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THE EFFECTS OF EMBEDDED INTERNAL DELAMINATIONS ON COMPOSITE LAMINATE COMPRESSION STRENGTH; AN EXPERIMENTAL REVIEW

By Alan T. Nettles

Materials and Processes Laboratory
Science and Engineering Directorate

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Delaminations in laminated composite materials can degrade the compressive strength of these materials. Delaminations can form as a result of impact damage or processing flaws. In order to better understand the effects of these delaminations on the compressive behavior of laminated composite plates, programs have been conducted to assess the criticality of prescribed delaminations of known size, shape, and location on the compression strength of laminated composites. A review of these programs is presented along with highlights of pertinent findings from each.

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INTRODUCTION

Delamination of composite laminates is an issue that has been the focus of much attention. It has been shown both experimentally and analytically that laminates can have free edge effects which tend to deply the material at these free edges when the material is subjected to in-plane tensile loads.[1 2] For most practical cases, however, the delamination zone is restricted to the edges and does not grow into the laminate except at final failure.[3] However, it is entirely possible for delaminations to exist in a composite laminate at sites that are not at or even near a free edge. Such defects result from processing flaws and more commonly from foreign object impact damage.[4]

Delamination can be considered as "subcritical damage" in the sense that it usually does not cause immediate laminate failure when first formed. Delamination is a part of a series of events that can ultimately cause laminate failure. Stress redistribution and changes in local geometry due to delaminations cause further damage in a laminate.

Compressive loading tends to be a much more severe contributor to the growth of a delamination, as compared to tensile loading, due to local buckling of the delaminated plies (i.e., the delamination area can "bulge" out when loaded in compression and thus reduce the stability of the laminate). The growth of the delamination under compressive loads is dependent on many variables such as toughness of resin, initial size of delamination, depth of delamination, number of delaminations, and loading history.

By processing laminates with delaminations of known size, shape, and placement within the laminate, an experimental program can help identify the criticality of these delaminations and some of the mechanisms that are important to delamination growth.

THEORY

The compressive behavior of laminates containing delaminations can best be understood by examining a laminate with similar layers. Some playing cards from a deck provide a good analogy. Suppose about 10 cards from the deck are removed. Now imagine (or actually do this with a sacrificial deck of cards) the 10 cards placed together to form a thin deck. This represents an extreme case of total delamination between all layers of a laminate. By applying a compressive load to the ends of the cards, one can visualize (or actually see) the cards buckling and sliding across one another such that no appreciable load can be held by the cards. Now, if the cards are pulled at the ends in tension, quite a bit of load can be carried by the thin deck. Now suppose the 10 cards are bonded together (or actually glued together if using playing cards to perform this simple visualization experiment). When pulled at the ends in tension, the thin deck behaves much like it did before the layers were glued together. However, upon applying a compressive load the cards can carry much more load than when the cards were not glued together. This is because the cards cannot separate or slide across one another and buckle individually. As long as the cards are glued together, all of the 10 cards must buckle together. If only 5 of the 10 cards were glued together, the thin deck could still carry more load than if no cards were bonded together, but not as much load as if all the cards were bonded together. It is obvious that as the amount of bonding increases (less delaminations), the amount of compressive load that the cards can carry increases.

This is a very crude, but visually helpful, analogy of delamination in composite laminates. The individual cards, all similar in mechanical properties, represent the individual plies (laminae) of the composite. In actuality, the plies are of different fiber orientation, and, thus, effects due to anisotropy are expected to be observed. As mentioned in the introduction, tensile stresses can actually cause delaminations at free edges due to some of these effects. However, the focus of this report is on the effects of compressive loads on delaminations since these loads are known to be much more severe to delaminations.

As a delamination grows, it will tend to "blister out" due to local buckling (fig. 1). This blister can grow by the mechanisms shown in figure 2. Note the mechanisms are dependent on whether the blister is growing along or perpendicular to the direction of compressive loading. In general, mode I (peeling) delamination takes less energy to form a unit delaminated area than does mode II (shearing) delamination. Fiber orientation between delaminated plies can change the magnitude of these values.[5] In order to minimize the energy to fracture (delaminate), a delamination will want to grow in the direction of fibers of one of its interfaces, even if the delamination must "crack through" plies in order to find an interface which has its fibers aligned in the direction of peeling.[5] Thus, it is expected that delaminations will grow perpendicular to the applied load and along 90° fibers if possible (assuming the applied load is in the 0° fiber direction).

EXPERIMENTAL STUDIES

One of the first research papers examining the effect of prescribed, controlled delaminations on the compressive behavior of composite laminates was published by Konishi and Johnston.[6] They examined the effects of circular delaminations embedded between the third and fourth plies ([+45/-45] interface) of 24-ply $[90/0/+45/-45]_{3S}$ laminates of AS-4/3501-5 material. Three different delamination diameters were used, 6.35, 12.7, and 25.4 mm (0.25, 0.55, and 1 in), all placed at the center of a 38.1-mm wide by 50.8-mm long (1.5- by 2-in) gauge length test coupon. In order to prevent global buckling of the specimen during compression tests, a pair of antibuckling faceplates were used to support the gauge length. These faceplates contained 25.4-mm (1-in) square cutouts such that the delamination could bulge out. Figure 3 is a schematic of a typical antibuckling jig that is used in many of these studies. Proof testing was performed in both tension and compression. For the tensile loads, the delamination did not grow. However, for the compression tests, the delamination grew a significant amount, and the remainder of the test program concentrated on the effects of compressive loads (both static and dynamic) on the test coupons.

For static loading, it was found that the delamination grew in a stable manner as an ellipse with its major axis perpendicular to the loading direction. Upon encountering the edge of the faceplate window, the delamination continued to grow, but at a slower rate. Near the highest loads tested, the delamination showed some growth in the ±45° directions. For fatigue loading, the delaminations grew in a similar manner. The 25.4-mm (1-in) diameter delaminations quickly grew to the edge of the test specimen. For the 12.7- and 6.35-mm (0.5- and 0.25-in) delaminations, the delamination growth was in a direction perpendicular to the applied load. In some of the specimens, growth in the ± 45° direction was seen. Note that the delamination growth was stable in all of the specimens tested.

The specimens that had been subjected to compressive loads to make the delaminations grow were subsequently tested for ultimate compressive strength. The specimens with larger delaminations, caused by either fatigue or static loading, failed at a lower stress value. The most significant observation was the large amount of scatter that existed in these data for the fatigue loaded specimens. As the number of fatigue cycles increased, the scatter in ultimate compressive strength data increased.

Byers[7] examined the effects of embedded delaminations on 36- and 38-ply laminates. The layups were $[\pm45_2/0_2/\pm45/90/\pm45/0/\pm45/90/\pm45_2]_S$ = 38 plies and $[\pm45/0/90/0/90/\pm45/0/90/0/90/\pm45/0/90/\pm45]_S$ = 36 plies. Two epoxy resins were examined, one brittle and one toughened. Both fatigue and static compressive loads were used to fail the specimens. For the static case, three different delamination diameters were used, 12.7, 25.4, and 38.1 mm (0.5, 1, and 1.5 in). These were placed either 4, 6, or 12 plies deep (i.e. a [90/0], [90/+45], or [90/+45] interface for the 36-ply specimen or a [-45/0], [0/+45], or [0/+45] interface for the 38-ply specimen). For the fatigue case, only the 38-ply specimens were tested. Moire techniques were used to monitor delamination growth. The specimens were compressed using a Boeing CAI device with the specimen size being 10.16-cm wide and 15.24-cm high (4-in wide and 6-in high).

