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A LOW COST METHOD OF TESTING COMPRESSION-AFTER-IMPACT STRENGTH OF COMPOSITE LAMINATES

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ABSTRACT

A method has been devised to test the compression strength of composite laminate specimens that are much thinner and wider than other tests require. The specimen can be up to 7.62 cm (3 in.) wide and as thin as 1.02 mm (.04 in.). The best features of the Illinois Institute of Technology Research Institute (IITRI) fixture are combined with an anti-buckling jig developed and used at the University of Dayton Research Institute to obtain a method of compression testing thin, wide test coupons on any 20 kip (or larger) loading frame. Up to 83% less composite material is needed for the test coupons compared to the most commonly used compression-after-impact (CAI) tests, which call for 48 ply thick (~ 6.12 mm) test coupons. Another advantage of the new method is that composite coupons of the exact lay-up and thickness of production parts can be tested for CAI strength, thus yielding more meaningful results. This new method was used to compression test 8 and 16 ply laminates of T300/934 carbon/epoxy. These results were compared to those obtained using ASTM standard D 3410-87 (Celanese compression test). CAI testing was performed on IM6/3501-6, IM7/SP500 and IM7/F3900. The new test method and associated fixture work well and will be a valuable asset to MSFC's composite materials damage tolerance program.

INTRODUCTION

Since the most critical damage tolerance feature of structural composite materials is their ability to carry a compressive load after damage, a simple, inexpensive method of testing this characteristic needs to be established. The two most commonly used methods, the Boeing and NASA CAI tests, both call for the use of 48 ply thick specimens. There are four big disadvantages to using such a thick specimen. 1) Most CAI testing is on new and experimental materials which are either expensive, in limited supply, or both. It would save time and money if less material were needed. 2) Foreign object impact characteristics are much different on a 48 ply specimen than on 16 or 8 ply specimens, regardless of boundary conditions. Since most functional parts are commonly in the vicinity of 16 plies in thickness, it would yield more meaningful data to test the actual lay-up sequence that the final product calls for. 3) A large amount of load is needed to cause failure in the Boeing and NASA 48 ply specimens. A much smaller, less expensive load frame can be used if 16 ply (or less) laminates are used. 4) Approximately 334 J (244 ft-lbs) of elastic energy can be stored in the 48 ply test specimens, (all of which is released upon specimen rupture), whereas the 16 ply specimens will only store about one-fourth as much energy, making for a safer test.

In order for impact damage to be accurately characterized by CAI testing, a long, wide gage length is needed to entirely contain the impact damage. This requirement, coupled with the desire to test specimens much thinner than 48 plies calls for a method to prevent global buckling of the compression specimen. Ryder and Black (1) wrote on compression testing large gage length specimens in 1977. They used a face-supporting fixture based on ASTM Standard Test for Compressive Properties of Rigid Plastics (D 695-69). This fixture made contact with the entire gage length surface of 140 mm (5.5 in.) long, 22.2 mm (.874 in.) wide, 16 ply specimens, tabbed and shear-loaded at one end and end-loaded at the other. Clark and Lisagor (2) introduced a face-supported fixture in 1981 that tested specimens as thin as 8 plies and up to 50 mm (2 in.) wide and 152 mm (6 in.) long. These specimens were tabbed at each end and tested in a hydraulic grip system. The anti-buckling jig was made up of inner and outer platens on each side of the specimen. The Boeing Open Hole Compression Test Standard (BSS 7260) is also a face-supporting compression test fixture (end-loaded).

Sjoblom and Hwang (3) of the University of Dayton Research Institute introduced a very simple method of supporting the gage length of a thin, wide compression test coupon in order to prevent global buckling of the specimen. This technique utilized two metal plates that would sandwich the test specimen along all but 1.9 mm (.075 in.) of the gage length. These plates were secured with just enough pressure to prevent the plates from freely moving on the specimen. In order to accommodate CAI specimens, holes were machined into the center of the plates to allow room for the protruding damage zone. A MTS hydraulic grip system was used to secure the specimens for compression loading. Since availability to hydraulic grips may be limited, Marshall Space Flight Center has developed a CAI fixture that can be used on any loading frame of 90 kN (20,000 lbs) capacity or larger. This fixture is a modified IITRI test apparatus that can accomodate specimens up to 76.2 mm (3 in.) wide. A face support system much like that used by Sjoblom and Hwang is used to prevent global buckling of the specimen.

TEST FIXTURE

A drawing of the test fixture labeling its components is shown in Figure 1. A photograph of the loaded test fixture and a view of the clamping wedges and load-alignment block is presented in Figures 2 and 3. Figures 4, 5 and 6 contain detailed drawings of the components of the test fixture. The entire fixture is fabricated of stainless steel (except for the anti-buckling faceplates) and measures approximately 28 cm (11 in.) in height when loaded with a specimen. The University of Dayton Research Institute's faceplate design was modified by increasing the cutout area to accommodate the damage zone which was often too large. A rectangular shape of 5.1 X 2.5 cm (2 X 1 in.) was utilized since the damage zone tended to protrude out lengthwise to the fibers in the outer ply. Thus all testing must be performed with the outer plies in the 0° direction (vertically). Like the Celanese fixture, the modified IITRI fixture was fitted with an outer sleeve to aid in proper alignment of the fixture and also to act as a protective shield should the fixture fail. In addition, four alignment rods were used between the upper and lower load-alignment blocks instead of two, as on the IITRI fixture. The entire fixture weighs in at a hefty 34 kg (74 lbs) but is set up in the loading frame by sections so it never needs to be lifted as one unit. All moving parts are greased to allow smooth movement. The anti-buckling faceplates were bolted onto the gage length of the specimen with just enough pressure so the faceplates would not move freely on the specimen. The inner surfaces of the faceplates were sprayed with a Teflon coating before each test to assure that fiction between the specimen and faceplate would not be a factor. The faceplates were machined from 16.8 mm (.66 in) thick aluminum to prevent any bending like that reported by Clark and Lisagor (2).

