College of Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

November 1994

VPI-E-94-08

Innovative Design of Composite Structures: Design, Manufacturing, and Testing of Plates Utilitzing Curvilinear Fiber Trajectories.

M.W. Hyer
R.J. Rust
W.A. Waters, Jr.

Department of Engineering Science and Mechanics

Final Report for NASA - Grant NAG - 1 - 901

Prepared for:

M.P. Nemeth
Structural Mechanics Branch
NASA Langley Research Center
Hampton, VA 26381

Design, Manufacturing, and Testing of Plates Utilizing Curvilinear Fiber Trajectories

Michael W. Hyer
Department of Engineering Science and Mechanics
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

Ralph J. Rust
Composites Business Group
Cincinnati Milacron Inc.
4701 Marburg Avenue
Cincinnati, OH 45209

W. Allen Waters, Jr.
Lockheed Engineering and Sciences, Co.
144 Research Drive
Hampton, VA 25238

ABSTRACT

As a means of improving structural design, the concept of fabricating flat plates containing holes by incorporating curvilinear fiber trajectories to transmit loads around the hole is studied. In the present discussion this concept is viewed from a structural level, where access holes, windows, doors, and other openings are of significant size. This is opposed to holes sized for mechanical fasteners. Instead of cutting the important load-bearing fibers at the hole edge, as a conventional straightline design does, the curvilinear design preserves the load-bearing fibers by orienting them in smooth trajectories around the holes, their loading not ending abruptly at the hole edge. Though the concept of curvilinear fiber trajectories has been studied before, attempts to manufacture and test such plates have been limited. This report describes a cooperative effort between Cincinnati Milacron Inc., NASA Langley Research Center, and Virginia Polytechnic Institute and State University to design, manufacture, and test plates using the curvilinear fiber trajectory concept. The paper discusses details of the plate design, details of the manufacturing, and a summary of results from testing the plates with inplane compressive buckling loads and tensile loads. Comparisons between the curvilinear and conventional straightline fiber designs based on measurements and observation are made. Failure modes, failure loads, strains, deflections, and other key responses are compared.

INTRODUCTION

Conventional design philosophies for fiber-reinforced composite structures are based on the idea of using multiple layers of fibers embedded in a matrix, the fibers in each layer being straight and aligned in a particular direction. Though each layer has a unique fiber orientation, the idea of allowing the fiber orientation to vary from point to point within a layer has not been seriously considered before. Past fabrication methods and available material forms have precluded the use of this concept, referred to here as the curvilinear fiber format. In addition, analysis techniques become more involved as the material properties of the structure, for example, in the sense of the A, B, and D matrices, vary from point to point. Thus, the use of the curvilinear fiber format has been minimal. However, aside from these practical issues, there are more fundamental issues associated with the curvilinear fiber format: What is the purpose of a curvilinear fiber format? Why should it even be considered? What are its advantages? What criterion should be used to determine the variation of fiber orientation with spatial location? Are there any disadvantages to the curvilinear fiber format? Each of these questions must be answered within the context of a particular problem. Here the use of the curvilinear fiber format is considered in the context of improving the performance of plates with a centrally located circular hole and subjected to inplane compressive or tensile loadings. The holes are structural level holes, where access holes, windows, doors, and other openings are the holes of interest. This is opposed to holes sized for mechanical fasteners. In this application, instead of cutting the important load-bearing fibers at the hole edge, as conventional straightline fiber formats do, the curvilinear design preserves the load-bearing fibers by orienting them in smooth trajectories around the holes, their loading not ending abruptly at the hole edge. Such a concept has been presented in the past by Cooper [1] and by Heller and Chiba [2]. More recently, Hyer and Charette [3] studied numerically the effect of the curvilinear format on the improvement in tensile capacity of uniaxially loaded plates with centrally located holes. Several plate designs were considered. Some designs consisted of plates with all layers having the curvilinear fiber format, and some designs consisted of plates with certain layers having the conventional straightline fiber format and the remaining layers having the curvilinear format. The fiber orientations in the curvilinear layers were determined by having the fibers in those layers aligned with the principal stress directions of those layers. A finite-element based analysis and an iteration scheme were used to determine the curvilinear fiber trajectories. A maximum strain criterion was employed to evaluate the performance of the designs. Relative to a baseline straightline format design, improvements in tensile capacity were achieved. However, the resistance of the improved tensile designs to compressive buckling loads was degraded by the curvilinear design. An example of the trajectories of the curvilinear layers that resulted from that study is shown in fig. 1. In fig. 1 it is assumed that the loading is vertical and only one quadrant of the plate is shown, the other three quadrants having identical fiber orientations. This figure also shows the finite-element discretization used. As can be seen, the fibers provided a path for the

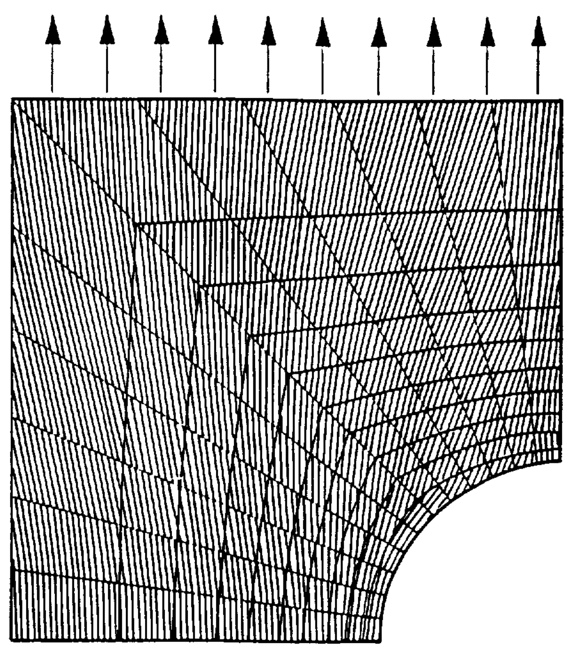


Fig. 1 - Fiber trajectories of curvilinear layers in design for improved tensile capacity (from ref. 3)

tensile load to 'flow' around the hole. Katz et al [4] used a maximum strain criterion and optimization techniques to obtain similiar fiber trajectories for this problem. To improve buckling resistance, Hyer and Lee [5] used finite-elements, a sensitivity analysis, and a gradient search technique to find the fiber orientation in specific regions of a plate simply supported on all four edges that resulted in higher buckling loads than the baseline straightline format design. This numerical study resulted in several curvilinear designs that improved the buckling capacity. However, a design was found that improved both the buckling capacity and the tensile capacity. The trajectories of the curvilinear layers that resulted from that work are shown in fig. 2. Again only one quarter of the plate is shown, the other three quadrants having the same fiber trajectories. The gradient search found the orientations in the six regions of the plate that resulted in the highest buckling load. (The finite-element discretization used in the study was finer than the six regions represented by fig. 2.) With the trajectories of fig. 2, the fibers transmitted the compressive inplane load outward toward the simply supported side edges. This resulted in the central portion of the plate, the region which contributes most to plate instability, being loaded less than with the baseline straightline format design. Hence the load to cause buckling was higher than for the straightline format design.

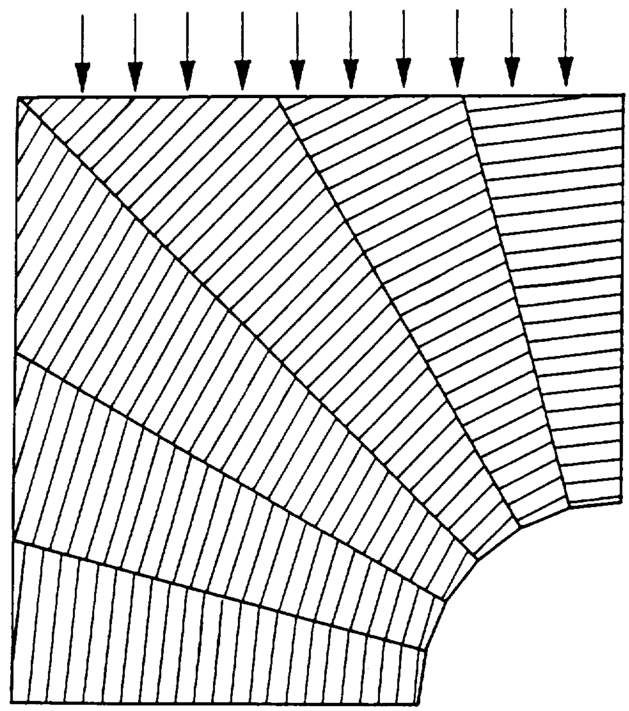


Fig. 2 - Fiber trajectories of curvilinear layers in design for improved buckling capacity (from ref. 5)

The results of these studies by Hyer and Charette and Hyer and Lee motivated the study discussed herein, namely the manufacturing and testing of plates which make use of the curvilinear design concept. Because of manufacturing constraints, to be discussed shortly, the specific designs of these two past studies were not directly implemented. However, an approximation to the design of fig. 1 was used. Two identical curvilinear fiber format plates were manufactured, one for testing in tension, and one for testing in compression. The plates were manufactured with a Cincinnati Milacron fiber placement machine. Two baseline straightline fiber format plates were also manufactured using the same machine. The four plates were tested by the Aircraft Structures Branch of the NASA Langley Research Center. The remainder of the paper discusses the manufacture of plates, the preparation of the plates for testing, and the testing procedure and test results. Comparisons between the curvilinear and baseline straightline designs based on observation and measurements are made. The failure modes, failure loads, strain gage measurements, deflection measurements, and other key responses are discussed.

