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Experimental Investigation of the Impact Response of Cylindrically Curved Laminated Composite Panels

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Abstract

An experimental investigation was carried out on three different geometries for specimens which are cylindrically curved: 8 ply panels, with two radii of curvature, 0.381 m and 1.524 m; and 16 ply panels, with a radius of cuvature of 0.381 m. The panels were impacted by a mass dropped from a selection of heights. The impact force and panel center deflection were recorded with time. Each panel was C-scanned to determine the amount of damage present after impact, if any.

Experimental results revealed that the geometry of a laminated composite structure strongly influences its impact response. It was shown that stiffer structures produce higher impact forces, smaller center deflections, and shorter contact duration times. The relative stiffness of each panel was explained by considering its load-deflection response. Normalization of the force with respect to the critical dynamic load and the displacement with respect to the panel height is essential when comparing the response of panels with different radii of curvature. A static nonlinear finite element model was developed and used for comparison with the experimental impact data in an attempt to interpret the response behavior of these cylindrically curved panels.

Introduction

Damage resulting from impact and stress concentrators such as holes is a major concern for structural designers because they are commonly the limiting design criteria for aerospace structures made of composite materials. Impact damage may occur during fabrication, maintenance, or operational use of a composite structure due to foreign object impact such as dropped tools, bird strikes, hail, or runway debris. The strength of an impacted composite wing panel, for example, may be severely reduced by extensive delamination and matrix cracking in the middle layers of the laminate, yet the impacted face may not reveal any visible damage and thereby go unnoticed during inspection. A clear need exists to predict the type and extent of damage in a composite structure subjected to impact and to understand how this damage affects the residual strength of that structure.

The response of laminated composite structures subjected to low velocity impact has been extensively researched. Much work has been done on the impact of flat composite plates, through both analysis [1-4] and experiment [5-9]. To a lesser extent, the influence of curvature on impact response has also been studied [10-12]. The purpose of the present paper is to present and discuss experimental impact tests which have been conducted on laminated composite cylindrically curved panels, with specific focus on the influence of curvature and thickness.

Test Specimens and Experimental Setup

Three different geometries of specimens were investigated: 8 ply panels, 1.02 mm thick, with two radii of curvature, 0.381 m and 1.524 m; and 16 ply panels, 2.03 mm thick, with a radius of cuvature of 0.381 m. The curved cylindrical specimens, 0.254 m in the axial direction and 0.127 m in arc length, were fabricated from Hercules Inc. AS4 graphite fiber tape and 3502 epoxy resin. Quasi-isotropic material properties were achieved by using a $[+45/0/-45/90]_{ns}$ laminate stacking sequence, where $n = 1$ or 2 for the cases considered here. The AS4/3502 lamina mechanical properties are given in Table 1.

The impact tests were conducted at NASA Langley at the impact facility in the Aircraft Structures Branch.

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The impact testing apparatus used consisted of a mass, instrumented with a force transducer, dropped vertically from any height up to 6 feet and caught after impact to prevent double hits. In these tests, a 1.13 kg mass was dropped from heights of 9.1, 12.2, 15.2, 24.4, 30.5, and 36.6 cm. The impactor was equipped with a 12.7 mm diameter steel hemispherical tip.

The curved edges of the test specimens were rigidly clamped while the straight edges were supported with knife-edge boundary conditions. The specimen, in its supporting fixture, was positioned such that the point of impact would coincide with the center of the specimen. To ensure the actual location of impact could be measured, the top surface of the specimen was painted in the impact region and a piece of carbon paper was placed over that area. In this manner, the actual contact zone left a mark on the panel during the impact tests, enabling measurement of its location relative to the center of the specimen. For the present tests, the observed variations from central impact were less than 2 mm. The sketch in Figure 1 illustrates the test configuration.

A Philtec Model H88NE3 fiber optic displacement sensor was used to measure the gap between the probe and the specimen. The optical sensor is sensitive to the amount of light present, the optical quality of the target surface, the level of voltage supplied by its power source, and the bending of the optical cable. A piece of vinyl yellow tape was placed on the underside of the specimen to unify the reflectance on the surface for the optical sensor. The sensor was calibrated to the reflectance of the yellow tape. The optical probe was positioned to measure the center displacement. Force and displacement signals were appropriately filtered and then recorded on a digital storage oscilloscope.

