CURVATURE EFFECTS ON THE DAMAGE TOLERANCE OF IMPACT DAMAGED COMPOSITE SANDWICH PANELS

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SUMMARY: An experimental program was conducted to investigate the effects of specimen curvature on the residual compression strength of impact damaged composite sandwich panels. The damage level studied corresponded to Barely Visible Impact Damage (BVID). Flat and curved (1.1 m radius) specimens of two widths (152 mm and 305 mm) were manufactured. A drop mechanism was used to create BVID on one facesheet of the panels (convex face of the curved panels). All specimens were then loaded axially in compression to failure. The results demonstrate that panel curvature does have some effect on the local BVID propagation. Panel curvature on the order of 1.1 m radius has little effect on the ultimate axial load capacity of test specimen.

KEYWORDS: damage tolerance, sandwich structures, barely visible impact damage

INTRODUCTION

Sandwich structures with thin composite facesheets are used extensively in aerospace structures because of their high efficiency (stiffness/weight). A disadvantage of these types of structures is their susceptibility to low velocity impact damage (low damage resistance). Low energy impact damage can cause a significant reduction in the ultimate compression strength of a composite sandwich panel and yet not be easily detected using visual inspection methods. Primary aircraft structures are routinely inspected using visual methods. Barely Visible Impact Damage is the damage level corresponding to the threshold of detectability of a visual inspection.

To determine design values for sandwich structures with BVID, empirical data is used with specimens impacted and tested in compression to failure. Typically, these specimens are flat and 82.6 mm in width.

Several studies have been done both to model the impact event (damage) and to predict the residual strength of the damaged panels. Kassapoglou conducted several studies related to the damage tolerance of composite laminates and thin gage sandwich panels by modeling the damage as delaminations and a debond[1-4]. Minguet presented a different approach to modeling the residual strength of damaged sandwich structures in which the damage is modelled as a facesheet indentation with core damage[5].

In the literature, damage resistance refers to the ability of the structure to remain undamaged after an impact event. Damage tolerance refers to the ability of the structure to withstand load after being damaged. Cairns conducted an extensive analysis of the impact response of composite laminates[6]. Damage is modeled as a reduced stiffness elliptical inclusion. Lie developed analytical models to describe the impact event and compression failure of thin gage composite sandwich panels[7]. As an extension to the work by Cairns, the damaged panels are modeled as an intact panel with an elliptical hole representing the damage. Lagace et al[8] investigate the damage resistance and damage tolerance of some specific layups and materials. It was noted that panels with low energy impact damage showed no reduction in tensile strength, but had a significant loss of compressive strength.

There is no data in the literature concerning the effects of curvature on the compression strength of damaged sandwich panels.

APPROACH

The energy level required to cause BVID in standard 82.6 mm flat test specimens was determined using 20 test panels. The impact energy level was varied for each panel until BVID level was determined. This energy level was kept constant throughout this test program.

Curved and flat panels were manufactured and cut into two widths. The testing program is given in Table 1. Each panel was damaged using the same impact energy level determined from the 82.6 mm specimens. All test specimens were instrumented with strain gages. The panels were then mounted in the test fixture and loaded axially in compression to failure. Load, stroke, and strain gage data were recorded during the test.

Table 1. Testing Matrix

	152 mm	305 mm
Flat	7	7
Curved	7	7

From the collected data, the effect of curvature and width on the ultimate compression strength of test specimens could be determined. Localized BVID propagation was also studied.

MANUFACTURING OF TEST PANELS

The curved panels were manufactured using an aluminum cure plate with a 1.1 m radius of curvature. All panels were assembled and loaded in the axial direction.

The sandwich panels were produced using a 25.4 mm, 48 kg/m^3 Nomex honeycomb core with 3.2 mm hexagonal cells. The facesheet material is AS4/3501-6 pre-impregnated uni-directional graphite epoxy and assembled in a $[90/0]_S$ configuration. FM300 film adhesive was used to bond the facesheets to the core.

The facesheets were cured and bonded to the core concurrently (co-cured). The prepreg manufacturer's recommendations were followed for the cure in the autoclave with one exception; a reduced autoclave pressure of 276 KPa was used during the cure so as not to crush the honeycomb core. Aluminum bars were used around the free edges of the panel in order to prevent core damage at the edges of the panel during the cure due to vacuum bag pressure. Cured panel size was 508 mm by 356 mm.