PLATE MANUFACTURING

Until the development of the fiber placement process, there was no method available to automatically produce curvilinear, or steered, paths of fiber-reinforced composite material with differential fiber payout. The fiber placement process has evolved from tapelaying and filament winding for producing composite aircraft components. Tapelaying is used to produce more gently contoured parts. Filament winding is used to produce rotational convex parts, and the process has difficulty with concave parts. Fiber placement is used to produce more highly contoured, concave, and rotational parts. In tapelaying, 76, 152, and 305 mm (3, 6, and 12 in.) wide tape, backed with film or paper, is applied ply upon ply to a mold surface until a complete part is fabricated. Fiber placement uses 3.18 mm (1/8 in.) wide tow material, but with no backing film, in a similiar manner.

A band of placed fibers consists of 8, 12, 24, or more tows, depending on the machine that is being used. This produces a 25, 38, 76 mm (1, 1.5, or 3 in.), or wider band. In tapelaying, the cuts at the beginning and end of the fiber path, or course, are formed by cutting across the piece of tape with a stylus or rotary cutter. Cuts are produced in fiber placement using a separate guillotine cutter to cut each individual tow. Since each tow is cut individually, scrap is eliminated between courses. With fiber placement, the band width can be varied by changing the number of tows being laid onto the mold. Because of the multiple tows within a band, this variation in width can occur during the application of a single band.

Fiber placement is able to produce a steered fiber path better than tapelaying can. In tapelaying of 76 mm (3 in.) wide tape, the minimum steering radius without significant buckling of the fibers, in the plane of the tape, is around 20 m (800 in.). With fiber placement of 3 mm (1/8 in.) wide tows, the minimum steering radius is around 380 mm (15 in.), a considerably tighter radius. In tapelaying, each of the fiber bundles is fixed with respect to adjacent fiber bundles. With fiber placement, each of the 3 mm (1/8 in.) tows is allowed to be dispensed independently of the adjacent tows. Figure 3 shows a schematic of how the tow material is fed through the fiber placement head and dispensed onto the mold surface. The important components of the fiber placement head are shown in fig. 3. Using the compaction roller, the fiber placement machine uses seven axes of motion to compact the tow onto the mold surface. These seven axes are described in fig. 4. As shown in fig. 3, the tow can be preheated to increase the tack of the resin for better adhesion of the tow onto the surface. Electronic tensioners accurately control the tension of each spool of tow material at the despooling point. With the study here, the 380 mm (15 in.) steering radius dictated the minimum size of the specimens fabricated.

The four plate specimens in this study were produced on Cincinnati Milacron's 12 tow FPS fiber placement machine with an A975F control. This machine was a joint development effort between Cincinnati Milacron Inc. and Thiokol Corporation, is owned by Thiokol Corporation, and is

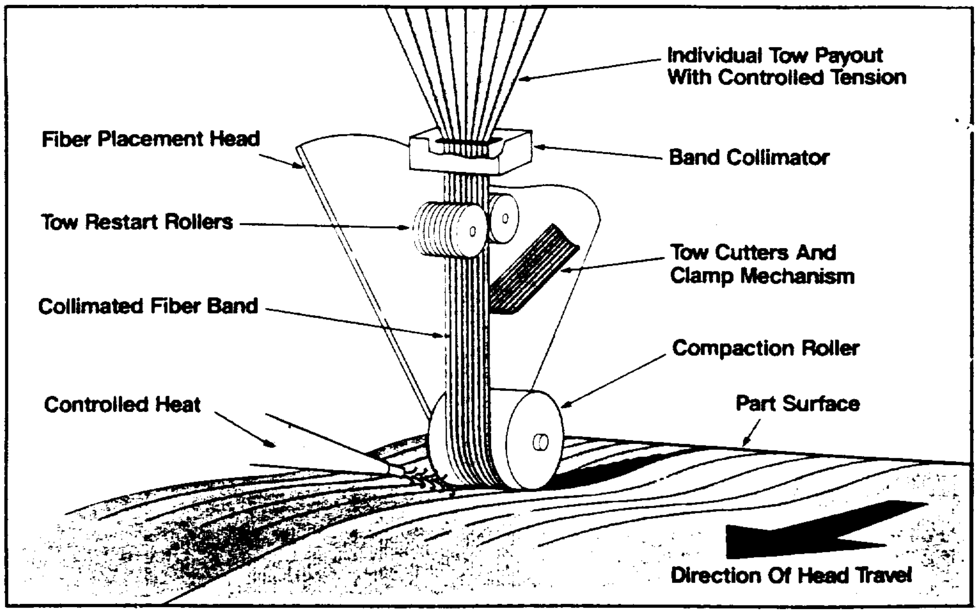


Fig. 3 - Tow path through fiber placement head

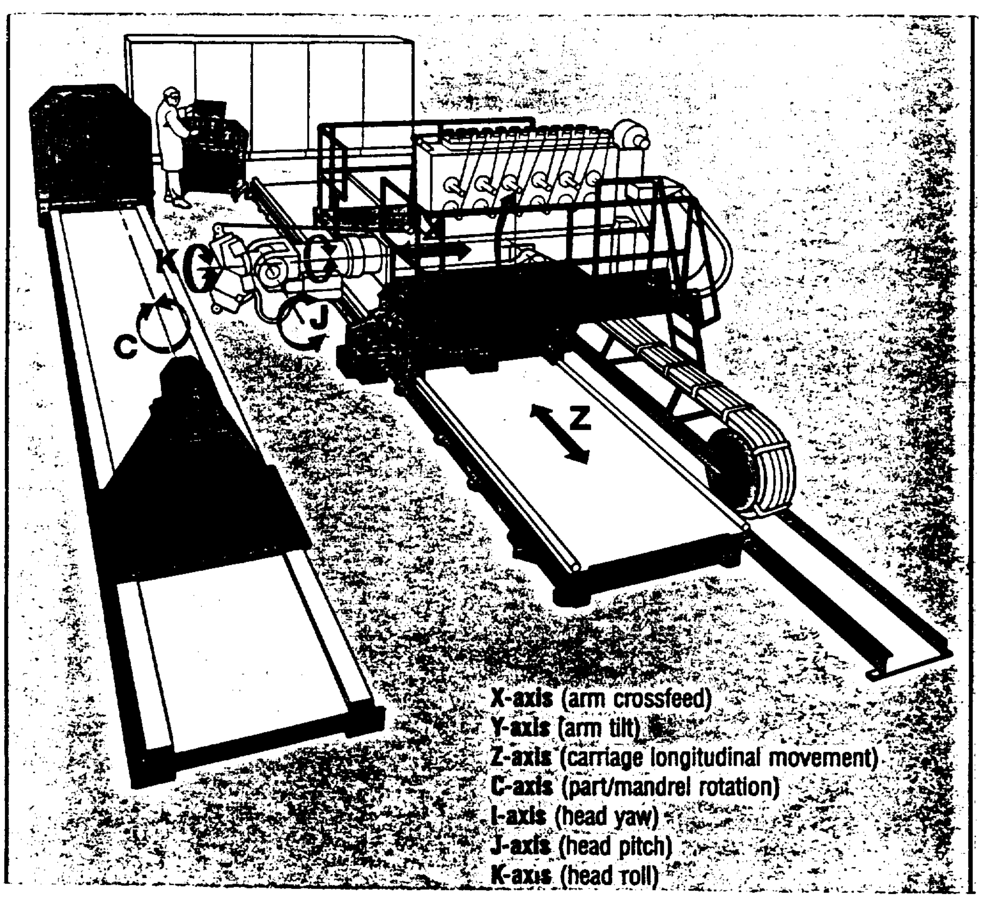


Fig. 4 - Cincinnati Milacron fiber placement machine with seven major axes

located at NASA Huntsville. Two similiar machines have been sold to General Electric Aircraft Engines Co. in a developmental program for the manufacture of the GE90 engine wide chord fan blades. Another machine is nearing completion for delivery to Boeing Helicopters for production of the aft fuselage of the V22 Tiltrotor.