Results and Discussion

To identify the level of impact energy at which damage is initiated for the particular circumstances, the specimens underwent a C-scan after each impact test to determine if any damage had been produced. If no damage was evident, that panel was impacted again until damage occurred. Table 2 lists the test matrix values for these impact tests. Force and displacement measurements were taken for each of nine cases. An example of typical force and displacement measurements is shown in Figure 2(a) and Figure 2(b) for the three different geometries, each subjected to 1.36 N-m of impact energy.

The maximum force as a function of impact energy is plotted in Figure 3, for every case tested. The thicker 16 ply specimens exhibit a higher maximum force than the 8 ply specimens for the same radius of curvature. For the same thickness, the larger radius of curvature results in a higher maximum force. The larger radius of curvature appears to behave like a stiffer structure. This behavior may be explained by considering the large deformation response of a cylindrically curved panel under a centrally applied point impulsive load with focus on the stiffness relaxation exhibited in the force-deflection response, which for some cases is similar to the dynamic stability phenomenon observed in thin, shallow, clamped, spherical shells (13, 14).

A snap-through event occurs when the load increases until the panel deflects through some critical amount, after which the load relaxes, until the panel resists the motion again in its inverted state. For the cylindrically curved panels tested, the boundary conditions (clamped on the curved edges and knife supports on the straight edges) make the panels stiffer than panels which are simply-supported on all sides, and as such are less likely to exhibit snap-through behavior. Instead, for some of the impact tests the force-deflection response reaches an inflection point, where at some load the displacement experiences a large jump, but then the stiffness increases again as the panel resists motion in its inverted state. If at some load the displacement does experience a large jump, that load can be defined as the dynamic critical load, according to the Budiansky-Roth criterion (13). In other cases, the impacted panels did not even experience an inflection point in the force-deflection response, thereby continuously increasing in stiffness.

Figures 4-7 show the force-deflection response of the cylindrically curved panels examined for a static nonlinear finite element model and the impact test data. A dynamic nonlinear FEM model is currently under development for completeness of comparison. For each impact test result shown, the sampled data was fitted with a fifth order curve for both the increasing and decreasing portions of the force-deflection history. Arrows indicate the directions of those curves. For all but one case (8 ply, 1.524 m radius panel impacted with 1.36 N-m), the loading path leads the unloading path. In those cases where the loading path leads, the difference between the curves might possibly be accounted for through consideration of inertia, vibration, friction, or energy lost due to damage formation, if any, but such effects were not included in the present analysis. In the other case where the loading path lags, the paths are close enough together to fall within the scatter-band of error which may come from the actual gathering of data and fitting the data to a curve.

In the present FEM analysis, the clamped curved edges are modelled as fixed in all degrees of freedom. The knife supports on the straight edges are modelled as fixed in the radial direction (r), but may or may not be fixed in the circumferential direction (s). Static FEM results are given for either set of constraints. By allowing the model panels to move in the circumferential direction, a reduction in the stiffness is noticeable in the force-deflection response.

The thicker, 16 ply, panels with the smaller 0.381 m radius of curvature is shown in Figure 4. Three curves are for the impact data at various impacting energies and two curves are shown from the FEM using the different circumferential boundary conditions. Each impact response curve approximately follows the static model where the circumferential boundary is free.

The thinner, 8 ply, panels with the 0.381 m radius of curvature is displayed in Figure 5. Again, each impact response curve more closely follows the static model where the circumferential boundary is free. The initial dynamic stiffness for both impact energy levels lies between the initial stiffnesses of the static model with the two boundary conditions. Yet in the large deformation regime, the dynamic stiffnesses are lower than the static model with the circumferential direction free. Comparison of the impact data for the two impact energy levels reveals that the higher impact energy produces a stiffer force-deflection response. The response of the thinner, 8 ply, panel with the 1.524 m radius is shown in Figure 6. Here, the impact response curves more closely follow the static model where the circumferential boundary is fixed.

