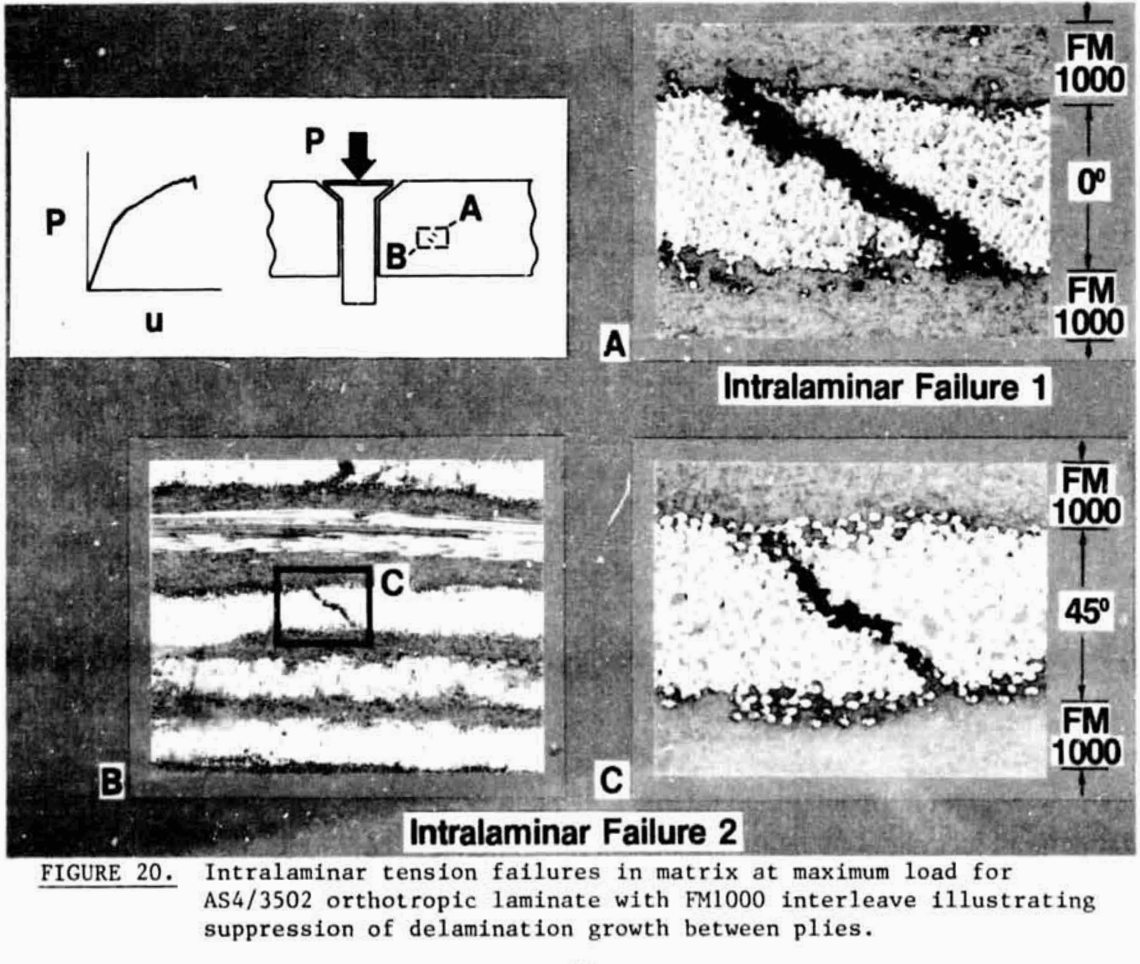


FIGURE 20. Intralaminar tension failures in matrix at maximum load for AS4/3502 orthotropic laminate with FM1000 interleave illustrating suppression of delamination growth between plies.