The plates were produced using Fiberite FX13F77-2 graphite-epoxy tow material. The tow material was 0.28 mm (0.011 in.) thick, with a nominal width of 3 mm (1/8 in.). Figure 5 provides a detail of the dimensions of the plate, and details of the curvilinear fiber trajectories used. Other layers in the plate construction used straight fibers. As can be seen by comparing fig. 5 with figs. 1 and 2, the curvilinear design was neither of the two previously studied. The design actually used was simpler to make than either the design of fig. 1 or the design of fig. 2. The philosophy used was to make the curvilinear design as simple as possible, and learn from this case before going to either of the other two designs.

Cincinnati Milacron's ACRAPLACE programming system was used to create the straightline fiber paths. Due to the developmental nature of this program, the curvilinear part programs were generated using a special purpose path generation progam. Limitations of this special purpose program allowed only courses that extended from one end of the panel to the other to be machine laid. The curvilinear courses that did not extend all of the way across the panel were filled in by hand. The corners of the +/-45° plies contained tows that were too short to be machine laid due to cut length limitation, so these tows were placed by hand. As shown in fig. 5, some of the curvilinear courses that steered around the hole extended outside the net panel dimensions. As a result, the overall specimen width was 0.610 m (24 in.). This was later trimmed to a useful width of 0.457 m (18 in.). The overall length of each specimen was 1.197 m (47 in.). The central hole was 76.2 mm (3 in.) in radius. Each plate was 16 plies thick. While the curvilinear plies were steered around the holes, the straightline fiber format plies were cut at the edge of the hole. Thus the hole, at least in rough form, was fabricated into the specimens from the onset. The final hole size was achieved by machining. Though not available when these plates were made, the latest version of the ACRAPLACE programming system can be programed to automatically drop and add tows to create a hole in a part. Figure 6 shows the fiber placement head laying a curvilinear ply for one of the specimens. Figure 7 shows one of the curvilinear plies after it has been produced by the fiber placement machine. Figure 8 depicts a specimen after trimming has been completed. One can easily observe the hole in the center of the plate.

The plate specimens were prepared for curing by sandwiching each uncured plate between two aluminum caul plates. The top aluminum caul plate contained a hole for inserting a 152 mm (6 in.) plug into the composite specimen. The plug limited resin flow at the hole, and provided a form for the shape and size of the hole. The assembly of aluminum caul plates and composite specimen was vacuum bagged and the specimen was cured. The cured plates were removed from between the caul plates and were prepared for testing.

The stacking sequence of the curvilinear plate was $(\pm45/C_2/0/90/C_2)_S$, where the C denotes layers with the curvilinear trajectories of fig. 5. The 0° direction is along the length of the plate. The stacking sequence of the baseline straightline fiber format plate was $(\pm45/0_3/90/0_2)_S$. As can be seen, the curvilinear design was derived from the baseline design by the replacement of 8 0° layers with curvilinear layers. Each plate weighed approximately 3.4 kg (7.5 lbs.).

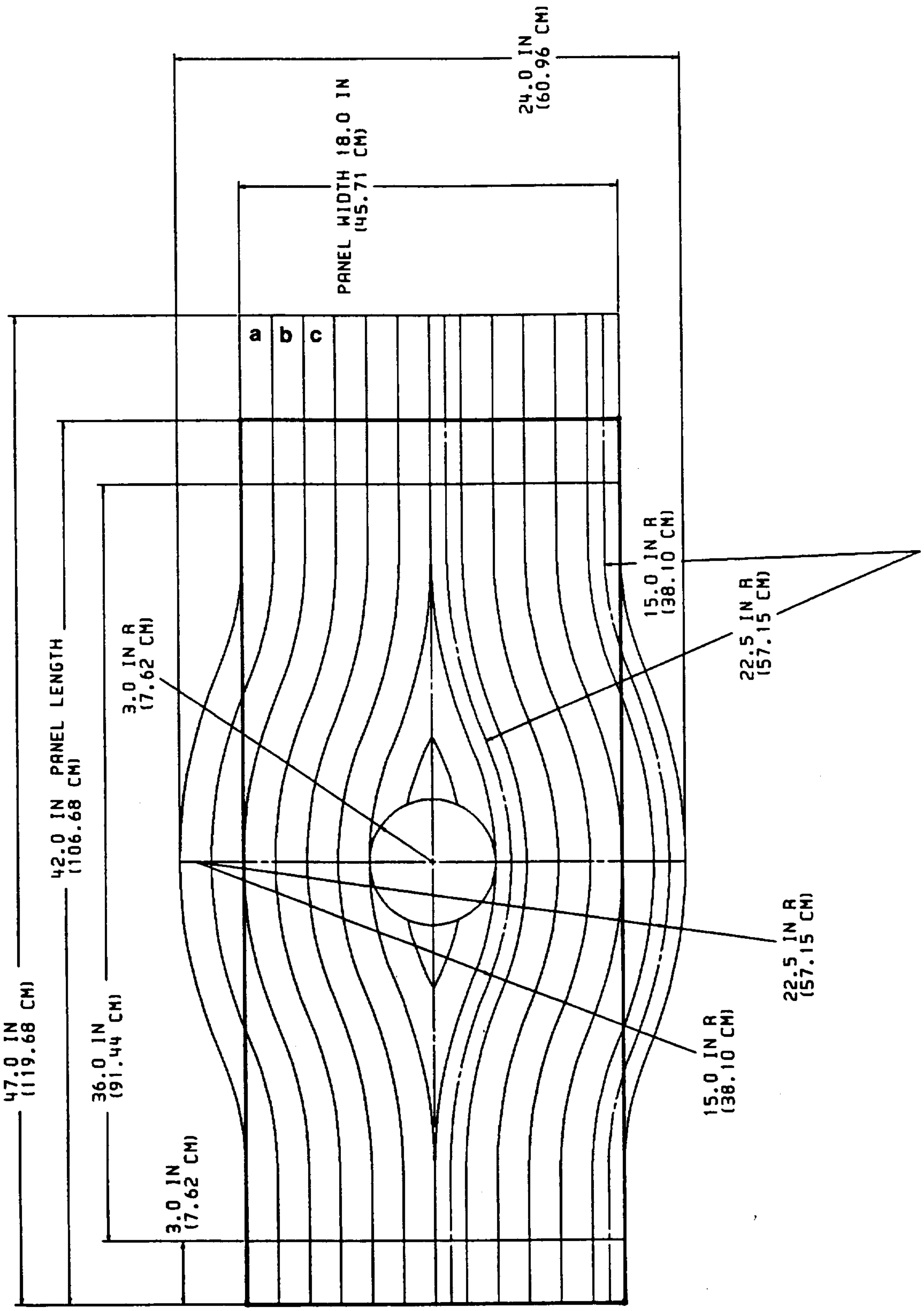


Fig. 5 -Tow paths of curvilinear layers in present design

Fig. 6 - Cincinnati Milacron fiber placement head laying curvilinear ply

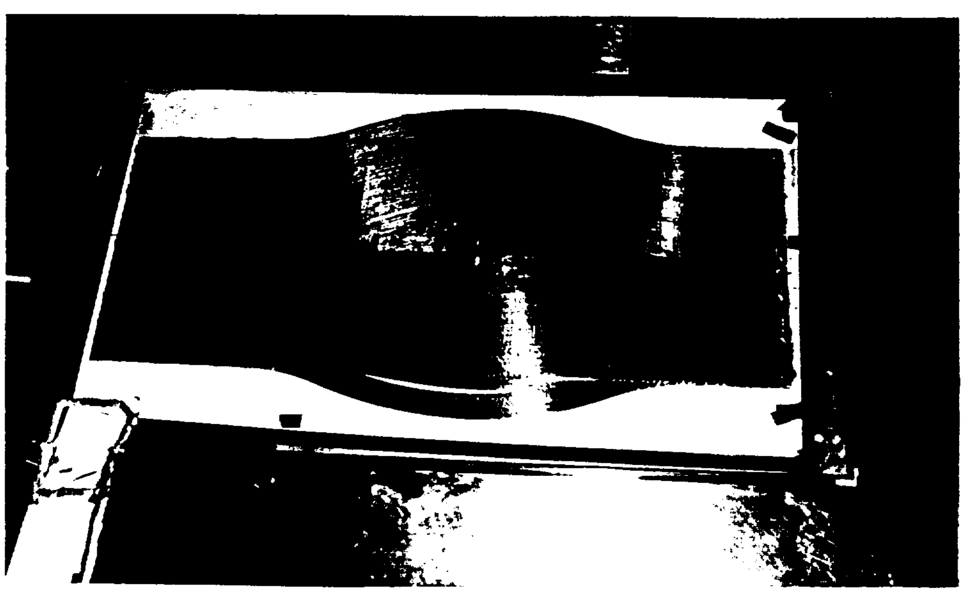


Fig. 7 - Curvilinear ply produced by Cincinnati Milacron fiber placement machine

Fig. 8 - Panel with hole cut in center after trimming

C-scans of the four plate specimens are shown in fig. 9. The plates labeled C_1 and Q_1 were compression test specimens, C_1 being a plate with the curvilinear format. The plates labeled C_2 and Q_2 were tensile test specimens, C_2 also being a plate with the curvilinear format. The areas of the C-scans that are in contrast in fig. 9 differ by 1 decibel out of 15 in their C-scan signal. Except for specimen Q_1, a compression specimen, the C-scans of the specimens are quite uniform. With specimen Q_2 the cutter drilling the central hole was inadvertently started at the wrong lengthwise location. The C-scan shows the circular line, just below the hole, from the cutter slightly scoring the surface of the specimen. This slight scoring seemed to have no effect on the specimen's performance.