SPECIMEN PREPARATION

The specimen dimensions were kept the same as those used by Sjoblom and Hwang (3) and are given in Figure 7. The fiberglass end tabs were processed so one side would contain a crisscross pattern to allow the wedge grips to better "bite" into the specimen. This was achieved by using a Teflon coated, woven fiberglass cloth as a peel ply on one of the sides. The other side was smooth to aid in the adhesion of the glass/epoxy tabs to the carbon/epoxy specimen. It is important to note that no adhesive should run out from under the glass tabs and onto the gage length of the specimen since the faceplates must fit properly into this region. This can be accomplished by using flashbreaker tape or a similar non-stick substance at the area were the glass tabs edges meet the carbon/epoxy, or by using just the right amount of adhesive between the glass tabs and the specimen so no excess is produced. At MSFC it was found that a 19 mm (.75 in) wide strip of Cyanamid's FM 300 film adhesive, placed at the top edge of the glass tabs would produce acceptable specimens (see Figure 7.).

IMPACT TESTING

A Dynatup 8200 instrumented drop weight apparatus was used in this study to inflict impact damage on the carbon/epoxy specimens. The falling crosshead was outfitted with a 1.27 cm (.50 in.) diameter tup and had a mass of 1.77 kg (3.9 lbs). The specimens were impacted at their geometric centers and held fast by a pneumatic clamping device over a 6.35 cm (2.5 in.) diameter hole. Just about any specimen support and impact device can be used, as long as the damage zone is not so large as to cover the entire specimen width.

TEST RESULTS

Test of Faceplate Stiffness Criticality

Since it has been reported that the stiffness of the specimen face supporting jig can be a critical parameter (2,3), a series of compression tests were performed on 16 ply, undamaged laminates of T300/934 with three different thicknesses of aluminum faceplates, and a 6.1 mm (.24 in.) thick stainless steel faceplate. The thinnest aluminum faceplate was 6.1 mm (.24 in.) thick and gave an average breaking stress of 310 MPa (45,000 P.S.I.). The next aluminum faceplate tested was 16.8 mm (.66 in.) in thickness and gave an average breaking stress of 482 MPa (70,000 P.S.I.). The thickest aluminum plate measured 25.4 mm (1.0 in.) and also gave a breaking stress of 482 MPa (70,000 P.S.I.). The steel faceplate gave a value of 455 MPa (66,000 P.S.I.) Thus it was concluded that the 16.8mm (.66 in.) aluminum faceplates were robust enough not to deflect significantly enough to affect the outcome of the tests and were utilized for the remainder of the test program.

Comparison With Celanese Fixture

Compression tests were carried out on undamaged specimens of 16 ply $(0, +45, 90, -45)_{S2}$ T300/934 carbon/epoxy utilizing ASTM Test Standard D3410 (Celanese compression) and the new fixture presented in this paper. A total of 26 Celanese tests and 16 tests with the new fixture were performed. The average compression breaking stress for the Celanese test specimens was 434 MPa (63,000 P.S.I.) with a standard deviation of 55 MPa (8,000 P.S.I.). The new fixture gave an average compression breaking stress of 482 MPa (70,000 P.S.I.) with a standard deviation of 41 MPa (6,000 P.S.I.). Although the values are close (within 11 %), previous studies (2) have shown that a face-supported compression test specimen yields values slightly *lower* than a short gage length test. However, this study utilized very robust faceplates which ensured no out of plane stresses in the specimen. The low standard deviation seen with the new fixture suggests that the friction between the faceplates and the specimen is negligible since the torque on the bolts in the faceplates was a very arbitrary value that was not measured with any instruments. In addition, some tests were performed without any Teflon lubricant on the faceplates and values were obtained which were not significantly different than when the Teflon was used. Edge views of broken specimens from each type of test are presented in Figure 8. These breaks are typical of specimens that have undergone extensive interlaminar failure between dissimilar oriented plies, (see references 1,2).

CAI Testing

Compression-after-impact tests were performed on three different materials, IM6/3501-6, a standard early generation carbon/epoxy system and two new toughened systems, IM7/SP500 and IM7/F3900. A 16 ply quasi-isotropic layup configuration was used, $(0, +45, 90, -45)_{S2}$. A large range of impact energies was used to better understand and compare the materials. As expected, the two new, toughened systems could carry much more load at a given impact energy level than the old generation IM6/3501-6. A plot of impact energy versus residual strength is given in Figure 9. Figure 10. normalizes this data by laminate thickness.