Results showed that the delamination grew perpendicular to the loading direction in all cases where delamination growth occurred. For the toughened epoxy resin system loaded in fatigue, the embedded delamination never grew appreciably, rather failure was initiated by delaminations and broken fibers near the ends of the specimen (where stress concentrations are more likely to exist). This demonstrates that the postdelamination behavior of a composite laminate is heavily dependent upon the toughness of the matrix, especially in fatigue loading. The drop in ultimate compressive strength due to the delaminations was surprisingly small. This is attributed to the fact that the deep (12 ply) embedded delaminations did not "buckle out" to cause instability, and the 6- and 4-ply deep embedded delaminations, which did blister out, were such a small fraction of the cross sectional area of the composite that little strength loss was seen, even though the remaining base laminate was unsymmetric. The use of a large plate that is not laterally supported at the edges could also explain this, since a panel should be at least 48 plies thick to be used with this test fixture. The failure may have been precipitated by gross buckling.

Ramkumar[8,9] published experimental work on growth of embedded delaminations. In this investigation, 64-ply laminates of carbon/epoxy contained embedded circular delaminations of 12.7 mm (0.5 in) in diameter at the interface between the first and second plies, or between the fourth and fifth plies. Three layup configurations were tested, $[0/+45/90/-45]_{8S}$, $[+45/90/-45/0]_{8S}$, or $[90/45/0/-45]_{8S}$. The test coupons had a gauge length of 38.1-mm wide and 38.1-mm high (1.5-in wide and 1.5-in high). The delamination was placed at the center of the gauge length. No faceplates to prevent global buckling were needed in this study since the specimens had a large thickness-to-height ratio. Both static and fatigue loading were examined in this study. For both types of loading, delamination "failure" was defined to have occurred when the delamination grew into the tabbed region of the specimen. It must be noted that for unflawed specimens, the static strength was dependent on the orientation of the outermost ply. The specimens with 0° plies on the outside were the strongest, followed by specimens with 45° outside plies being the next strongest, and specimens with 90° outside plies were the weakest. This is in contrast to Byers' findings[7] and further supports the argument that the specimens in that study experienced Euler buckling since Ramkumar has shown that even for a 64-ply laminate, the outermost ply *does* matter in compression strength.

For all of the statically loaded specimens, no stable delamination growth was observed. Thus, only strength data are presented. For specimens with outer ply orientations of either 45° or 90°, an embedded delamination under the top ply did not reduce the compressive strength of the specimen. For the specimens with a 0° outer ply, the compressive strength was reduced by approximately 30 percent when a delamination was placed below the top ply. When the delamination was placed between the fourth and fifth plies, a strength degradation occurred for all specimen layups. A 34-percent strength degradation occurred for the specimens with a 0° outermost ply, and a 20-percent strength degradation was observed for both of the remaining layup configurations.

For specimens loaded in fatigue with embedded delaminations between the fourth and fifth plies, the life expectancy was longer than for embedded delaminations below the outermost ply for all three layup configurations. For delaminations located under the surface ply, if the surface ply was at an orientation of 0° or 45°, then the delamination grew in a stable manner. If the surface ply was at a 90° orientation, the embedded delamination did not grow at all. The delamination growth pattern for the 0° outer ply specimens consisted of delamination extension in the direction of the applied load (along the 0° fibers). For these specimens, the delamination did not grow more than the width of the embedded delamination. For the specimens with a 45° outer ply embedded with a delamination below this ply ([45°/90°] interface), the growth was perpendicular to the loading direction with some growth in the ±45° direction being observed. If the delamination was between the fourth and fifth plies, delamination growth was unstable and occurred only right before specimen failure. If the outer ply was at 0° (which meant the delamination was at a [-45°/0°] interface, the delamination grew in segments along the 0° fiber direction, with the segments running along the ±45° direction. If the outer ply was oriented at 45° (delamination at [0/+45°] interface), then the unstable delamination growth consisted of segments peeling away in the 45° direction with the segments aligned in the 90° direction (perpendicular to the applied load). For the specimens with a 90° outside ply (a [-45/90] interface), the delamination grew perpendicular to the loading direction along the 90° fibers, spreading out in a parabolic shape to one of the edges.

Some of the specimens in this study were fatigue loaded for one-half their fatigue life and subsequently tested for residual strength. For all of the specimens in which the delamination was between the fourth and fifth plies, the half-life fatigue loading did not degrade the strength. This finding is not surprising since the delaminations embedded at this interface showed unstable growth only just before catastrophic failure. If the delaminations did not grow, no loss of strength should be expected. If the delamination was one ply down, a small decrease in residual strength was seen. The thickness of these specimens (64 plies) makes the loss of an outer ply less significant.

Mousley[10] presented a paper on the effects of imbedded delaminations and impact damage on carbon/epoxy coupons. He used 24-ply $[0/+45/-45/90]_{3S}$ laminates with an embedded delamination between the second and third plies ([+45,-45] interface). These delaminations were rectangles of size 25.4 by 19 mm (1 by 0.75 in) and were oriented with the long side either perpendicular or parallel to the loading direction. The test coupons were 100-mm (3.94-in) wide and used a face supporting antibuckling jig to prevent global buckling. The antibuckling jig had a window of 56 by 75 mm (2.2 by 2.95 in) through which the delamination blister could deform in the out-of-plane direction. Shadow moire was used to monitor the out-of-plane deflection of the delamination blister. Results showed that for the case in which the long side of the rectangular delamination was oriented perpendicular to the load, the delamination grew in a quasi-stable (in steps) manner in a direction perpendicular to the applied load. If the delamination was oriented such that its long side was parallel to the loading direction, then the delamination formed two blisters that grew independently. The two blisters formed because there was sufficient length in the loading direction for the blister to form a double wave. These blisters also grew perpendicular to the loading direction. The specimens were statically loaded to failure; however, quantitative results were not given except for compression-after-impact data which is beyond the scope of this paper.

An attempt to measure the loss of structural stiffness due to an embedded delamination was performed by Reddy et al.,[11] who embedded various sizes of rectangular delaminations at the mid-plane of a 16-ply $[+45,-45,0,90]_{2S}$ laminate. The stiffness of the laminated panels was determined by global buckling tests on the test specimens. The results showed no loss in stiffness. However, since the delaminations were located at the midplane of the plates and in light of the criticality of their proximity to the surface (as demonstrated by Ramkumar[8] and Konishi and Johnston[6]), the results are not surprising.