The cured panels were cut to the determined specimen size using standard diamond saw tooling. In this test program, panels were cut to widths of 152 mm and 305 mm. All test specimens were 356 mm long.

To validate the manufacturing process used in this program, some of the panels were non-destructively examined using a pulse-echo ultrasonic scan. Any voids or other flaws in the facesheets could be detected.

IMPACT DAMAGE

The impact damage was performed using a standard drop tower with a 25.4 mm diameter stainless steel hemispherical tup. The mass of the impacting apparatus was 1.31 kg. The specimens were clamped across the width (top and bottom) with a span of 229 mm and impacted at the center of the specimen.

BVID has been characterized[4] as the energy level required to cause the indentation left by the impact and the associated local damage to be barely visible from a distance of 1.2 m. The required energy level for BVID of this material and lay-up was determined in a previous study[9] where 20 test specimens were impacted at increasing energy levels until BVID was reached. Using the methods recommended by Kassapoglou, it was determined that the BVID energy level for the test specimens was 5.88 J. This impact energy level was used for all test specimens.

On these specimens, BVID is typically a small indentation (less than 0.51 mm in depth) with little or no matrix cracking or fiber breakage.

INSTRUMENTATION

Strain gages were installed on the test panels to capture the response to loading (Figure 1-2). The gages were installed near the damage and in line with the expected indentation propagation. Gages were also installed on the back facesheet in order to gain insight into the transfer of loading to the back facesheet.

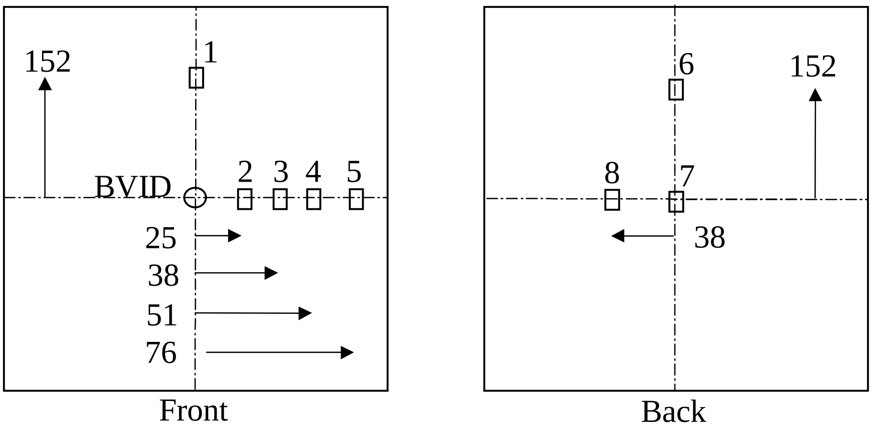

Figure 1. Strain gage locations for 305 mm specimens (mm)

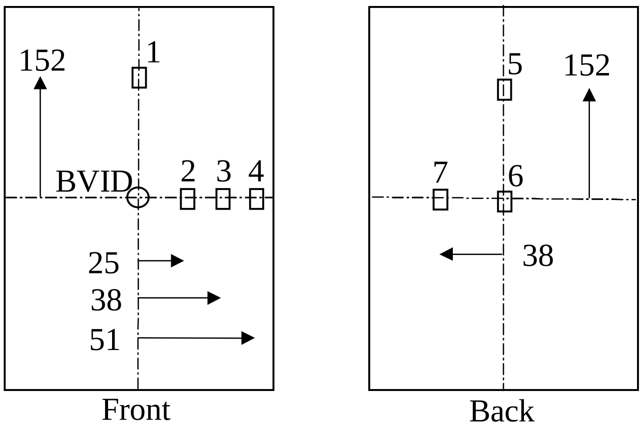

Figure 2. Strain gage locations for 152 mm specimen (mm)

TEST FIXTURES

Some investigation went into the development of an appropriate gripping system for the test specimens that could be used for flat or curved panels up to 305 mm in width. Because of the relatively low out of plane strength of the Nomex honeycomb core, a conventional gripping system could not be used. In addition, limitations in the grip width of the testing machine and the curvature of the test specimens necessitated an alternative method.