Compression Testing of 8 Ply Specimens

A total of six undamaged and two impact damaged 8 ply quasi-isotropic specimens of T300/934 were tested in the new fixture. The average undamaged strength was 407 MPa (59,000 P.S.I.), much lower than the 16 ply specimen's average value of 482 MPa (70,000 P.S.I.). The impact damaged specimens, hit with 1.2 J (.88 ft-lbs) of incident impact energy, failed at 282 MPa (41,000 P.S.I.) and 276 MPa (40,000 P.S.I.). Sixteen ply quasi-isotropic specimens impacted at 1.2 and 2.4 J (.88 and 1.76 ft-lbs) had CAI strengths of 447 and 319 MPa (65,000 and 46,000 P.S.I.) respectively. While the residual strength of impact damaged 8 ply specimens are difficult to compare with thicker specimens,mostly due to the different damage mechanisms involved during impact, the fixture does cause failure of the 8 ply specimens at the impact damage zone. Undamaged 8 ply coupons gave values significantly lower than the 16 ply specimens. Thus 8 ply specimens that have been damaged severely enough to cause a drop in strength can be tested with the new fixture, but it is not recommended to test for virgin strength.

CHARACTERISTICS OF THE NEW FIXTURE

As the test program evolved, some methods to better test the compression coupons were discovered.

Tabbing the Specimen

As mentioned earlier in this paper, the tabs to be bonded to the test coupon needed to be applied so that no flashing of adhesive would occur in the gage length of the specimen so as to not interfere with the anti-buckling faceplates. It was found that on occasion the wedge grips would not "bite" into the tabs and would simply slide down. This problem was solve by "roughening" the outer surface of the fiberglass tabs during processing by using a Teflon coated, woven glass fabric as a peel ply on one side of the glass/epoxy laminate to be used for tab material. In rare instances, one of the tabs would debond from the specimen. This was usually the result of the adhesive material between the carbon/epoxy specimen and the tabs not being fully cured (as indicated by color of the adhesive). If a tab does debond it can be picked up on the load curve as a sudden, but not large drop in force. If this occurs the test should be stopped immediately and the specimen checked since extreme uneven loading would occur, possibly damaging the fixture. In this study a tab debond occurred and the test was not stopped and the result was four bent pins between the clamping wedges. Fortunately these were easily replaced.

Placing Faceplates on Specimen

Although it was determined that friction between the faceplates and specimen was negligible, a Teflon spray was applied to the faceplates prior to testing and wiped clean after the test had been performed to assure no catching of the specimen by the faceplate. Teflon tape was tried but was found to be too easily damaged, thus the use of spray. The four bolts and nuts that secured the faceplates to the specimen were finger tightened in a crisscross pattern with great care being taken to ensure that the faceplates were completely flat against the surface of the carbon/epoxy specimen. Calipers were used to make sure that there was an even gap between the two faceplates around their perimeters. The faceplates were mounted on the specimen before loading into the fixture.

Loading of Specimens

The most important aspect of loading the specimen into the fixture is to make certain that the specimen's length is perpendicular to the loading platens. This is not very difficult since the diamond pattern on the wedge grips is the same width of the specimen. Thus if the tabs are in contact with the diamond pattern without any overhang, the specimen is assured of proper alignment. In addition, if the specimens were tabbed and machined properly, any tab should be parallel to the clamping wedge that grips it.

The specimen, with faceplate, is then loaded into the bottom clamping wedge and load-alignment block which have previously been set on the bottom loading platen on the test frame. The four alignment rods are then placed in the bottom load-alignment block. The next step is to place the upper clamping wedges on the specimen and allow them to rest on the top surface of the faceplates. The upper load-alignment block is then placed on the four alignment rods and allowed to slide down over the clamping wedges. The wedges are then lifted slightly as is the loading block until the grips are at the point desired on the tabs. A little pressure pushing the clamping wedges up into the load-alignment block will lock the upper load alignment block in place. The outer sleeve is then placed over the entire fixture and the top loading platen is brought down to the top surface of the upper load-alignment block. Testing is now ready to begin.

Maintenance of Fixture

All moving parts are cleaned and regreased after 6-8 tests have been performed. The fixture is carefully examined for any galling or pitting of the metal parts. The most critical area of the fixture is the mating of the tapered surface of the clamping wedges to the inner tapered surface of the load-alignment block. These surfaces must always be clean and well greased.

CONCLUSIONS

The CAI fixture presented in this paper has been used successfully at MSFC for damage tolerance testing of composite materials. The device allows a small (20 kip) load frame to be utilized, thus saving time and cost by not having to test outside the Polymers and Composites Branch. In addition, much less material is needed to fabricate a CAI test specimen which also saves time and money. Furthermore, more specimens can be fabricated thus allowing a larger range of impact energies to be tested.

REFERENCES

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2. Clark, R.K. and Lisagor, W.B., "Compression Testing of Graphite/Epoxy Composite Materials," Test Methods and Design Allowables for Fibrous Composites, ASTM STP 734, 1981, pp. 34-53.

3. Sjoblom, P. and Hwang, B., "Compression-After-Impact: The $5,000 Data Point!," Proceedings of the 34th International SAMPE Symposium, Reno, NV, 1989, pp. 1411-1421.