A group of more recent papers have examined the effects of embedded delaminations in more detail. Doxsee et al.[12] used a transversely loaded plate to cause delamination growth in an attempt to characterize impact damage using quasi-static loading. Also, the strain energy release rate of delamination formation was calculated and compared to values obtained by standardized tests for mode I and II fracture. Sixteen-ply $[0_4,90_4]_S$ carbon/epoxy specimens were embedded with a 20-mm (0.787-in) diameter circular delamination between the [0/90] interface closest to the bottom of the plate. The plate was simply supported over a 40-mm (1.575-in) square frame and point loaded with a 10-mm (0.4-in) diameter hemispherically ended tup. The embedded delamination was at the center of the area of the plate which was loaded to a prescribed deflection and then unloaded. Force displacement curves were generated, and the specimens were examined for extent of damage by either c-scan, x ray, or cross sectioning. For a deflection of 0.8 mm (0.03 in), matrix cracks were observed in the bottom 0° plies and middle 90° plies. (The nomenclature for the ply orientations could be switched since the specimen was a transversely loaded square plate.) At a deflection of 1 mm (0.039 in), a delamination in the direction of the bottom set of fibers (0°) began to propagate from the end of the crack in the center group of plies (90° plies). At this point, the matrix cracks ran completely through the bottom set of 0° plies and the center group of 90° plies. The only undamaged plies were the upper four plies of 0° material. At 1.2 mm (0.047 in) of deflection, the delamination had grown more in the 0° direction, and another crack had formed in the middle group of 90° plies. Upon loading to 1.4 mm (0.055 in), a third matrix crack formed in the center group of 90 plies, and a delamination began to propagate in the 0° direction between the [0/90] interface closest to the top of the specimen, again forming from the end of a crack in the middle group of 90° plies. The energy needed to form cracks was measured from the load/unload-displacement curves. For deflections up to 0.8 mm (0.032 in), most of the energy went into forming matrix cracks. For displacements greater than this (displacements that caused delamination), most of the energy released was due to growth of delaminations. The energy to form a unit area of delamination was calculated as ~600 J/m^2 (3.4 in-lb/in^2) and was consistent between all tests. For the material tested, a mode II energy release rate of this magnitude is close to measured values for a [0/90] interface. No in-plane loading was performed in this study.

Greenhalgh[13] examined the effects of embedded delaminations in test coupons and stringer panels. A stringer panel is a structural element consisting of a flat laminate stiffened by composite I-beams. The coupons consisted of 24-ply $[+45/-45/90/0]_{3S}$ carbon/epoxy specimens embedded with a rectangular delamination of dimensions 25 by 19 mm (1 by 0.75 in) with the long side oriented perpendicular to the loading direction, placed between the fourth and fifth plies ([0/+45] interface). The specimen was 75-mm wide and 230-mm long (3-in wide and 9-in long) and had an antibuckling jig attached to the faces to prevent global buckling. The antibuckling jig had a window of size 40 by 50 mm (1.57 by 1.97 in) so that the embedded delamination could grow out-of-plane. The coupons were loaded in static compression and the delamination growth was monitored via shadow moire. After failure, the specimens were dissected and the fracture surfaces were examined with a stereo-optical and electron microscope so the mode of fracture could be determined for different regions. For coupons loaded in static compression, the embedded delamination grew perpendicular to the loading direction for a small amount and then propagated between the third and fourth plies, a [0/90] interface, and continued to grow along this interface. Upon postfailure analysis, it was observed that at the embedded delamination, mode II fracture dominated, and, when the delamination was propagating along the 90° direction, mode I peel dominated. These specimens are direct evidence that delaminations, in general, have a very strong tendency to propagate in the direction of fibers of one of the two interfaces occupied. Since delaminations grow in mode I peeling perpendicular to the direction of load and in mode II shear in the direction of the applied load and given that mode I fracture requires less energy, the delamination will want to grow perpendicular to the applied compressive load in the direction of a 90° ply (direction of least resistance). Experiments conducted on the stringer panels showed similar results as for the coupons. Worth noting is that different sizes of delamination were embedded in the stringer panels, yet the micromechanisms of delamination growth remained the same.

The effects of embedded delaminations in a thermoplastic matrix were studied by Pavier and Chester.[14] The carbon/polyetheretherketone (PEEK) specimens were 250-mm (9.8-in) long 18-ply $[+45/-45/0_3/+45/-45/0_2]_S$ coupons, 50-mm (2-in) wide with delaminations of either 12 by 12 mm (0.47 by 0.47 in) or 25 by 19 mm (1 by 0.75 in), embedded at one of two sites within the laminate at the boundary between the third and fourth plies (a [0/0] interface), or between the fifth and sixth plies (a [0/+45] interface). Global buckling was prevented by the use of faceplates, with a window of size 100 by 28 mm (3.9 by 1.1 in) to allow the embedded delamination to blister out-of-plane. Results of static compression tests showed that the delaminations did not grow an appreciable amount before specimen failure. Residual strength was only slightly less than for an unflawed specimen. This demonstrates the radically different fracture behavior that a tough matrix resin can exhibit.

Whitcomb[15] also examined PEEK and an epoxy resin AS4/PEEK 8-ply specimens with a layup of $[0/90/90/0]_S$ or $[90/0/0/90]_S$ were fabricated with either a 30-, 40-, or 60-mm (1.18-, 1.57-, or 2.36-in) diameter circular delamination embedded at the midplane of the specimen. IM7/8551-7 carbon/epoxy specimens were fabricated that consisted of 24 plies in a layup configuration of $[0/90/90/0]_{3S}$ or $[90/0/0/90]_{3S}$. An embedded circular delamination of 30-, 40-, or 60-mm (1.18-, 1.57-, or 2.36-in) diameter was inserted between the fourth and fifth plies (a [90/90] or [0/0] interface). As in most of the previous tests, global buckling of the specimen was prevented by using faceplates with a cutout for the delamination to bulge out of plane. Static tests on the PEEK specimens did not cause delamination growth, but fatigue loading did cause some growth. The growth that was observed propagated in a stable manner perpendicular to the applied load. If the delamination was traveling against the fibers (across a [0/0] interface), the growth was small and did not grow into an interface with fibers at 90°. If the delamination was at a [90/90] interface, the growth was more extensive, indicating that even in tough resins, the delamination propagates most easily along the direction of fibers in one of the interfaces. Even though the epoxy is a toughened system, delamination growth during static loading was observed. The growth patterns were similar to the fatigue loaded PEEK specimens. If a delamination was propagating perpendicular to the fibers in a [0/0] interface, the delamination would switch interfaces via matrix cracking so it could travel with the fibers at a 90° interface within the sublaminate. Also, delamination growth was seen to start at a lower stress level when the delamination was at a [90/90] interface. Approximately 30 percent more stress was needed to initiate delamination in the [0/0] interface since the delamination grew perpendicular to these fibers.

The effect of mode II shear stress on embedded delaminations was examined in references 16 and 17. Shear stresses were induced by performing three-point bend tests on 64 ply $[0_4/(+45/-45)_2/(-45/+45)_2/0_4]_{2S}$ composite beams. The beams were 7.62 cm (3 in) wide with a span of 15.24 cm (6 in). The delaminations were circular with diameters of 25.4, 31.75, or 38.1 mm (1.0, 1.25, or 1.5 in), placed at two locations at the midplane ([0/0] interface) of the beam. The delaminations were located 5.08 cm (2 in) from the center of the beam in each of the two directions longitudinal to the beam. Some delaminations were placed between the 16th and 17th plies (([0/0 interface) compressive side of the beam), or between the 32nd and 33rd plies (([0/0 interface) tension side of the beam). These locations, not at the midplane, would produce some mode I peeling stresses in addition to the mode II shearing stress. The static strength of the beams was not greatly affected by the presence of the delaminations, unless the delaminations were large (138.1 mm (1.5 in)). For fatigue loading, it was observed that the delamination grew as an ellipse with its major axis along the length of the beam. The growth tended to be toward the center of the specimen where the bending stresses are higher, indicating that some mode I fracture was responsible for the delamination growth. If the delamination was not at the midplane of the laminated beam, then more mode I fracture was present and the delamination grew slightly faster.