It is important to note that with the curvilinear specimen C-scans there was no evidence of curvilinear fiber trajectories. Obviously, the curvilinear tows consolidated well.

TEST CONDITIONS

For testing, the specimens were further trimmed. The trimmed size depended on whether the specimen was to be tested in compression or tested in tension. Strain gages were bonded at specific locations on both the tensile and compression specimens. An outline of the compression and tensile specimens is illustrated in fig. 10, as are the strain gage locations. All gage installations were back-to-back pairs. The double-headed arrows in fig. 10 show the location of the gages and indicate that the gages measured strains in the loading direction. Strains near and far away from the hole edge were monitored. As can be seen, the gages were symmetrically placed on the specimens, the symmetry of the gage pattern being indicated by having more than one gage location with the same letter, i.e., a, c, ..., m, etc. More gages than shown in fig. 10 were actually used, but

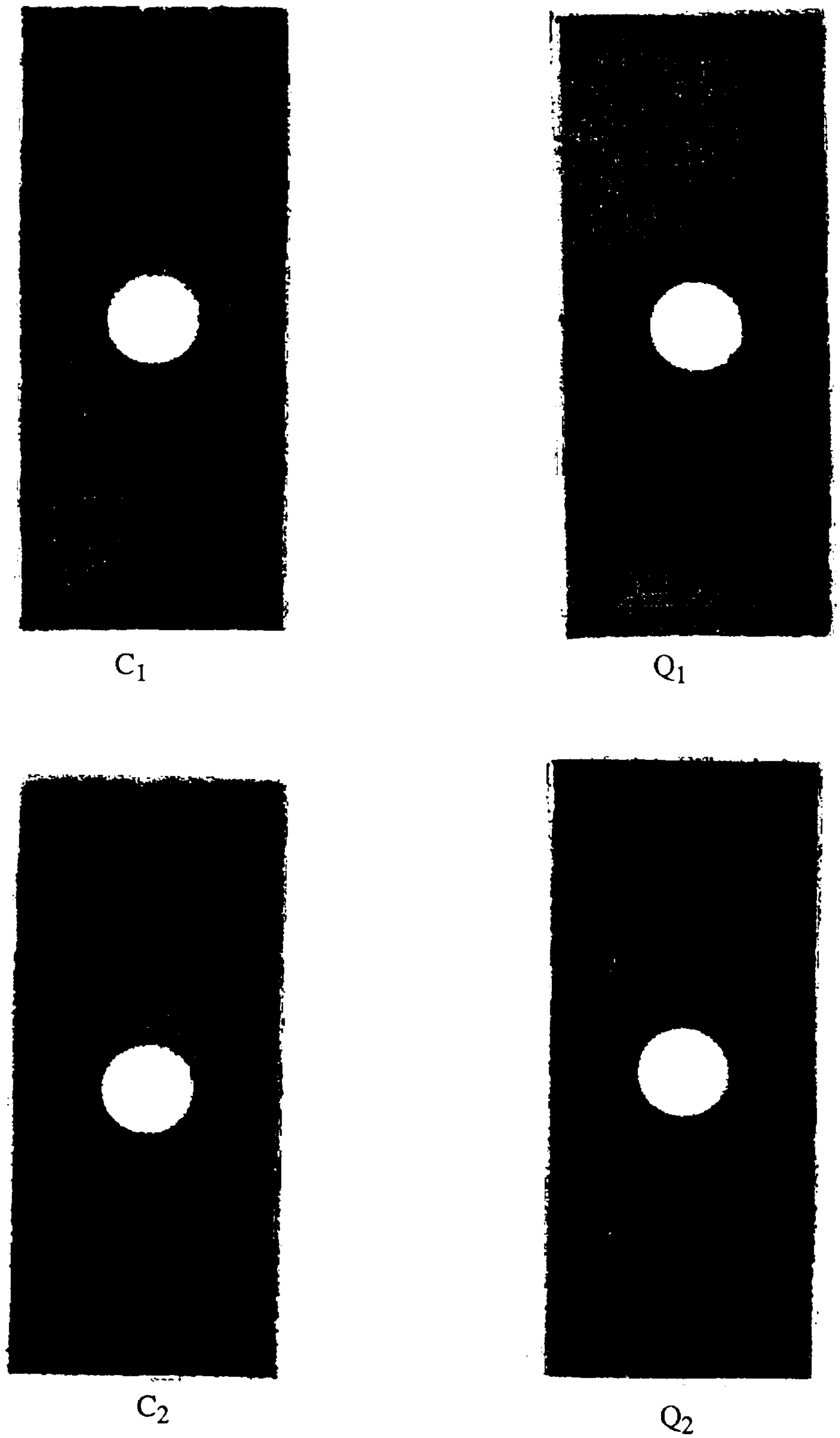


Fig 9 - C-scans of the four specimens

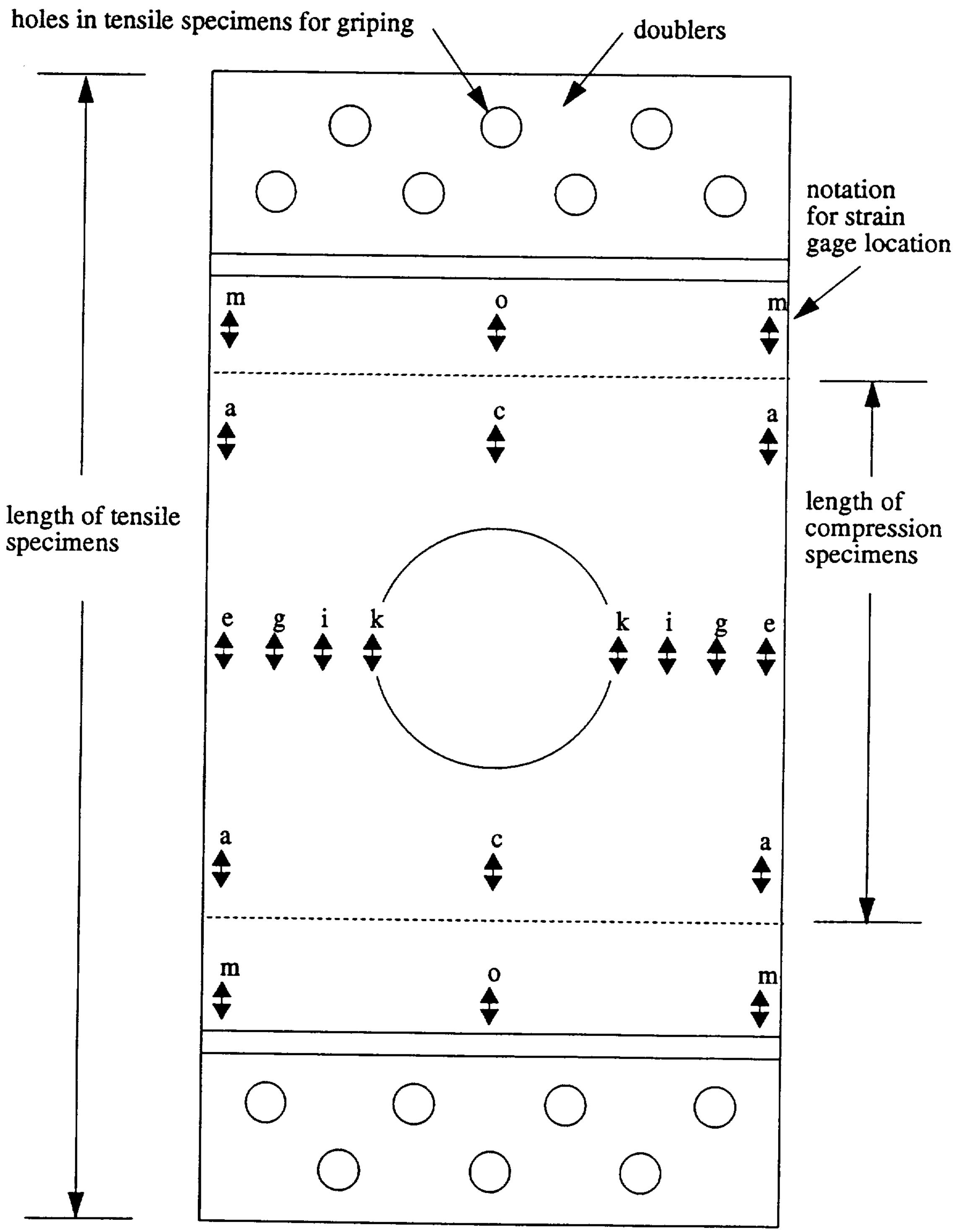


Fig. 10 - Outline of specimens and strain gage locations

for this discussion only these gages will be considered. Displacement transducers measured out-of-plane deflection, overall inplane shortening during the compression tests, and overall inplane lengthening during the tensile tests.