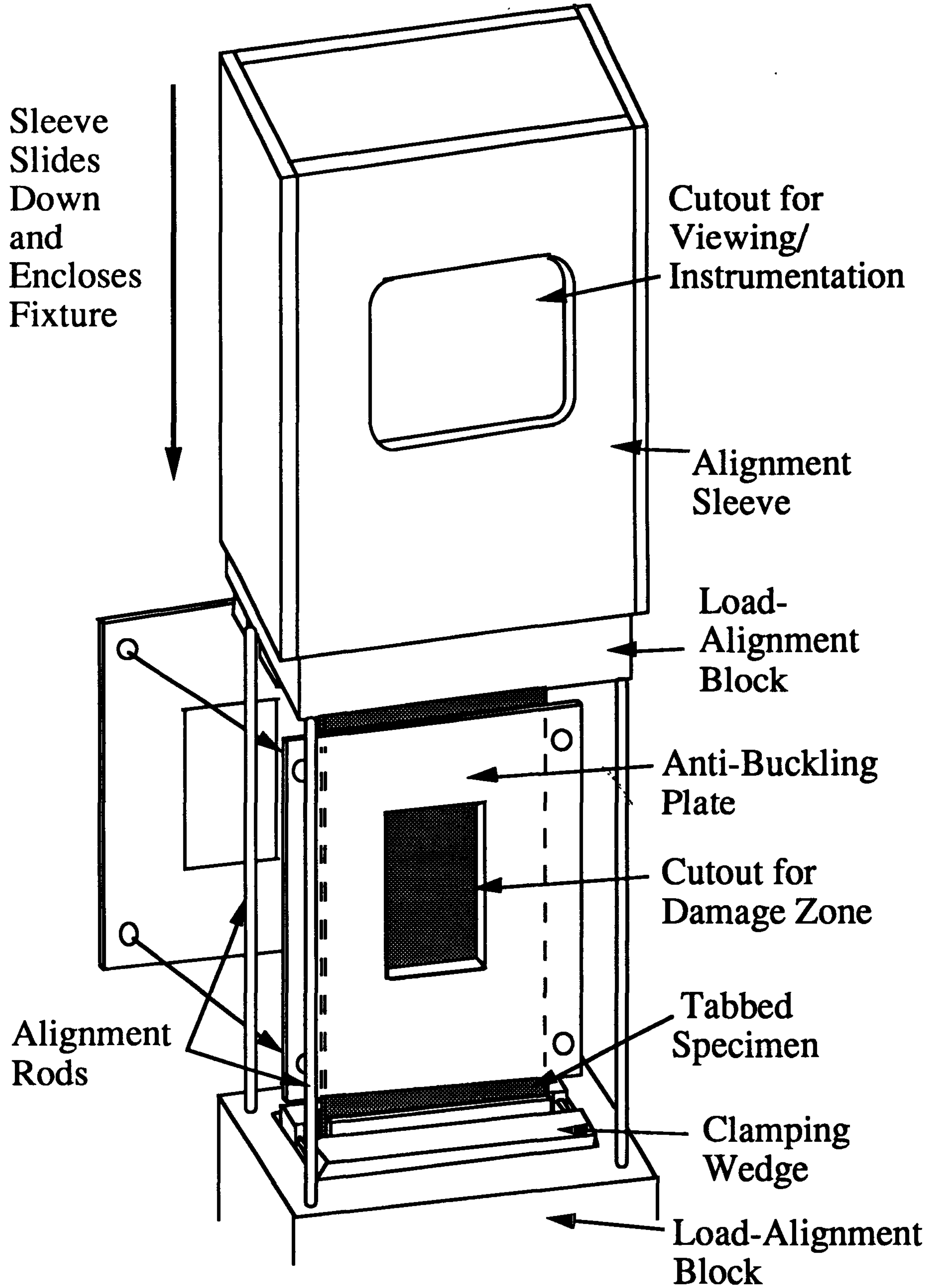

Figure 1. New Compression-After-Impact Fixture

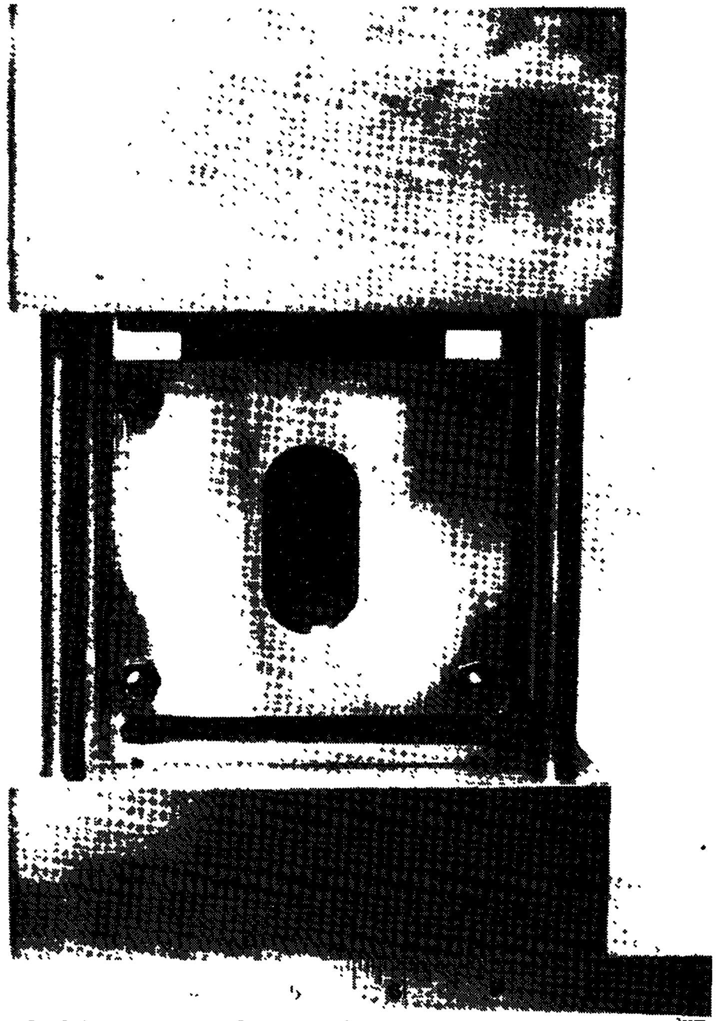

Figure 2. Photograph of Test