The same fatigue tests were performed on off-axis specimens with a layup of $[+15_4/(+60/-30)_2]_{S4}$ or $[+30_4/(+75/-15)_2]_{S4}$. This indicated that the delaminations at the midplane of these beams were at either a [+15/+15] interface or at a [+30/+30] interface. The delaminations tended to grow in the direction of the fibers at its interface in these tests, much like the results seen for delamination growth due to mode I fracture.

Across-the-width delaminations were implanted in 25.4-mm (1-in) wide specimens to determine the effect of "sharp" versus "blunt" delamination fronts. Embedded delaminations have blunt edges since they are processed within the laminate. The "sharp" delaminations were produced by fatigue loading of three-point bend specimens with small delaminations and allowing the delamination to grow to a given size (as measured by C-scans). The results showed no difference in values calculated for strain energy release rate between the "sharp" and "blunt" specimens. Maximum load to failure was also unaffected. This helps to validate the use of process embedded delaminations to represent naturally occurring delaminations, at least for mode II fracture.

DISCUSSION AND CONCLUSIONS OF EXPERIMENTAL STUDIES

As noted earlier, many of these studies used faceplates to support the specimen gauge length during compression loading. It has been shown[18] that the size effect of the window cut into the faceplates can affect compression strength values to some degree since the boundary where the edge of the window lies prevents delaminations from "bulging out" as they tend to do. Thus, ultimate strength values, especially for near surface delaminations, cited in the studies that used faceplates must be used with caution.

Figure 4 is a schematic summary of the test specimens and supports used in the experimental studies cited in this report. These are included to help the reader visualize the type and scale of the test specimens, faceplates, and embedded delaminations in each of the studies.

Some conclusions that have been drawn from these embedded delamination studies are:

(1) Delaminations tend to grow along a fiber direction in one of its two interfaces.

(2) For in-plane compression loads, the delamination tends to grow perpendicular to the direction of the applied load.

(3) Delaminations do not cause appreciable degradation of tensile strength of a laminate.

(4) For transversely applied loads, mode II fracture dominates at the ends of the delamination along the direction of bending. Only for delaminations on the order of one-half the specimen width did a delamination-induced failure occur in the specimen.

(5) Usually a mixed mode fracture occurs consisting of modes I, II and III. There are components of peeling, shearing, and tearing.

(6) A delamination can jump interfaces if doing so will mean less strain energy is needed for delamination growth. The lowest energy needed for growth is along a fiber direction in mode I fracture (peeling).

(7) Tough matrix resins can greatly reduce the tendency for a delamination to grow.

(8) Embedded delaminations do not accurately represent impact damage-induced delaminations. The impact-induced delaminations can occur on many planes and result in extensive matrix cracking. Thus, impact damage-induced delaminations cause a much larger reduction in compression strength than an embedded delamination of equal size.

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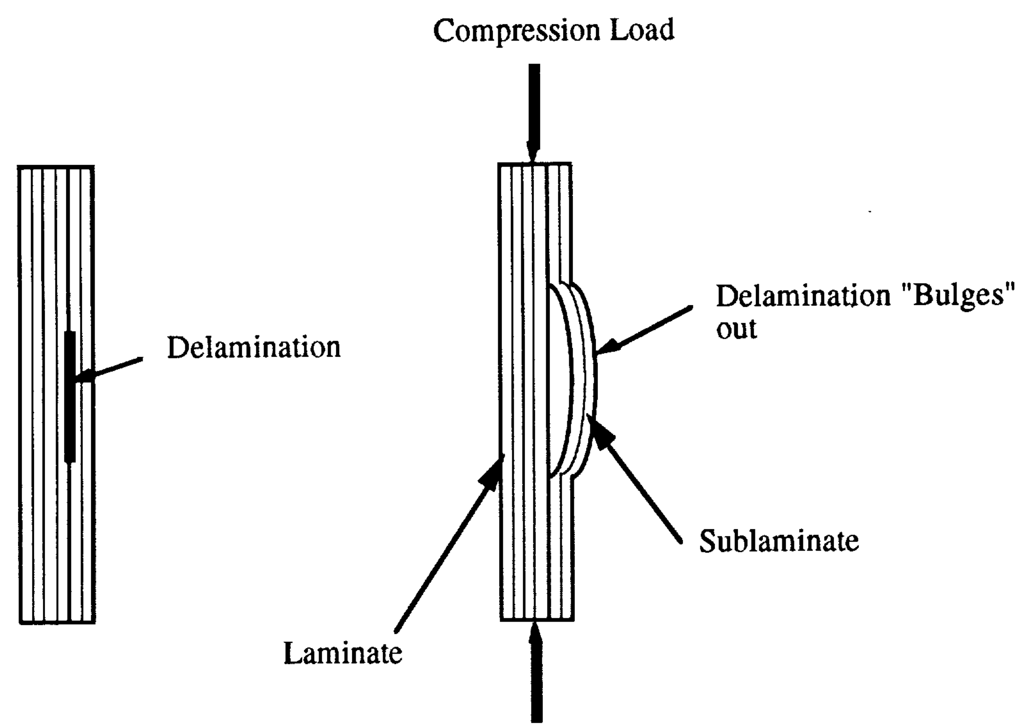


Figure 1. Out-of-plane deformation of a delamination.