A method in which the ends of the test specimens were potted provided a suitable alternative. Typically, sandwich panels are potted in a resin material. The resin is then machined to be compatible with the testing machine grips. This method is time consuming due to the required steps and the failed specimen cannot be removed from the resin after testing. In this program, the specimens were potted in a low melt (70 ºC) Bismuth metal alloy. The melting temperature of the alloy was sufficiently low so as not to cause damage to the composite facesheets or Nomex core. This potting system had several advantages in that the test specimens could be removed intact, no machining was required between tests, and the potting material could be reused.

The fixed end condition was accomplished by using aluminum end molds to contain the ends of the test panels and the potting material. These end molds could be attached to the testing machine. Alignment plates were used to fix the end molds in the proper position. The test panel was centered in the fixture with tabs and secured in place. To prevent voids due to rapid cooling of the potting alloy upon contact with the molds, the end molds were heated to the melting temperature of the alloy. The alloy was heated to 82 ºC and poured around the test panel. The mold was allowed to cool before the process was repeated for the other end. The alignment plates also prevented the heavy end fixtures from loading the test specimen during handling before the test.

When the ends of the specimen were potted, the end molds were fastened to the end plates and steel round bars. These round bars were then gripped in the testing machine. The alignment plates were removed before the compression test.

After testing, the broken panels were removed from the fixture by heating the end molds and draining out the potting material.

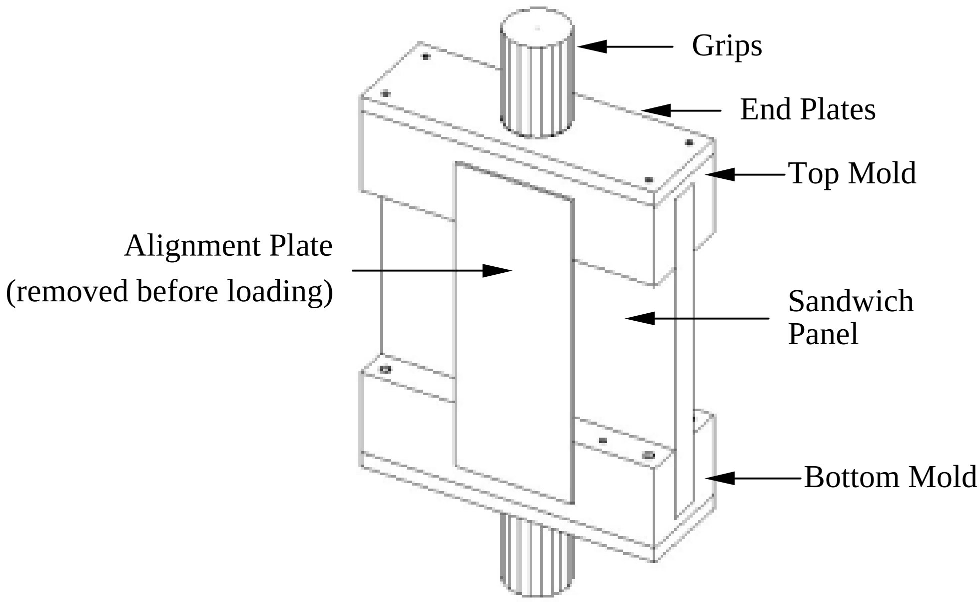

Figure 3. Gripping system (flat panel)

COMPRESSION TESTING

The test specimens were loaded to failure using a MTS uni-axial testing machine. The test was stroke controlled with a ramp rate of 0.0254 mm per second. Load, stroke, and strain gage data were collected at 0.2 second intervals.

Under compression, there appeared to be a point at which the indentation caused by the impact began to grow perpendicular to the loading direction. This observable indentation slowly propagated to approximately 25.4 mm from the centerline of the panel. At this point, it appeared as if the indentation propagation stopped.

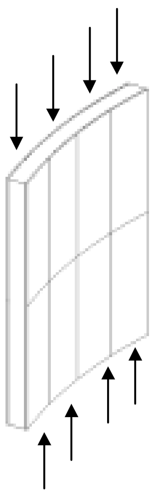

Figure 4. Axial loading direction

The final failure of the panel occurred when the front facesheet experienced a localized buckling (crippling) due to the stress concentration at the edge of the damage indentation. The front facesheet crippled suddenly across the width of the specimen. The weakening of the front facesheet caused the load to be transferred to the back facesheet where the high eccentric load caused a global type buckling of the back facesheet.