Compression testing

For compression testing the specimens C_1 and Q_1 were trimmed to be square, specifically 0.43 m (17 in.) square. The length of these shorter compression specimens are shown by the dashed lines in fig. 10. Because of the shorter length, gages 'm' and 'o' did not exist on the compression specimens. The edges represented by the dashed lines were ground flat and parallel, and clamping was accomplished by mechanical means, as opposed to using a potting approach. The compression specimens were loaded by placing the specimen vertically in the load frame and displacing the top clamped edge downward a known amount with the upper head of a load frame. The opposite lower clamped edge rested on the lower stationary head of the load frame. Due to the clamping mechanism, the line of clamping was 12.7 mm (0.5 in.) inward of the upper and lower edge of the specimen. The left and right vertical edges of the specimen were simply supported with knife edges running parallel to the loading direction. The line of simple support was slightly inward of the edge of the specimen to accommodate any decrease in plate width due to the out-of-plane deflections during buckling. Thus the unsupported dimensions of the specimen were somewhat less than 0.43 m by 0.43 m (17 in. by 17 in.). To allow for compression in the loading direction, the simple support mechanism did not support the entire length of the vertical edge, there being about a 6.35 mm (0.25 in.) unsupported length along that edge. The compression specimens were painted white on one side to enhance the shadow moire process used to study out-of-plane deflection patterns. Both the baseline straightline format and the curvilinear format plates were instrumented and loaded in compression in identical fashion.

Tensile testing

In preparation for tensile testing, the plates C_2 and Q_2 were trimmed to be rectangular. For the tension testing the plate length was 1.067 m (42 in.). On each end 0.152 m (6 in.) was used for gripping. Steel grips, which held the specimens by bolting them between the two halves of the grip, were used to load the tension specimens. Glass doublers were used in the region of bolting. The glass doublers are shown in fig. 10. The specimens were placed vertically in the load frame and the lower end was displaced downward, with the upper end being held stationary. Both the baseline straightline format and the curvilinear format plates were instrumented and loaded in tension in identical fashion.

TEST RESULTS

Compression

Specimens C_1 and Q_1 were loaded in compression to failure. From the strain response it was evident that for both plates the loading was symmetric across the width of the plate, and from top to bottom. Thus the test data acquired could be considered valid. Both specimens failed at one corner, near the intersection between the clamped end and the simply supported side. Failure was thought to be due to the presence of the gap in the side simple support needed to accommodate the endshortening of the specimen. The load vs. endshortening relation for the baseline and curvilinear specimens are shown in fig. 11. The prebuckling slopes of the two specimens were approximately the same, with the baseline specimen being slightly stiffer. However, the postbuckling slope of the baseline specimen was noticeably less than the postbuckling slope of the curvilinear specimen. Unfortunately, problems with deformations of the simple support fixtures masked the actual postbuckling response of the baseline specimen. Thus comparisons between the two specimens in the postbuckling range are not meaningful. However, the transition from prebuckling to postbuckling was not influenced by these fixture deformations problems. Furthermore, the tests of curvilinear specimens were conducted without any difficulties. The load vs. out-of-plane displacement relations for a point on the net-section edge of the hole are shown in fig. 12.

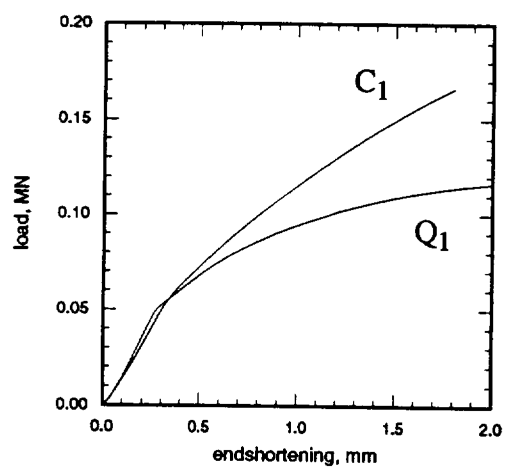


Fig. 11 - Load vs. endshortening during compression testing of curvilinear (C_1) and baseline (Q_1) specimens.

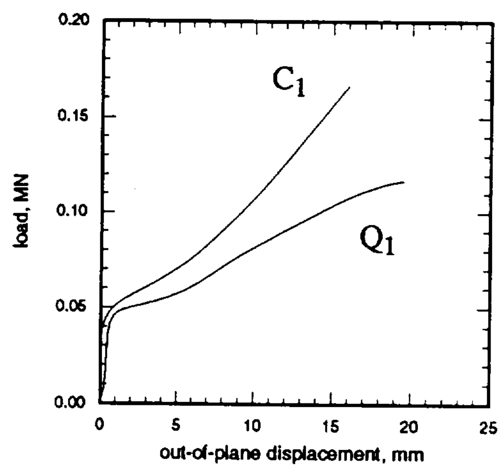


Fig. 12 - Load vs. out-of-plane displacement during compression testing of curvilinear (C_1) and baseline (Q_1) specimens.

Buckling loads were estimated from the experiments by the intersection of least-squares straight lines fit to the load vs. endshortening data just before buckling and just after buckling. With this approach, the buckling load of the baseline panel was estimated to be 49,800 N (11,200 lb.) and the buckling load of the curvilinear panel was estimated to be 56,500 N (12,700 lb.), a difference of about 13%. The various slopes for the two compression specimens are tabulated in Table 1
.

Table 1: Pre- and Postbuckling Slopes of Compression Specimens, MN/m

specimen designation	prebuckling slope	postbuckling slope	percent difference
C_1	188	97	52%
Q_1	204	79	39%

The strains from back-to-back gage pairs at locations 'a' through 'k' are shown in fig. 13. In this figure compressive load is considered positive, as is compressive strain. The back-to-back pairs near the simply supported edge, locations 'a' and 'e,' reflect the fact that both gages of the back-to-back pair are always in compression, whereas, away from the simply supported edges the strains generally start compressive, and as the specimen buckles, the strains on one side of the specimen experience tensile strain. The strains at location 'c' are small so they do not tend to follow either of these trends. Overall, the strain responses of the two specimens are quite similar.

Shadow moire fringe patterns for the two compression specimens at load levels beyond the buckling load area shown in fig. 14. The load levels in the two figures are almost identical and it is seen that both specimens buckled in the (1,1) mode with similar buckling patterns.

Tension

Specimens C_2 and Q_2 were loaded in tension to failure. The strain response indicated that the loading for both plates the loading was symmetric across the width of the plate, and from top to bottom. The baseline plate failed at a load of 0.836 MN (188 kips) and the curvilinear plate failed at 0.609 MN (137 kips). This represents a difference of 37%. The failed specimens are shown in fig. 15. As can be seen, the curvilinear plate failed completely across the net section in what appears to be tensile failure, a classic failure location and a classic failure mode. During the loading, very sharp noises emanated from this specimen, presumably due to fiber breakage. The baseline plate also failed at the net section, but only on the right side. On the left side there was failure at the doubler. The failure was so sudden that it was not possible to ascertain the sequence of events relative to the net section failing before or after the doubler failure. Despite the doubler failure, the tensile capacity of the baseline specimen was higher.