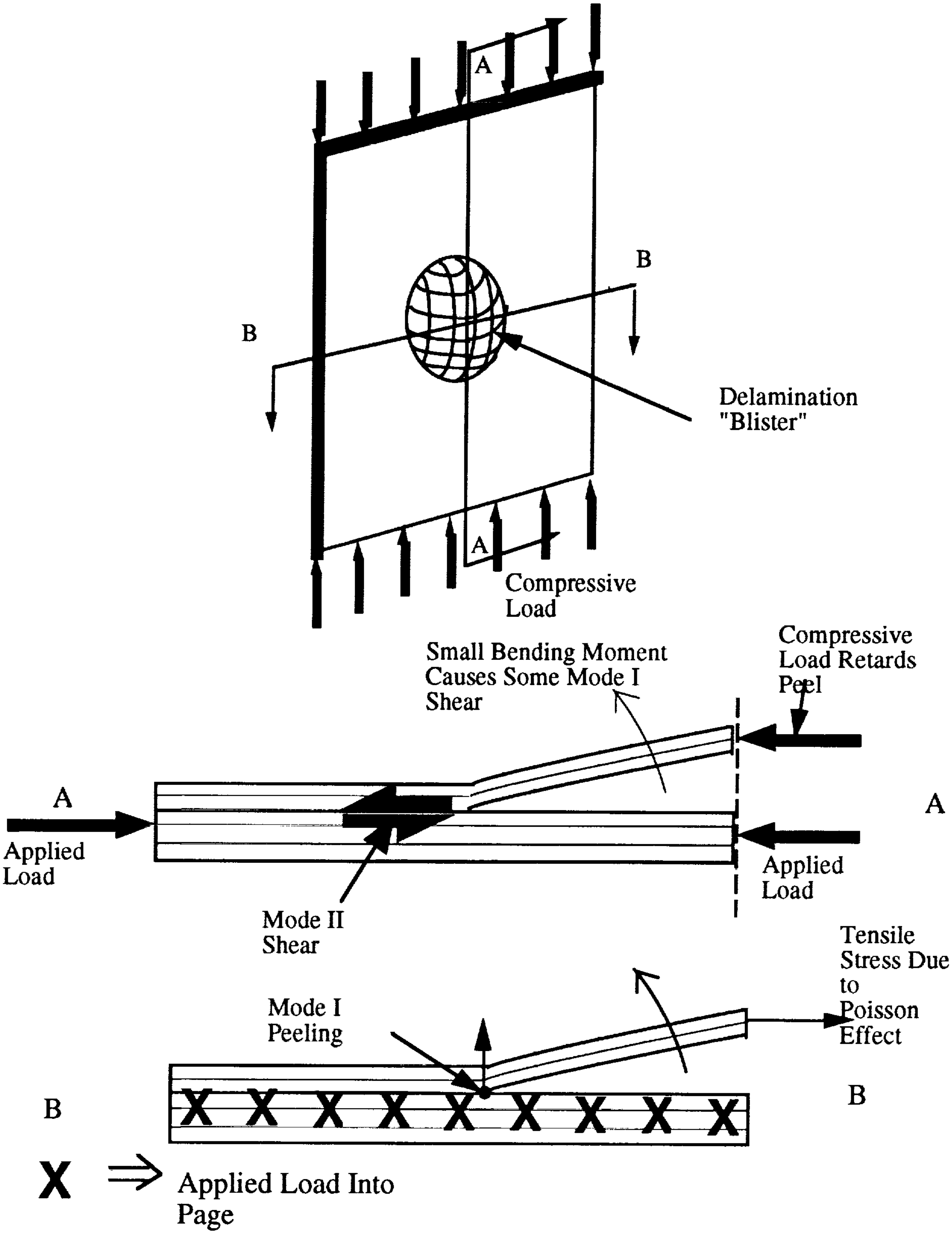


Figure 2. Mechanisms of delamination growth.

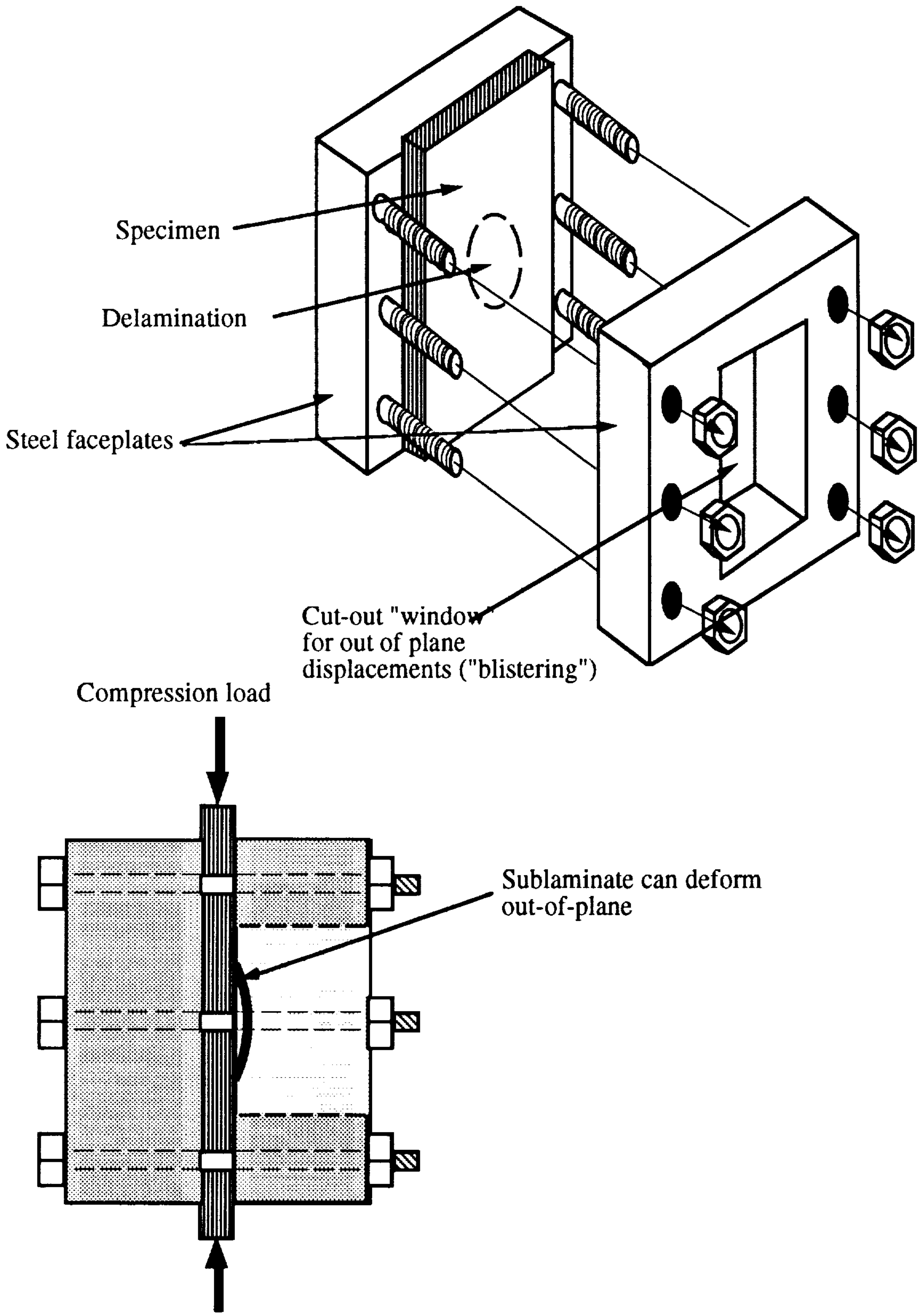


Figure 3. Typical antibuckling jig assembly.