Fixture Loaded With Specimen

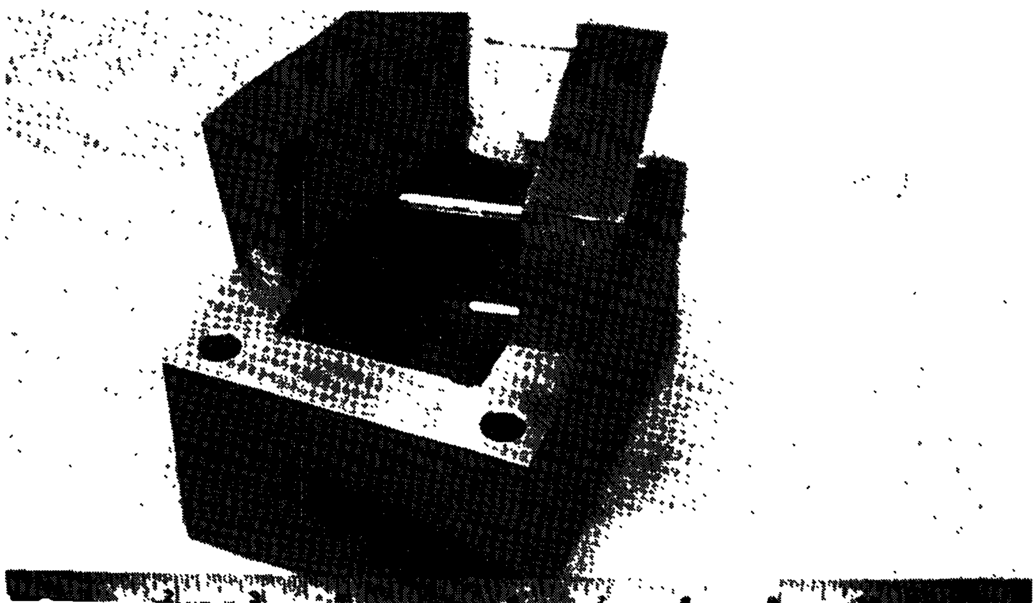

FIGURE 3. View of Clamping Wedges and Load-Alignment Block

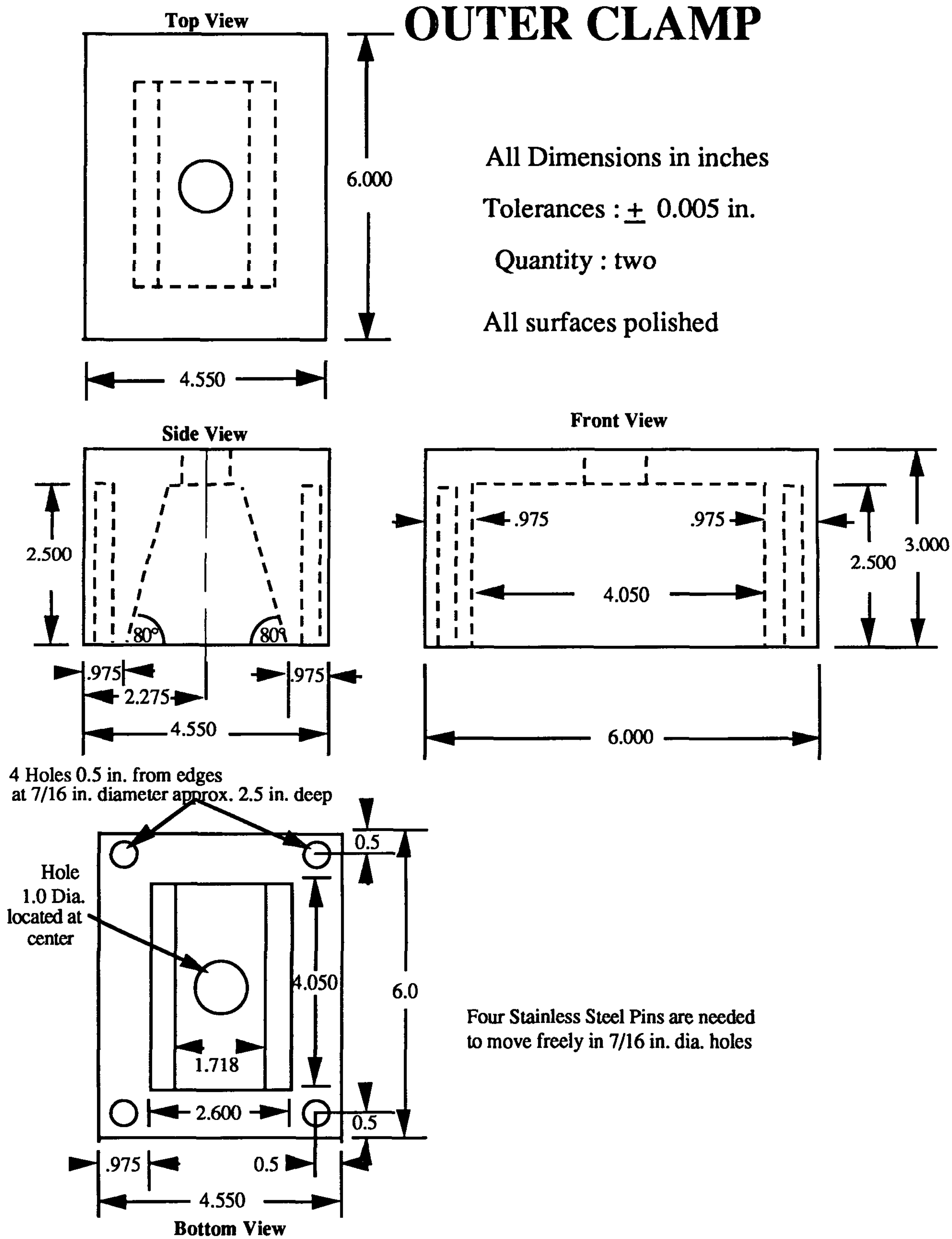