The strains as measured by the gages at the various location on the two specimens are compared in fig. 16. For this figure the strains from the back-to-back pairs were averaged. Until failure the gages at location 'm' registered very much the same strains in the two specimens. The gages at location 'o', however, indicate higher strain in the curvilinear specimen than in the straightline specimen. At location 'a' the curvilinear specimen is more highly strained. However, for the baseline specimen the strain at location 'a' is almost identical to the strain at location 'm'. Thus it appears that in going from location 'm' to location 'a' the strains on the baseline specimen are more uniform. On the curvilinear specimen, the strains increase in going from location 'm' to location 'a.' At location 'c' the two specimens experience about the same strain, and since the location is near the hole edge, the strain levels are quite low. Comparing other strains, the strains at locations 'e' and 'g' are practically identical. At location 'i' the strains for the baseline specimen are slightly higher, while at location 'k' the strains for the curvilinear specimen are higher, specifically 16% higher in the linear range of the load vs. strain relation.

The overall load vs. axial displacement characteristics for the two specimens are shown in fig. 17. It is seen that, overall, the baseline specimen is slightly softer. It must be noted that the displacement being shown in fig. 17 is the motion between the upper and lower heads of the load frame. There are a number of deformations included in this motion, including the deformation of primary interest, namely the deformation due to axial strain in the specimen. Thus is not possible to accurately determine the axial tensile stiffness of the specimens.

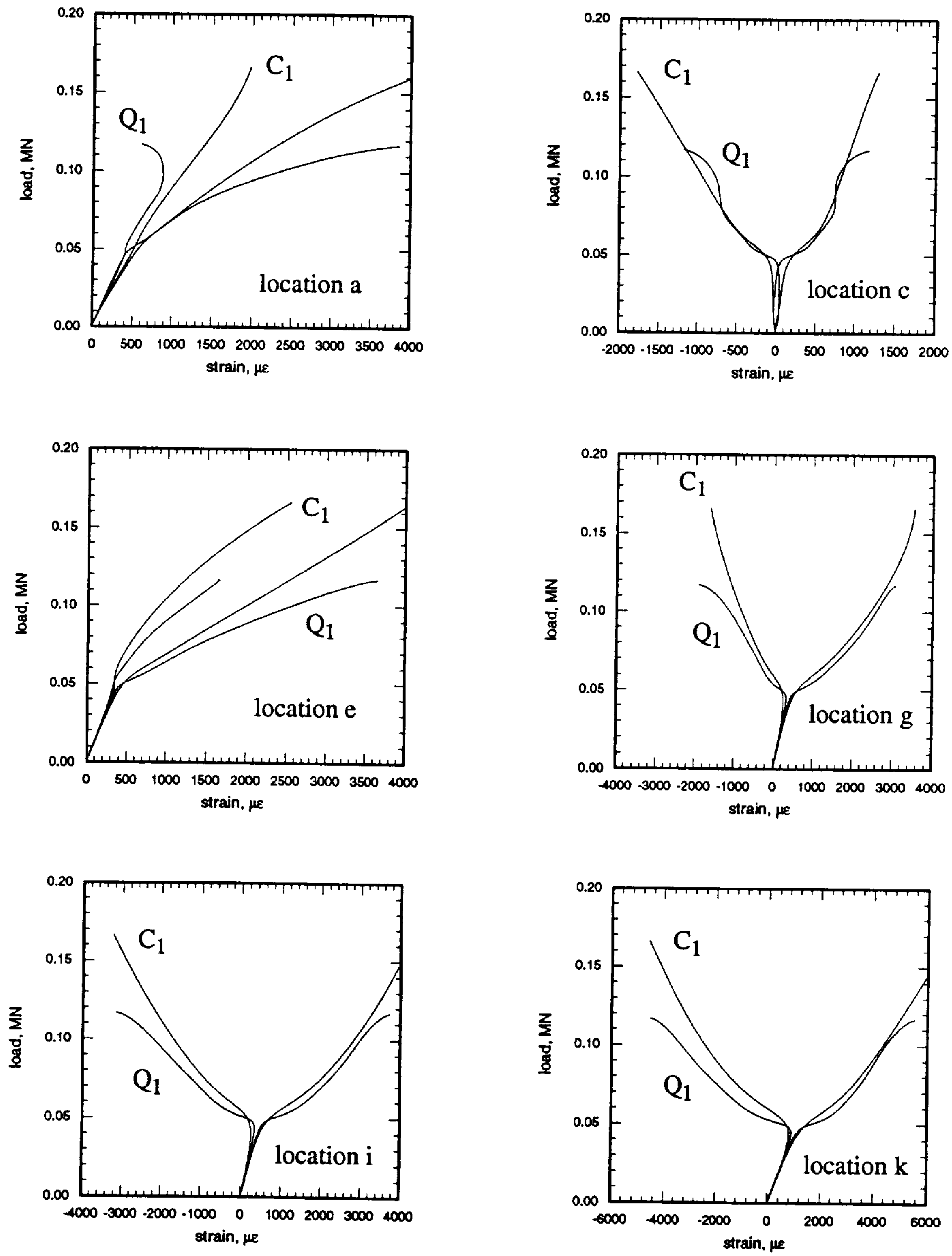
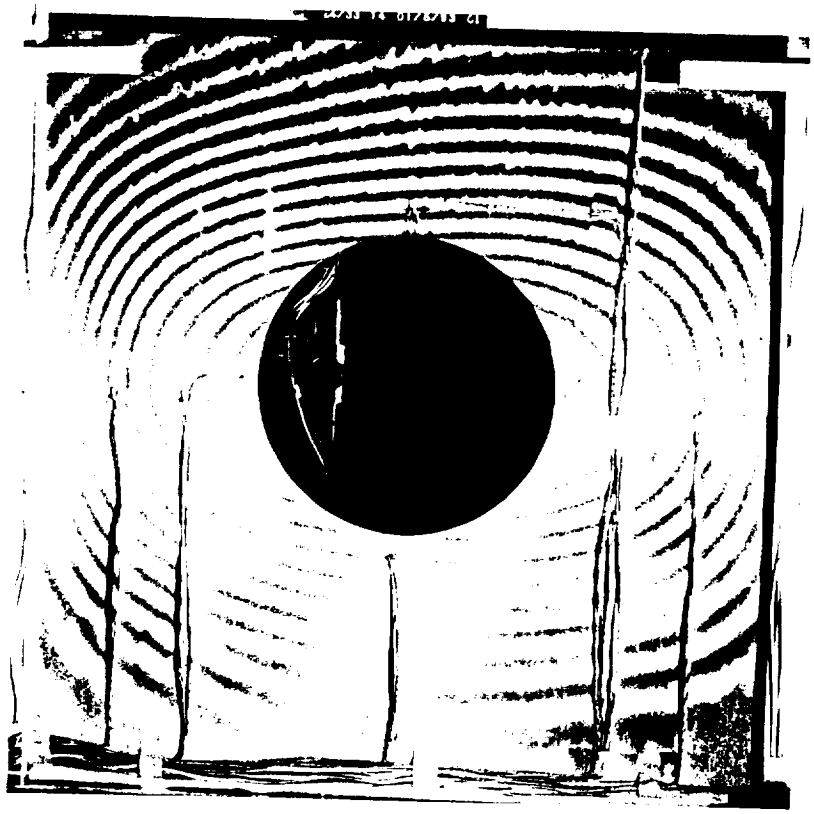
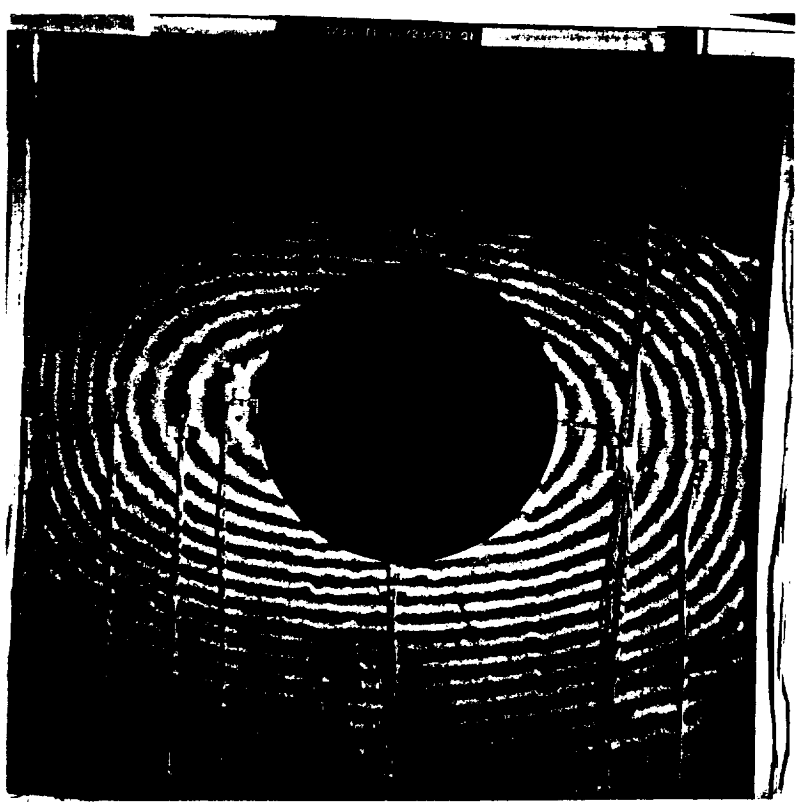