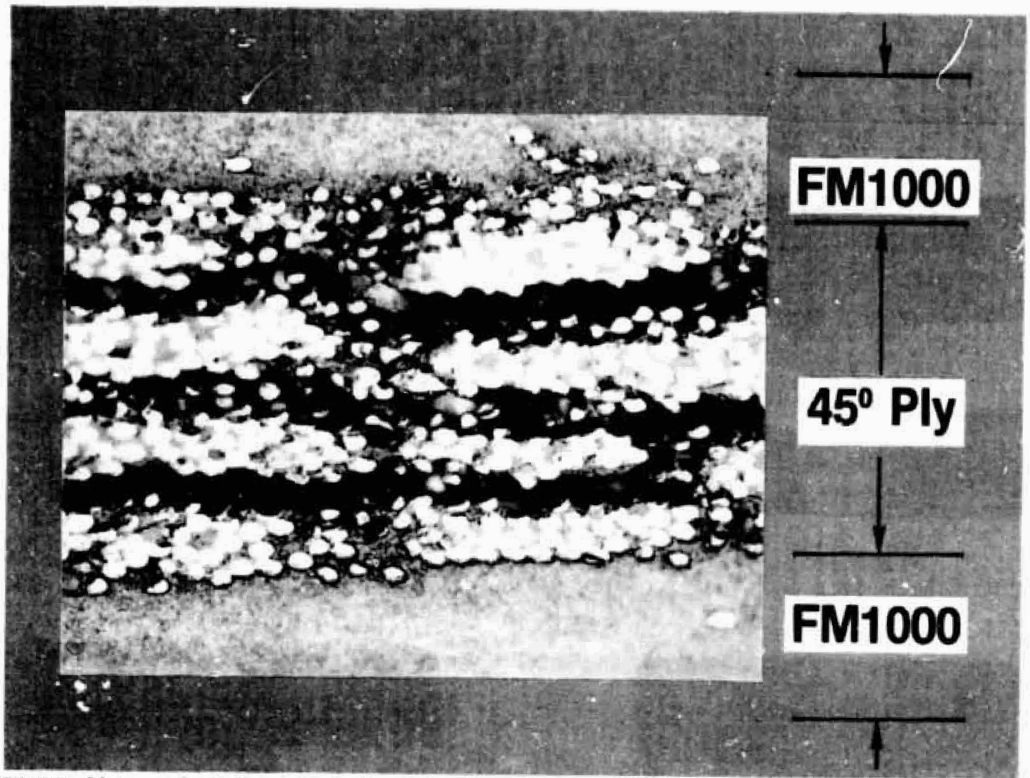


FIGURE 21. Multiple intraply delaminations exhibited by AS4/3502 orthotropic laminate with FM1000 interleave.

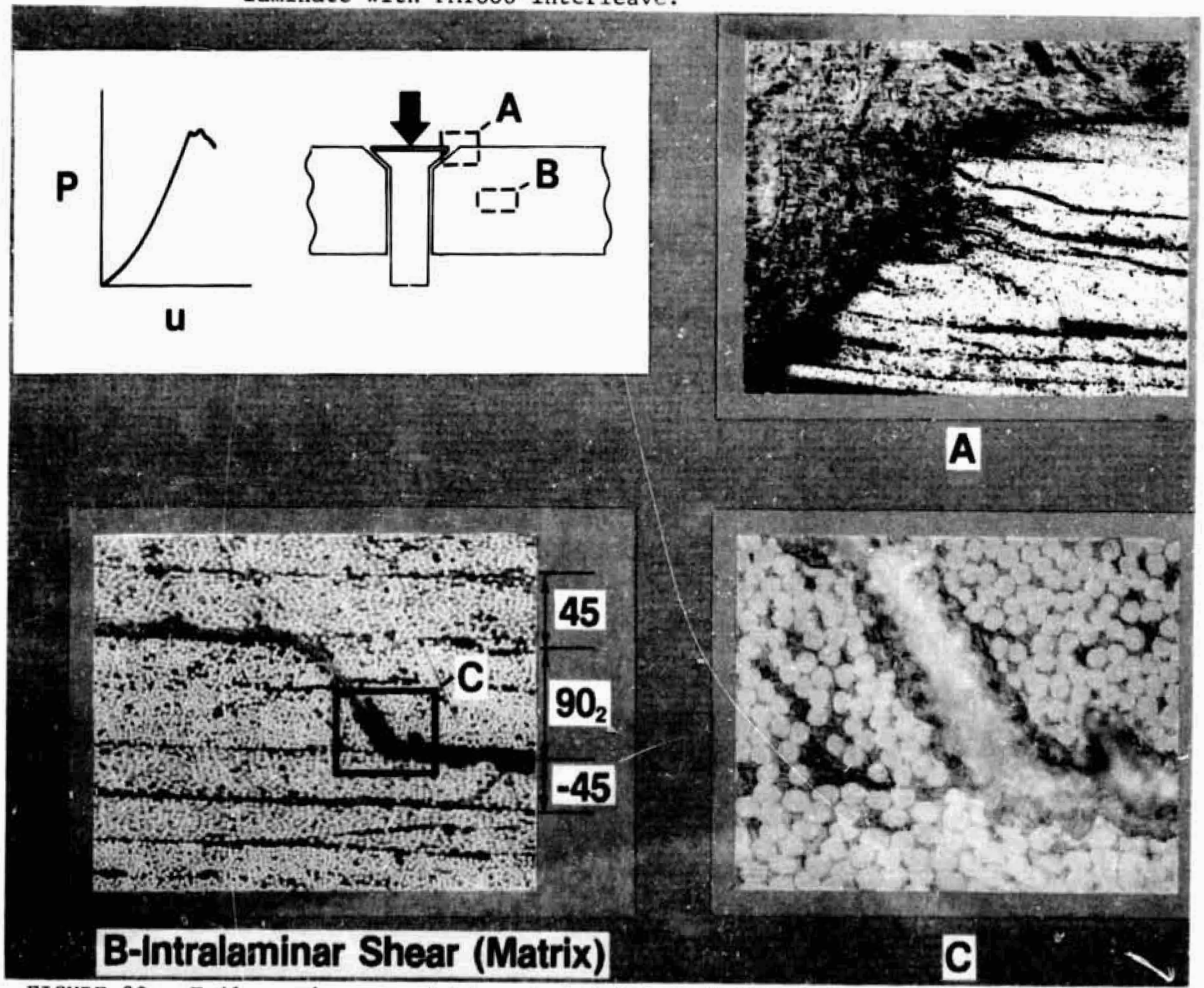
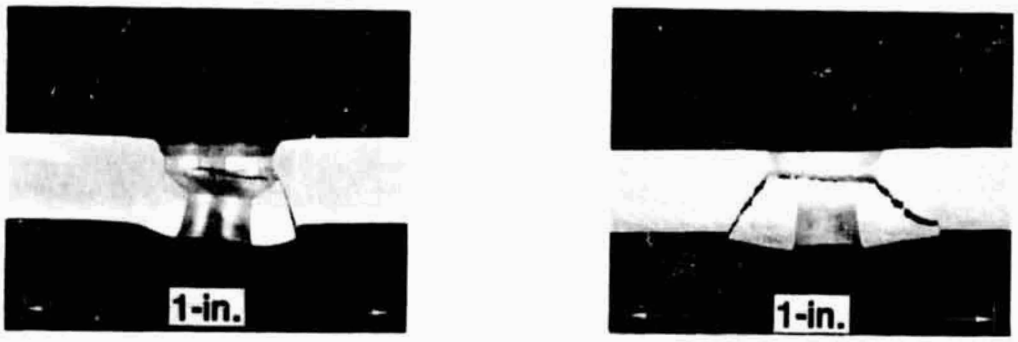