FIGURE 4. Detailed Drawing of Outer Clamp Piece

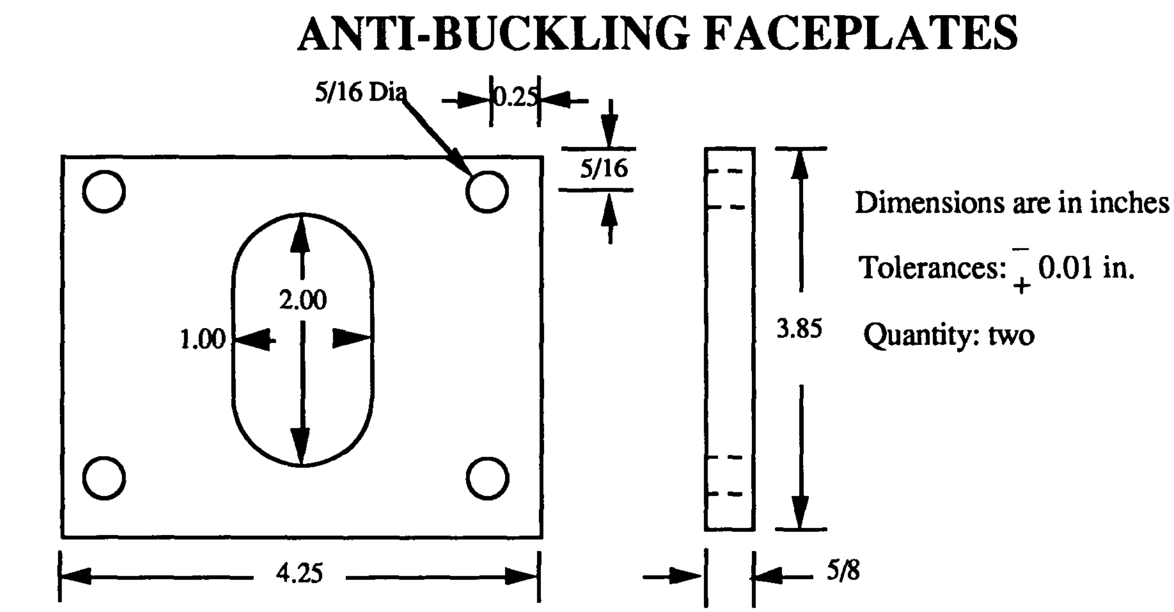

FIGURE 5. Detailed Drawing Of Anti-Buckling Faceplate.