Fig. 13 - Strains at selected locations measured by back-to-back pairs during compression testing of curvilinear (C_1) and baseline (Q_1) specimens

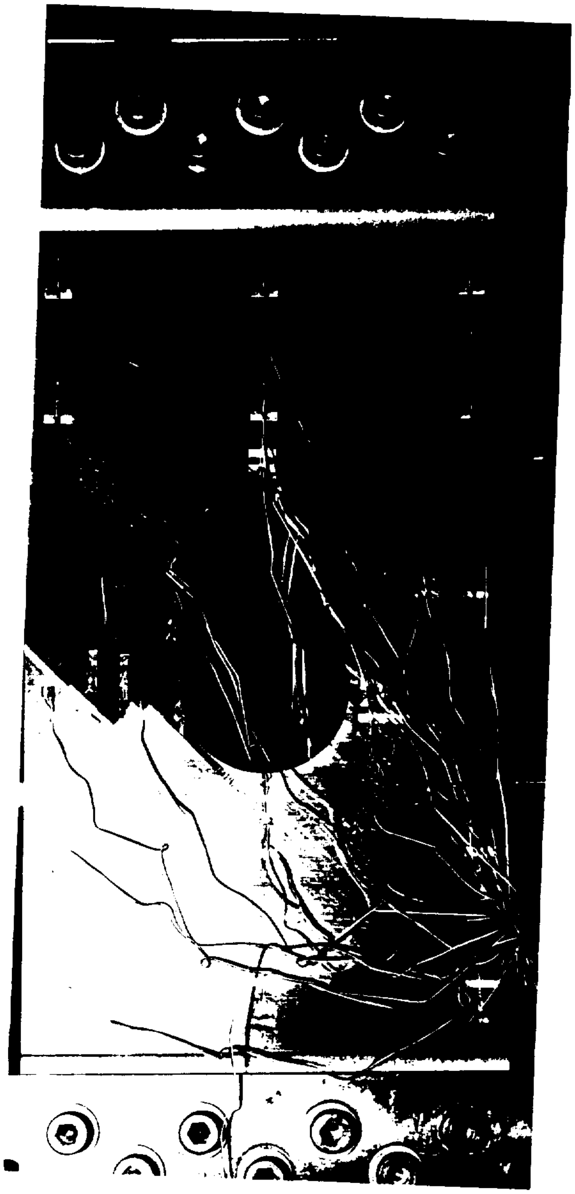


specimen C_1

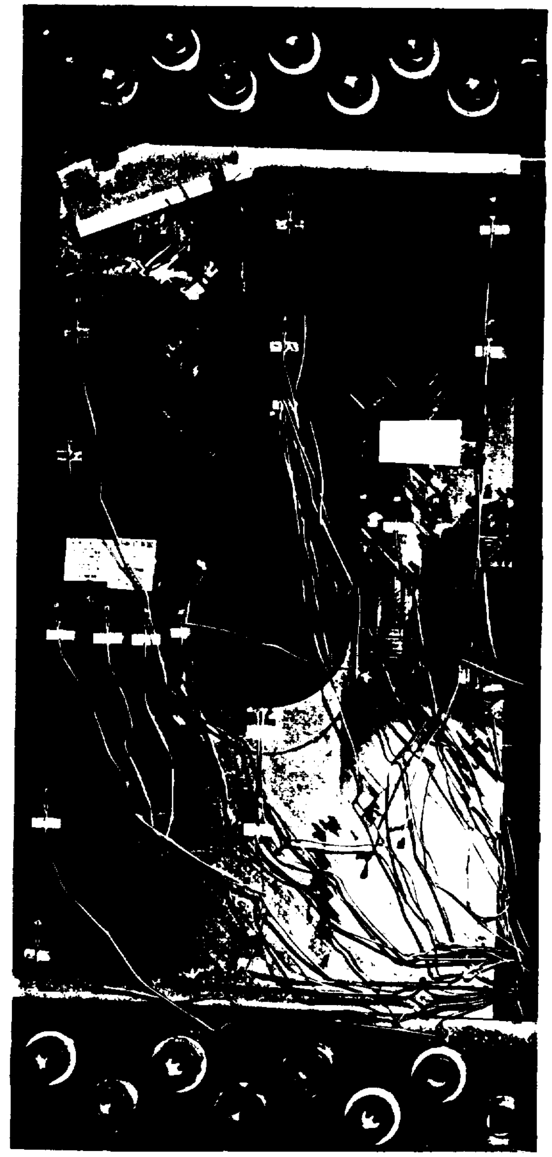


specimen Q_1

Fig. 14 - Shadow moire fringe patterns of postbuckled out-of-plane deflections of compression specimens



specimen C_2



specimen Q_2

Fig. 15 - Failed tensile specimens

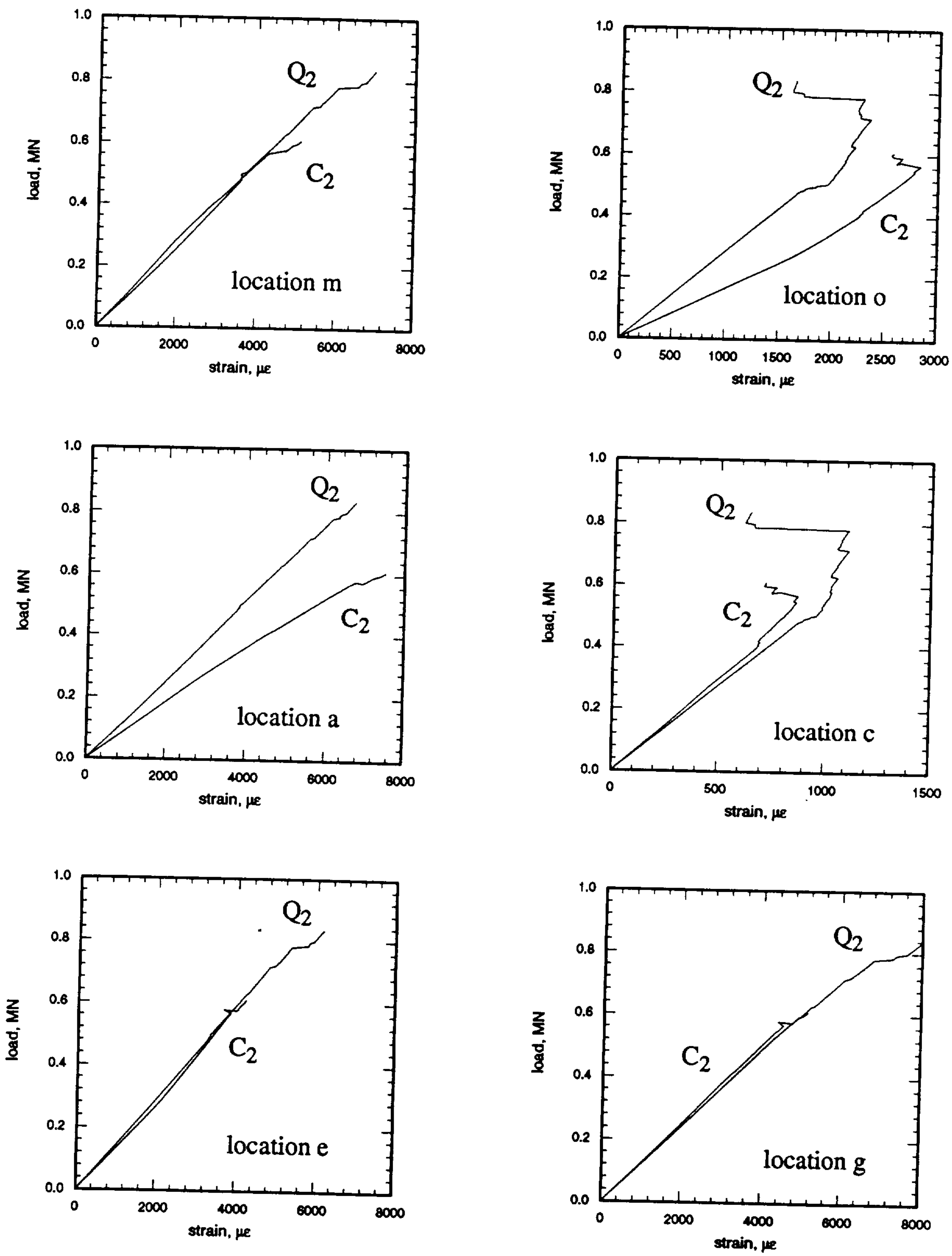


Fig. 16 - Strains at selected locations measured during tensile testing of the curvilinear (C_2) and baseline (Q_2) specimens (average of back-to-back pairs)