FIGURE 22. Failure characteristics at initial peak load for $[(\pm45/0_2)_2/\pm45/0/90]_{2S}$, Kevlar 29/3501-6 laminate.



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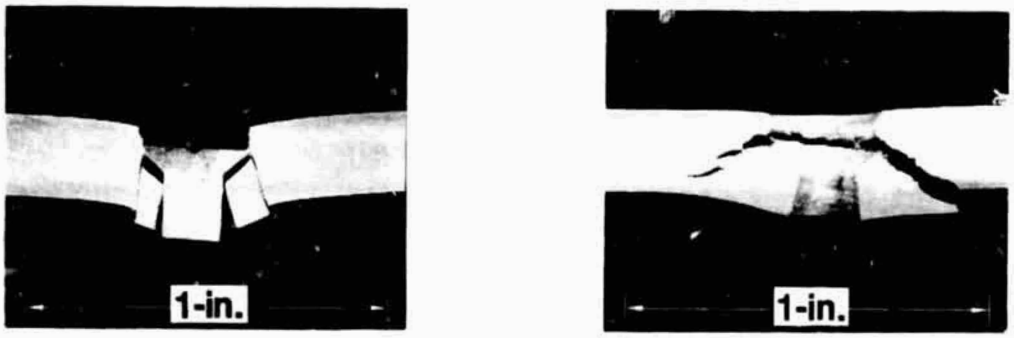
(a) 1-inch boundary.



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(b) 2-inch boundary.

FIGURE 23. Bolt push-through failure modes for aluminum.

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16. Abstract

Stiffened composite panels proposed for fuselage and wing design utilize a variety of stiffener-to-skin attachment concepts including mechanical fasteners. The attachment concept is an important factor influencing the panel's strength and can govern its performance following local damage. Mechanical fasteners can be an effective method for preventing stiffener-skin separation. One potential failure mode for bolted panels occurs when the bolts pull through the stiffener attachment flange or skin. The resulting loss of support by the skin to the stiffener and by the stiffener to the skin can result in local buckling and subsequent panel collapse.

This paper describes the characteristic failure modes associated with bolt push-through failure and presents the results of a parametric study of the effects that different material systems, boundary conditions, and laminates have on the forces and displacements required to cause damage and bolt push-through failure.

17. Key Words (Suggested by Author(s))
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