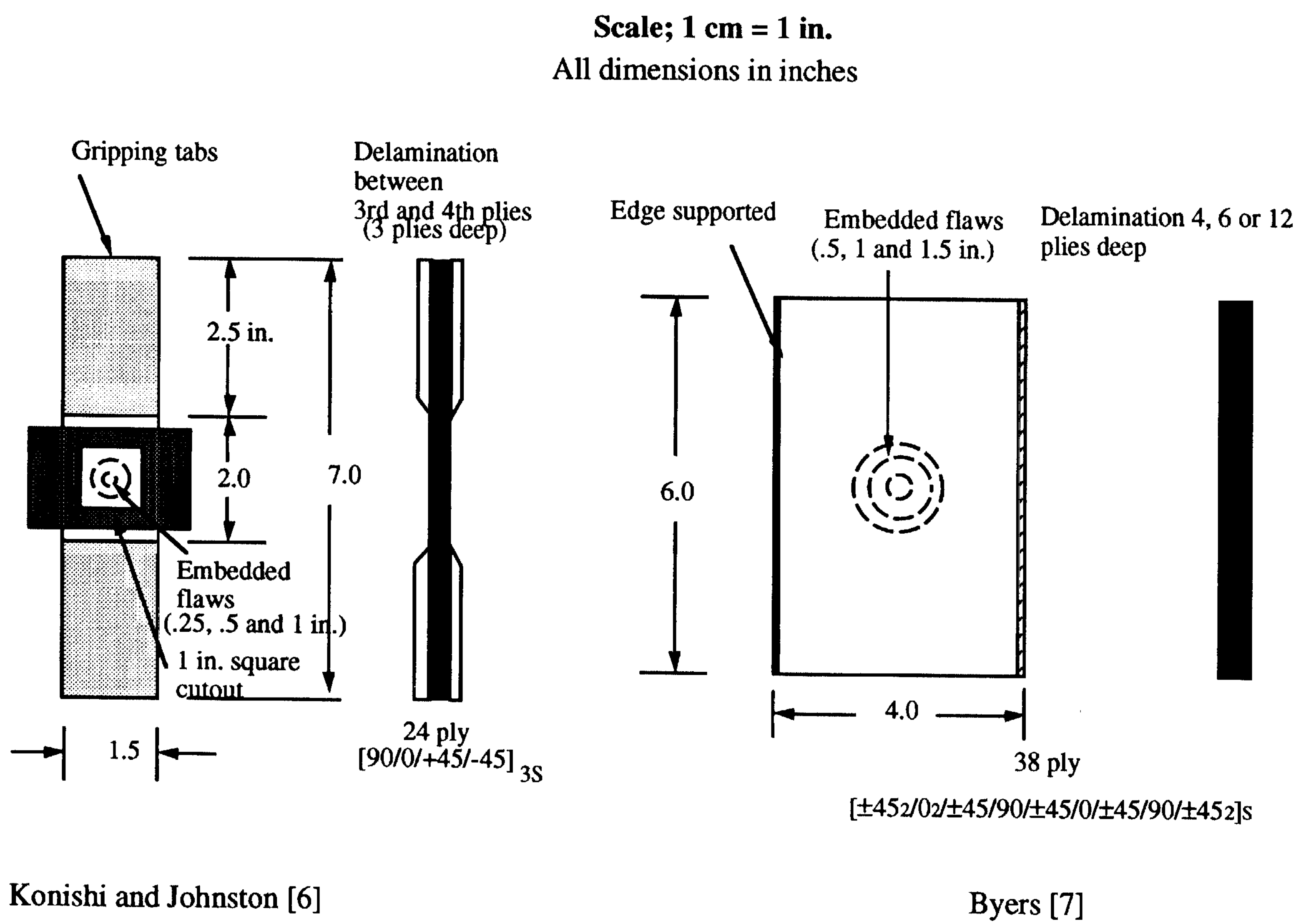


Figure 4. Drawings of specimens used.

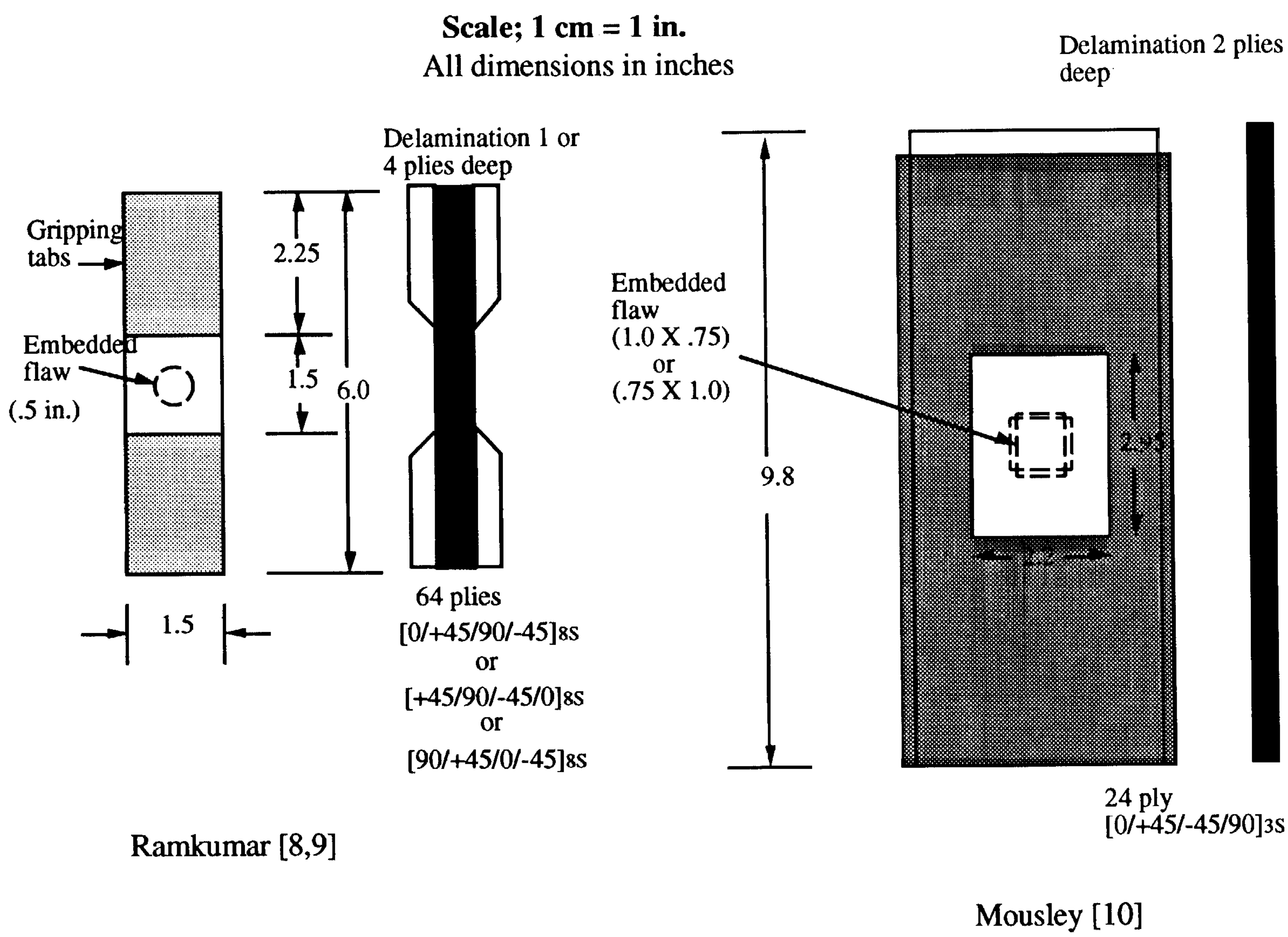


Figure 4. Drawings of specimens used (continued).