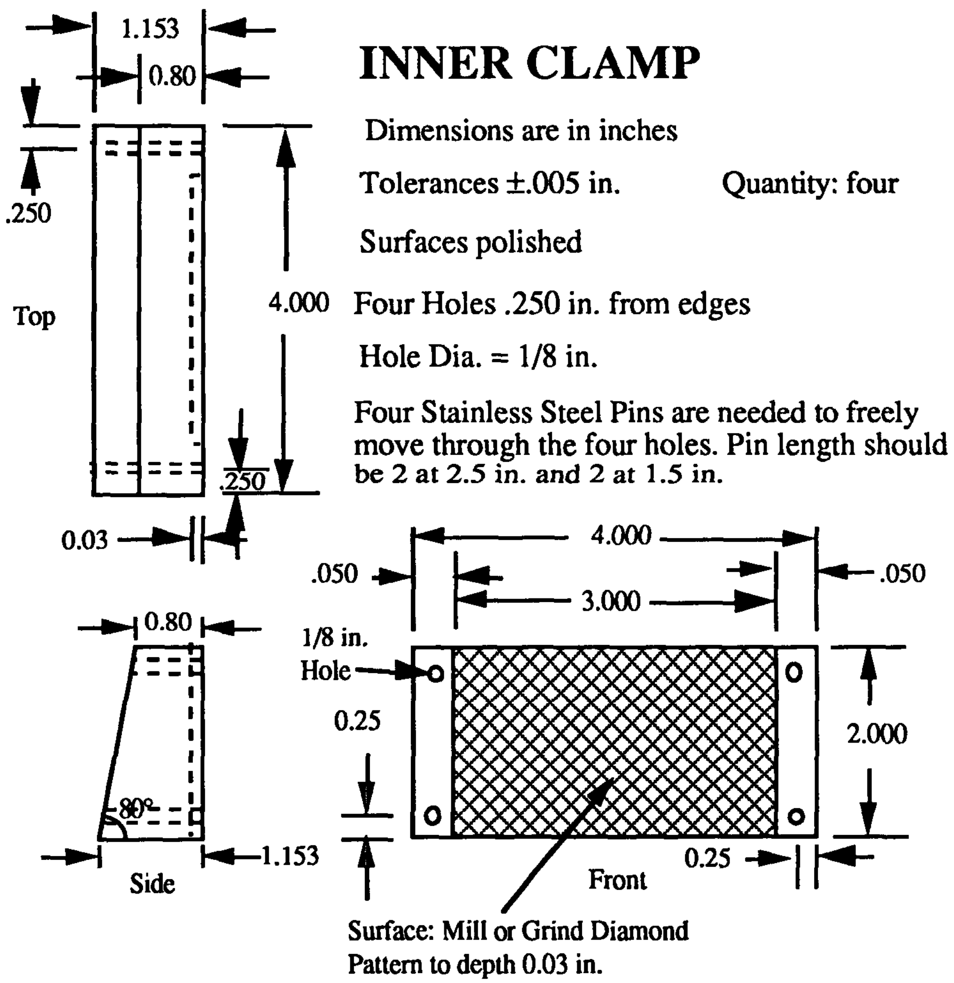

FIGURE 6. Detailed Drawing of Inner Clamp

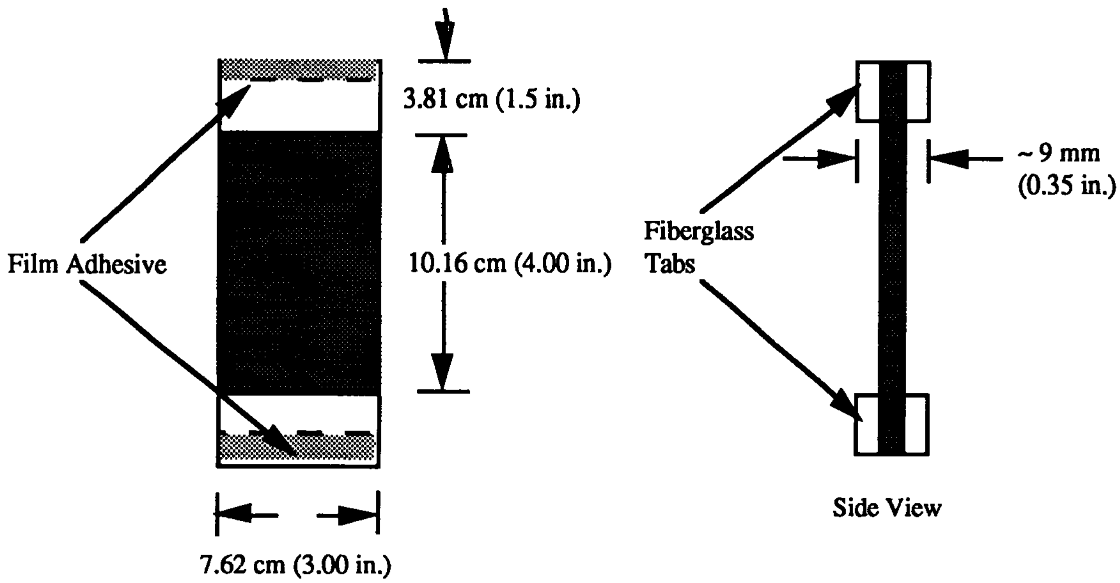

FIGURE 7. Dimensions of Compression-After-Impact Specimen

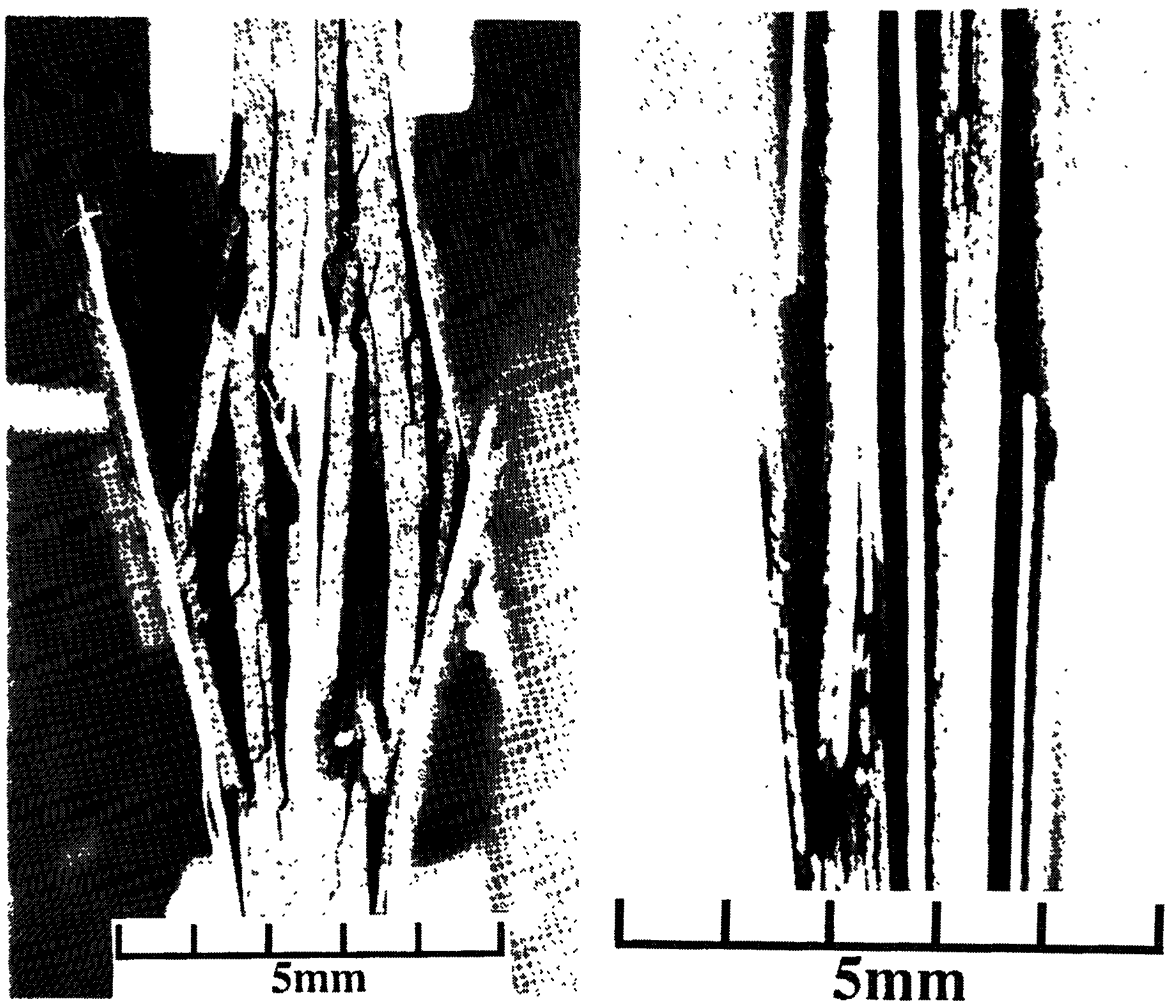