RESULTS

The testing program demonstrated the ultimate strength of the flat and curved test panels (Table 2). The results indicate that there is not a significant difference in the ultimate compression strength between flat and curved panels (on the order of 1.1 m radius).

Table 2. Average Ultimate Stresses

		Ultimate	
Flat	15.2 cm	181.0 (MPa)	13.1% (c.v.)
	30.5 cm	187.0 (MPa)	8.63% (c.v.)
Curved	15.2 cm	172.5 (MPa)	15.6% (c.v.)
	30.5 cm	188.6 (MPa)	4.70% (c.v.)

In addition to recording the ultimate strength of the test specimen, strain gage data was examined to look for evidence of the indentation propagation and stress concentration. This data was plotted against the average stress in the panel (Figures 5-8). In these plots, a change in slope indicates a change in load path. An increase in slope indicates a unloading in the area of the strain gage where a decrease in slope indicates an increased loading in the area of the gage.

Under compressive load, the indentation cause by the damage propagates perpendicular to the loading direction. When this indentation begins to spread to 25.4 mm from the centerline, gage #2 shows a change in slope. This load defines the point of damage propagation initiation. Lin6[10] calculates linear and transition sections of data as well as how close the data matches the linear sections. Lin6 was used to identify the load at which the slope of gage #2 changed, indicating damage propagation initiation. These points are shown on Figure 9.

The curved panels demonstrated damage propagation at a slightly higher load that the flat panels (Table 3).

Table 3. Average Damage Propagation Points

		Propagation Initiation Point	
Flat	15.2 cm	102.9 (Mpa)	13.1% (c.v.)
	30.5 cm	127.4 (Mpa)	8.63% (c.v.)
Curved	15.2 cm	110.6 (Mpa)	15.6% (c.v.)
	30.5 cm	139.5 (Mpa)	4.70% (c.v.)

It is apparent from the figures that gage #3 (located 38.1 mm from the panel centerline) does not change in slope until just before failure. This is consistent with the observed indentation propagation arrest event.