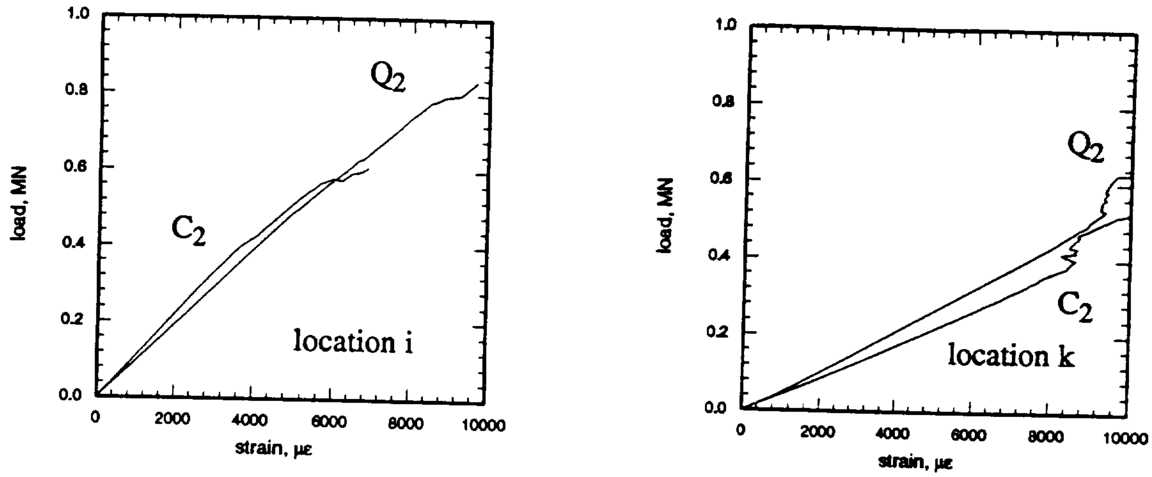


Fig. 16 (cont) - Strains at selected locations measured during tensile testing of curvilinear (C_2) and baseline (Q_2) specimens (average of back-to-back pairs)

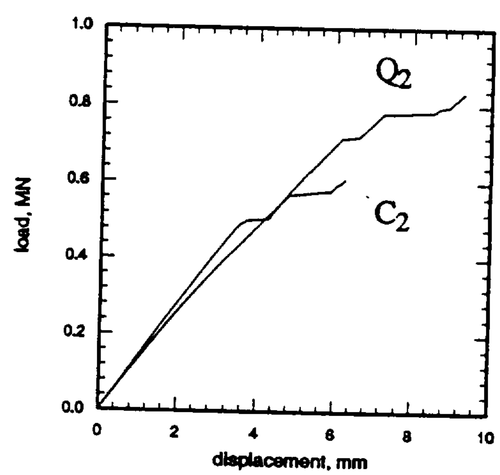


Fig. 17 - Load vs. extension during tensile testing of curvilinear (C_2) and baseline (Q_2) specimens

DISCUSSION

From the results presented here, it appears the curvilinear fiber format can successfully be manufactured with the Cincinnati Milacron fiber placement machine. The C-scans of the curvilinear specimens showed no tell-tale evidence of curvilinear tow paths, and the overall quality of the curvilinear specimens was the same as the quality of the baseline specimens. The particular curvilinear design had a slightly higher buckling capacity, whereas it had considerably less tensile capacity. The lower tensile capacity reflects a weakness in the particular curvilinear design, not in the overall concept of the curvilinear fiber format. To be specific, with the design of fig. 5, 1/3 of the curvilinear tows do not transmit the load from one end of the specimen to the other. In particular, the tows labeled ‘a’ and ‘b’ in fig. 5 cannot transmit much load because they terminate along the edge of the specimen. On the other hand, tows like ‘c’ transmit their load around the hole and to the other end of the specimen. The design of fig. 1 avoids this problem by not having a tow terminate along the edge. Thus tows ‘a’ and ‘b’ in fig. 5 must transmit what load they have to tow ‘c’ through intralaminar shear, an inefficient way for fiber-reinforced composites to transmit loads. Any intralaminar cracking renders tows ‘a’ and ‘b’ ineffective. To overcome this deficiency to the design, the fiber trajectories of tows ‘a’ and ‘b’ should be blended into the net section, as in the design of fig. 1.

ACKNOWLEDGEMENTS

The work reported here was supported in part by Grant NAG-1-901 from the NASA Langley Research Center’s Aircraft Structures Branch to Virginia Polytechnic Institute and State University. The financial support from the Grant is greatly appreciated.

REFERENCES

1. Cooper, A.A.G., “Trajectory Fiber Reinforcement of Composite Structures,” Ph.D. Dissertation, Washington Univ., St. Louis, MO, 1972.

2. Heller, R.A. and Chiba, T., “Alleviation of the Stress Concentration with Analogue Reinforcement,” *Experimental Mechanics*, vol. 13, no. 12, pp. 519-525, 1973.

3. Hyer, M.W. and Charette, R.F., “Use of Curvilinear Fiber Format in Composite Structure Design,” (Tech. Note) *AIAA J.*, vol. 29, no. 6, pp. 1011 - 1015, 1991.

4. Katz, Y., Haftka, R.T., and Altus, E., “Optimization of Fiber Directions for Increasing the Failure Load of a Plate with a Hole,” *Proceedings of the American Society of Composites 4th Technical Conference*, ed. K.L. Reifsnider, Technomic Publishers, Inc., Lancaster, PA, pp. 62-71, 1989.

5. Hyer, M.W. and Lee, H.H., “The Use of Curvilinear Fiber Format to Improve Buckling Resistance of Composite Plates with Central Circular Holes,” *Composite Structures*, vol. 18, pp. 239-261, 1991.

BIBLIOGRAPHIC DATA SHEET	1. Report No. VPI-E-94-08	2.	3. Recipient's Accession No.
4. Title and Subtitle Innovative Design of Composite Structures: Design, Manufacturing, and Testing of Plates Utilizing Curvilinear Fiber Trajectories			5. Report Date November 1994
			6.
7. Author(s) M.W. Hyer, R.J. Rust, and W.A. Waters, Jr.			8. Performing Organization Rept. No. VPI-E-94-08
9. Performing Organization Name and Address Virginia Polytechnic Institute and State University Department of Engineering Science and Mechanics Blacksburg, VA 24061-0219			10. Project/Task/Work Unit No.
			11. Contract/Grant No. NAG-1-901
12. Sponsoring Organization Name and Address Structural Mechanics Branch NASA Langley Research Center Hampton, VA 23681-0001			13. Type of Report & Period Covered Final Report 8/15/88 - 12/31/93
			14.

15. Supplementary Notes

Report appeared as paper in Proceedings of the 10th DoD/NASA/FAA Conference on Fibrous Composites in Structural Design, April 1994.

16. Abstract

As a means of improving structural design, the concept of fabricating flat plates containing holes by incorporating curvilinear fiber trajectories to transmit loads around the hole is studied. In the present discussion this concept is viewed from a structural level, where access holes, windows, doors, and other openings are of significant size. This is opposed to holes sized for mechanical fasteners. Instead of cutting the important load-bearing fibers at the hole edge, as a conventional straightline design does, the curvilinear design preserves the load-bearing fibers by orienting them in smooth trajectories around the holes, their loading not ending abruptly at the hole edge. Though the concept of curvilinear fiber trajectories has been studied before, attempts to manufacture and test such plates have been limited. This report describes a cooperative effort between Cincinnati Milacron Inc., NASA Langley Research Center, and Virginia Polytechnic Institute and State University to design, manufacture, and test plates using the curvilinear fiber trajectory concept. The paper discusses details of the plate design, details of the manufacturing, and a summary of results from testing the plates with inplane compressive buckling loads and tensile loads. Comparisons between the curvilinear and conventional straightline fiber designs based on measurements and observation are made. Failure modes, failure loads, strains, deflections, and other key responses are compared.

17. Key Words and Document Analysis. 17a. Descriptors

composite materials, composite structures, plates with holes, buckling, curvilinear fibers, manufacture of composites, tow placement

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group 24-01, 39-02, 39-08

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Unclassified	UNCLASSIFIED	21
	20. Security Class (This Page) UNCLASSIFIED	22. Price