FIGURE 8. Failed Compression Specimens. Left: Celanese Right: New Fixture

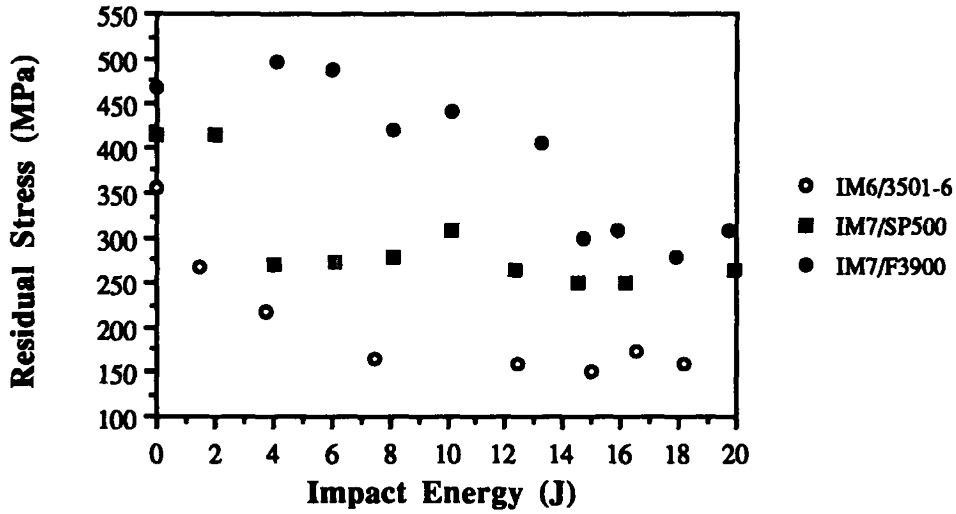

FIGURE 9. Residual Stress vs Impact Energy for Three Material Systems

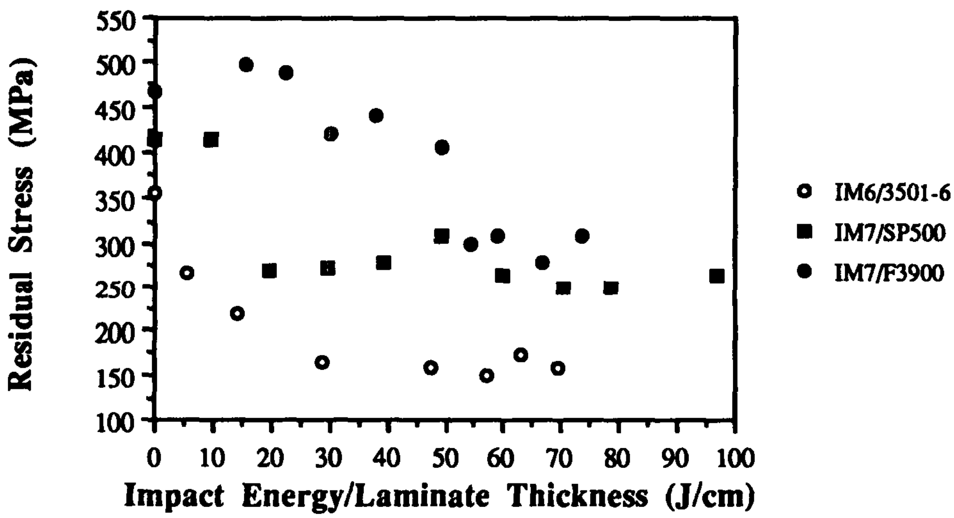

FIGURE 10. Residual Stress vs Impact Energy per Laminate Thickness