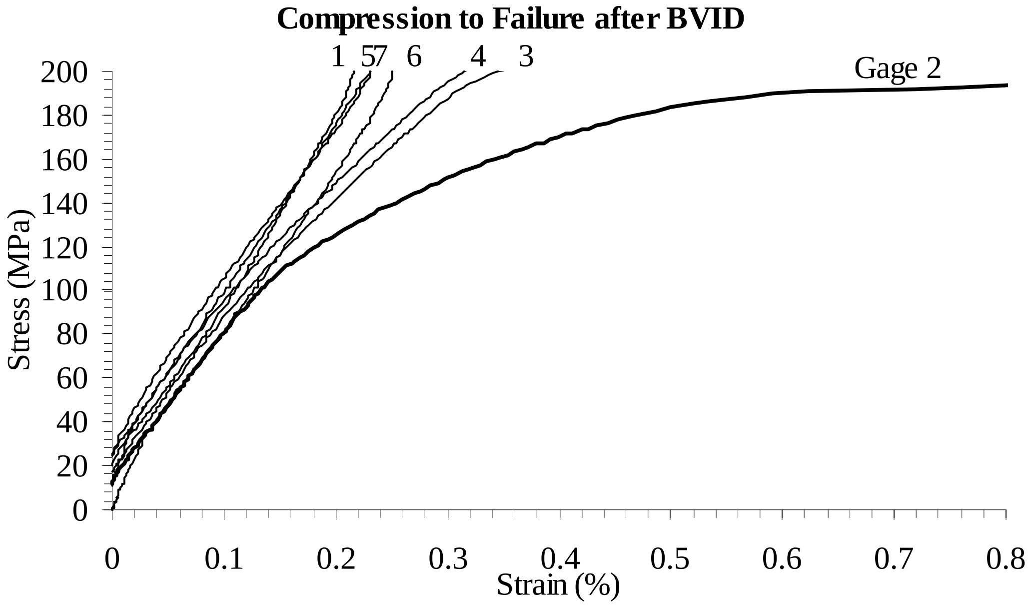

Figure 5. Strain gage data from flat 152 mm test specimen

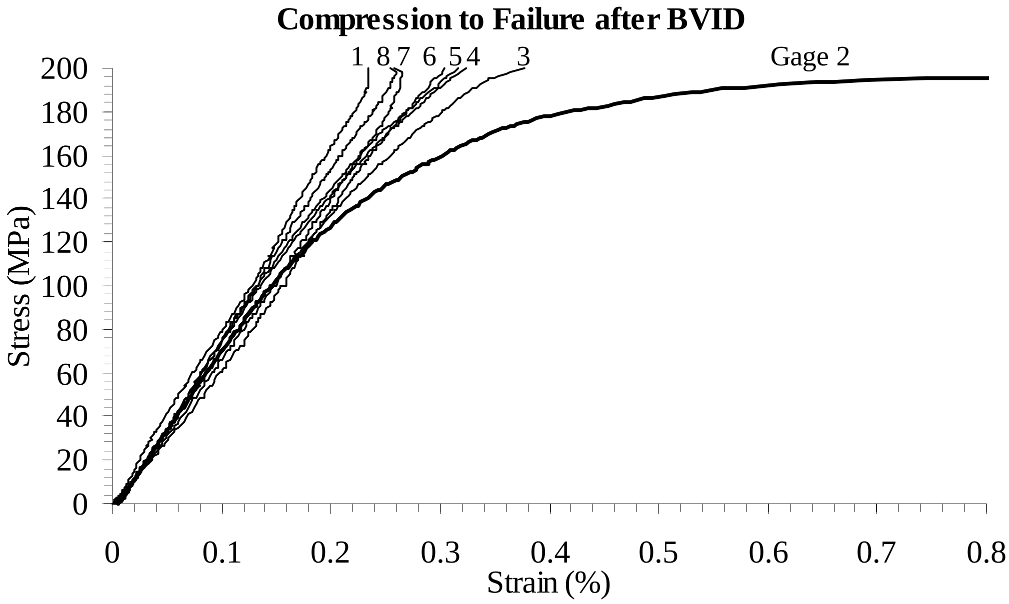

Figure 6. Strain gage data from flat 305 mm test specimen

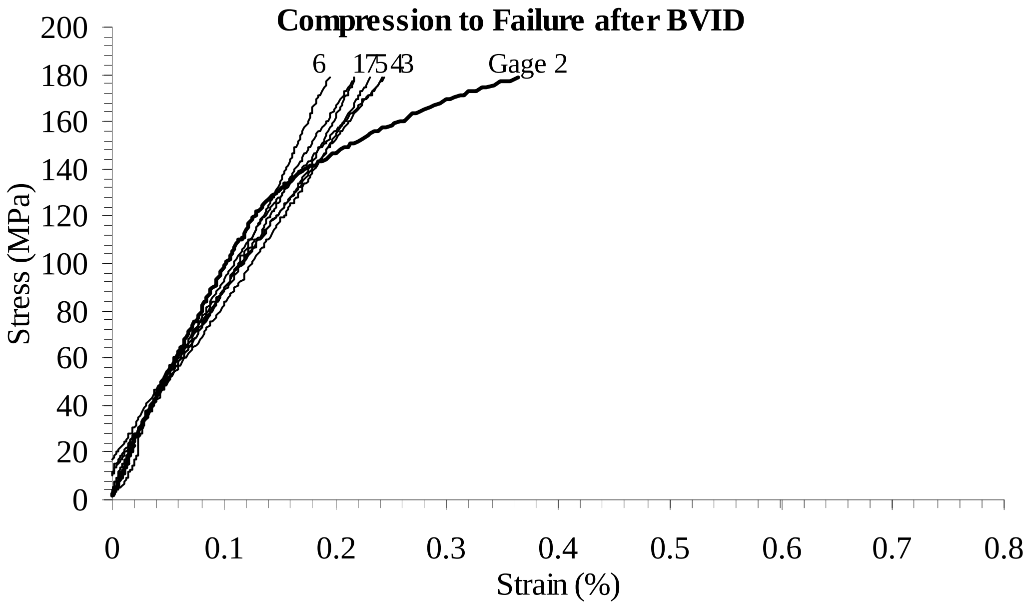

Figure 7. Strain gage data from curved 152 mm test specimen

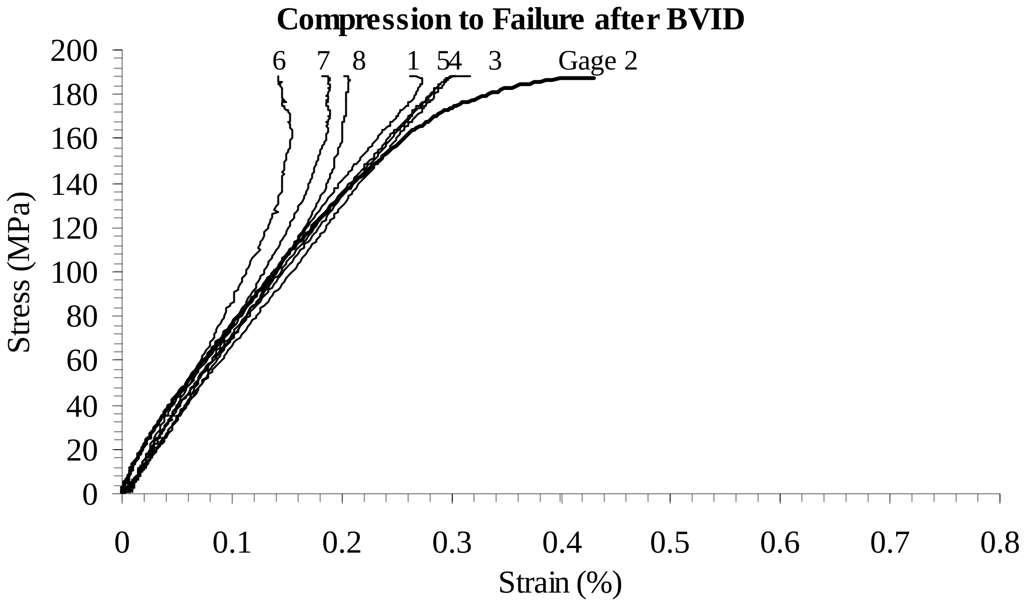

Figure 8. Strain gage data from curved 305 mm test specimen

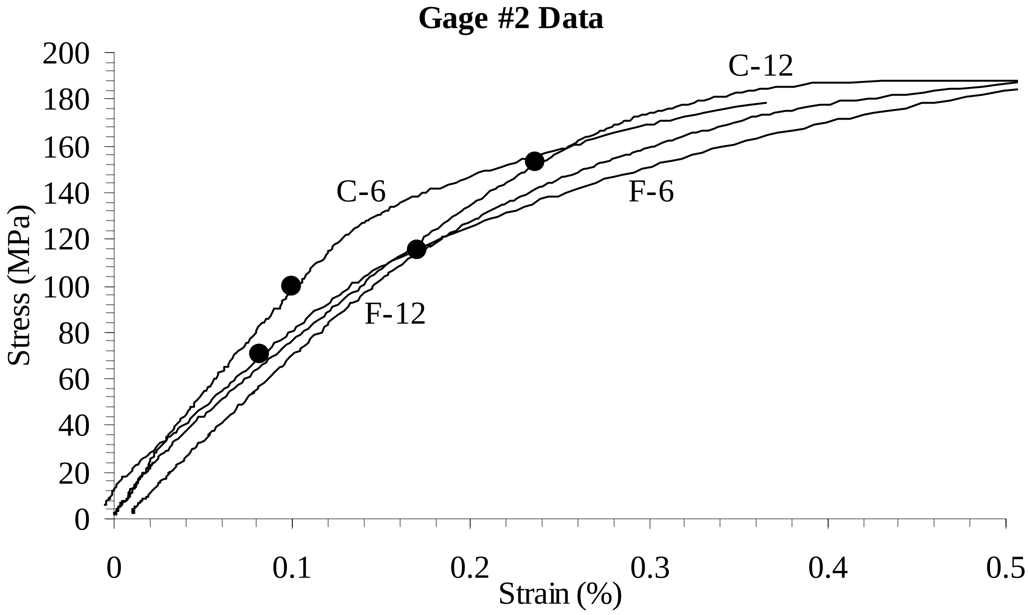

Figure 9. Gage #2 data from four test panels

CONCLUSIONS

The failure mechanism and ultimate strength of the BVID composite sandwich panels tested under axial compression is independent of the specimen curvature (with curvatures on the order of 1.1 m radius).

An investigation of the strain gage data shows that the damage begins to propagate in the curved panels at a slightly higher load than the propagation load of the flat panels.

The typical 82.6 mm flat test specimens can be used to determine the design values for both flat and axially loaded curved panels with some degree of accuracy.

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