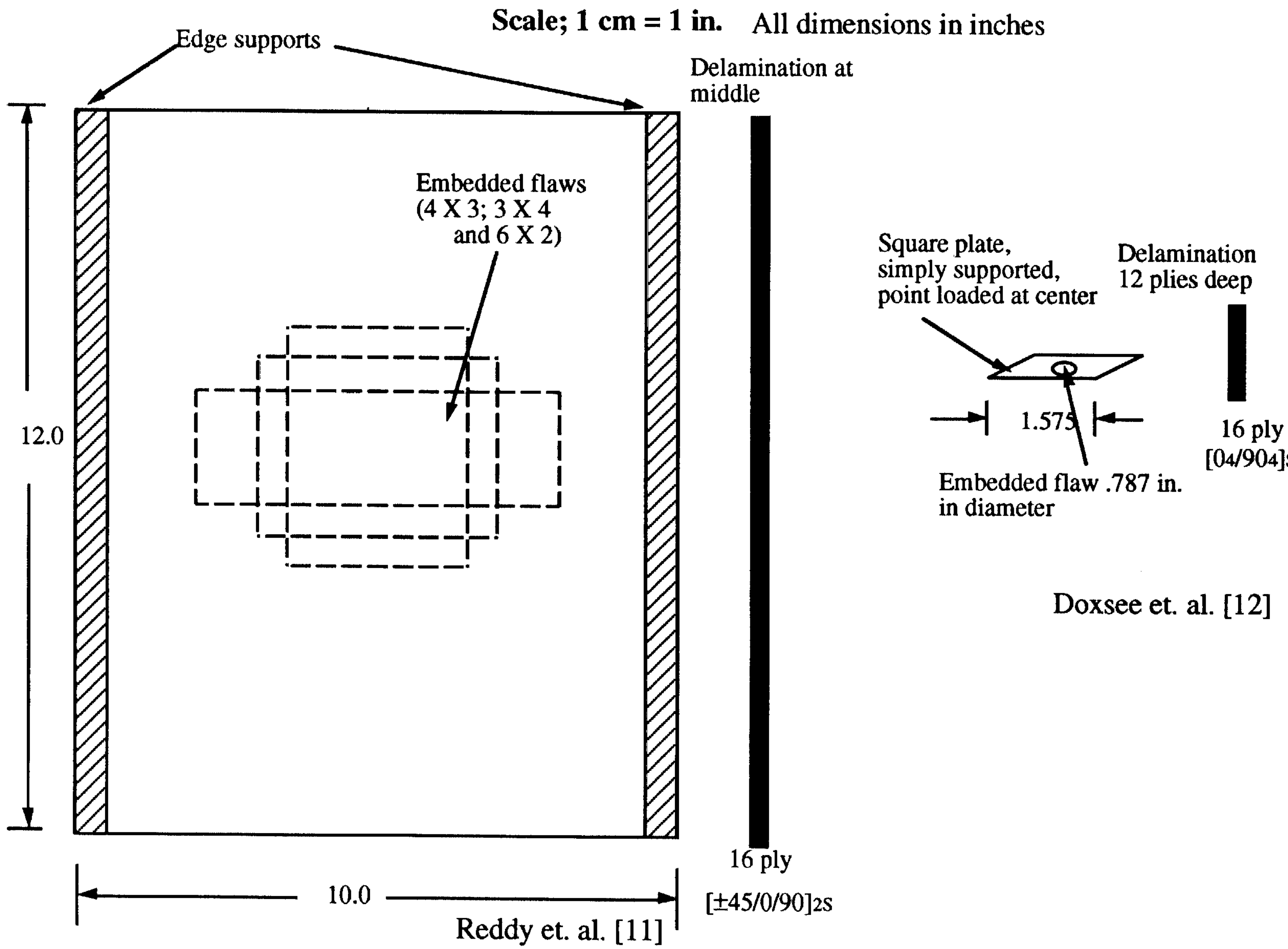
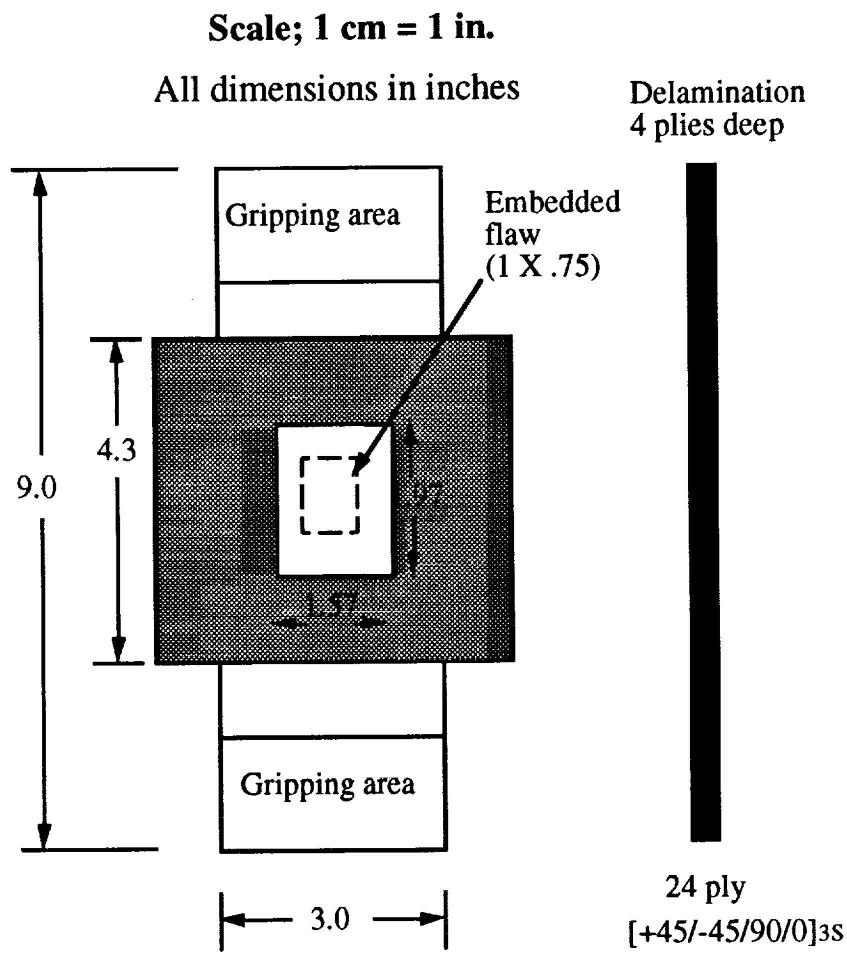


Figure 4. Drawings of specimens used (continued).



Greenhalgh [13]

Figure 4. Drawings of specimens used (continued).

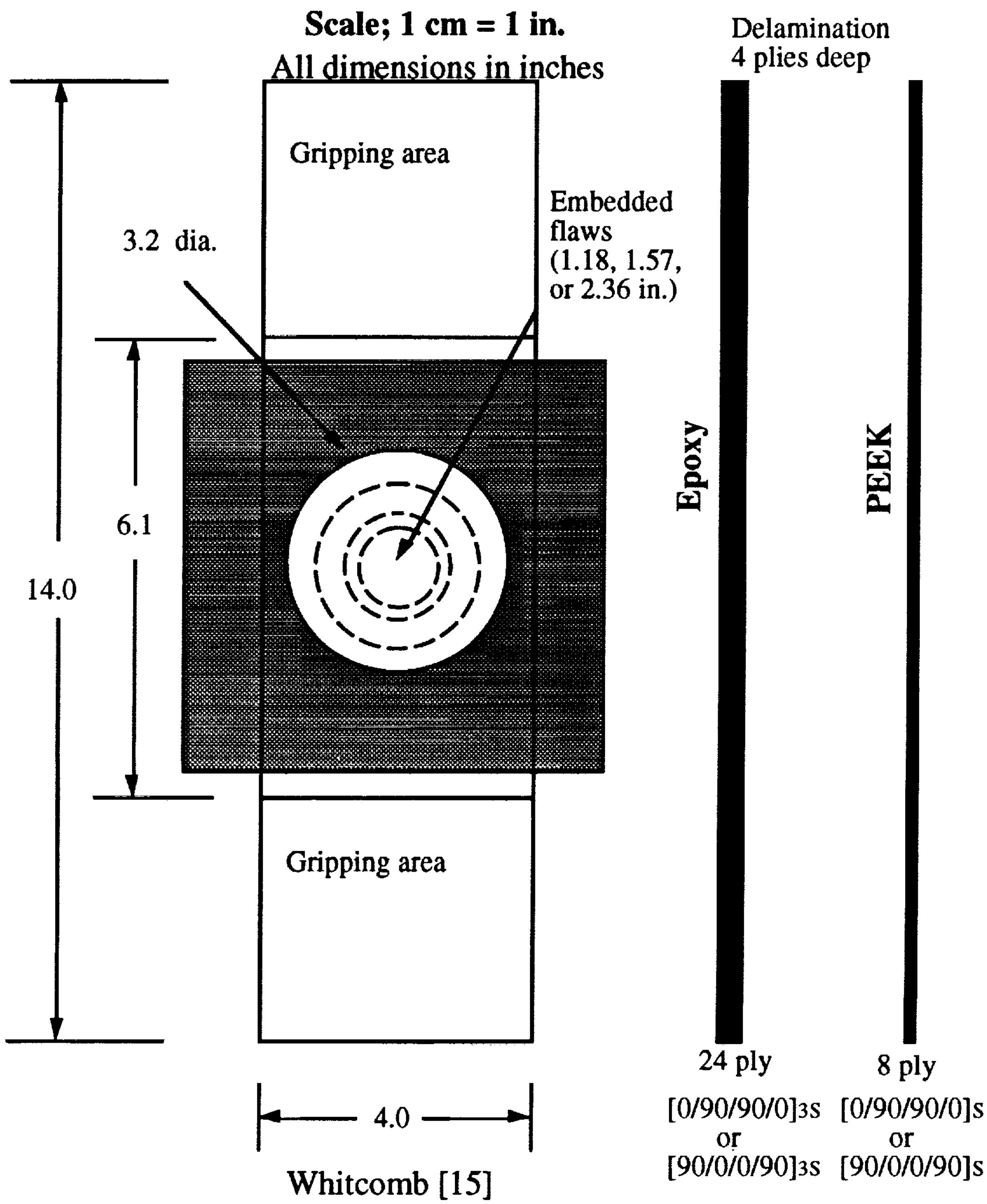


Figure 4. Drawings of specimens used (continued).

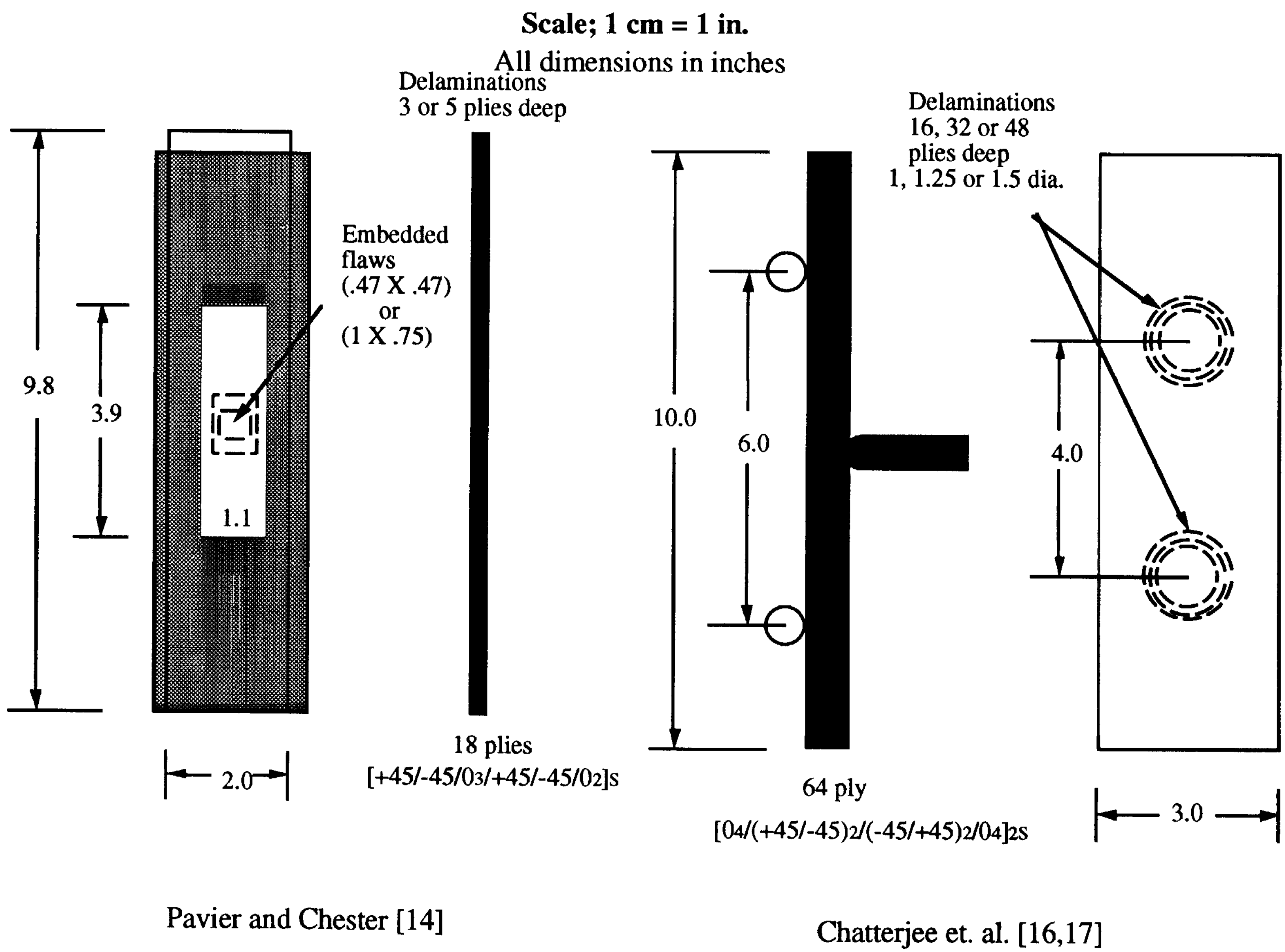


Figure 4. Drawings of specimens used (continued).

APPROVAL

THE EFFECTS OF EMBEDDED INTERNAL DELAMINATIONS ON COMPOSITE LAMINATE COMPRESSION STRENGTH; AN EXPERIMENTAL REVIEW

By Alan T. Nettles

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

P.H. SCHUERER
Director, Materials and Processes Laboratory

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