Perhaps the most interesting result from these experimental impact tests can be seen by comparing the influence of curvature on the force-deflection response for a fixed thickness and impact energy as shown in Figure 7(a) for the thinner, 8 ply panels, at an impact energy of 1.02 N-m. In the small deformation regime, the more curved (0.381 m radius) panel behaves more stiffly than the shallower panel. However, in the large deformation regime, the shallower panel apparently behaves more stiffly. Although counterintuitive, a clearer picture emerges when the data are appropriately normalized. The same force-deflection response is presented in Figure 7(b), but the force is normalized with respect to the critical dynamic load and the displacement is normalized with respect to the panel height. When normalized, and evaluating only the effect of curvature, it can be seen that the more curved panel has a response behavior with some similarity to the shallower panel, however each response has not progressed the same amount along its path. The critical dynamic load can be approximated in this case by the Budiansky-Roth criterion which was discussed earlier in terms of the inflection point. The panel height, H, is the distance from the center of the panel to the chord, as marked in Figure 1. This normalization is essential when comparing the response of panels with different radii of curvature.

Thus, when impacted with an impact energy of 1.02 N-m the shallower, 1.524 m radius, panel is perturbed into the re-stiffening branch of the load-deflection response, that is, the deflection is very large; it approaches three times its panel height (Figure 7(b)). The 0.381 m radius panel, on the other hand, might undergo a certain amount of bending before going through its inflection point when impacted with an impact energy of 1.02 N-m and therefore it deflects just beyond one of its panel heights.

Simitses, in his book (15) and previous work discusses the conceptual definition of dynamic stability. Dynamic stability applies to structures which are capable of unstable buckling under static loading. For the specific geometry, material, loading, and boundary conditions considered in these tests, it is not clear whether these cylindrical panels would experience unstable static buckling. Inspection of the impact test data indicates that some load-deflection responses approached an inflection point, while others monotonically increased. The nonlinear static FEM analysis did not generate unstable buckling for any of the cases studied. In structures which undergo stable buckling or do not buckle statically, the dynamic stability concept may be extended by defining the critical loads relative to limitations on the certain parameters in the dynamic response, such as a maximum allowable amplitude of vibration. Further examination of this topic is beyond the scope of this paper. However, one significant result of Simitses's work worth mentioning is that the dynamic critical load in some structures may be lower than the static critical load.

The variation of the maximum displacement with impact energy is shown in Figure 8. Here the trend is reversed from the force results. The thicker and larger radius of curvature specimens have smaller maximum displacement values. So the higher maximum forces correspond with lower maximum displacements. This is expected since stiffer structures deflect less than flexible structures. Inspection of the duration of contact reveals the higher forces to have shorter contact durations, as illustrated in Figure 2(a).

A summary of the C-scan results is shown in Figure 9 where the damage size, characterized by a maximum length, is plotted against the impact energy. Although not clear from this limited data, there may exist an impact energy threshold above which damage is observable from a C-scan and below which no damage occurs. For the 16 ply, 0.381 m radius of curvature specimens, this threshold may be between 2.71 and 3.39 N-m. For both the 0.381 m and 1.524 m radii of curvature, the possible impact energy threshold of the 8 ply specimens is under 1.02 N-m.

Concluding Remarks

The geometry of a laminated composite structure strongly influences its impact response. Three different geometries of specimens for cylindrically curved panels were impacted by a fixed mass dropped from a variety of heights. Stiffer structures produce higher impact forces, smaller center deflections, and shorter contact duration times. The relative stiffness of each panel may be explained by considering its load-deflection response. Normalization of the force with respect to the critical dynamic load and the displacement with respect to the panel height is essential when comparing the response of panels with different radii of curvature. When the loading path leads in the load-deflection response, the difference between the loading and unloading might possibly be accounted for through consideration of inertia, vibration, friction, and energy lost due to damage formation, if any. Applying different boundary constraints on the straight edges of the panel, in an attempt to model the actual test boundary supports, changes the response behavior in the nonlinear static FEM analysis model. Comparison of the impact data in one geometry for two impact energy levels reveals that the higher impact energy produces a stiffer force-deflection response. The work reported herein constitutes research results of an ongoing activity and therefore, much of the analysis and experiments is still underway to completely understand the dynamic response of curved panels. However, the preliminary results are encouraging and have been presented here.

Acknowledgements

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References

1. Sun, C. T., and Chattopadhyay, S., 1975, "Dynamic Response of Anisotropic Laminated Plates Under Initial Stress to Impact of a Mass," *Journal of Applied Mechanics*, September, pp. 693-698.

2. Dobyns, A. L., 1981, "Analysis of Simply-Supported Orthotropic Plates Subject to Static and Dynamic Loads," *AIAA Journal*, Vol. 19, May, pp. 642-650.

3. Cairns, D. S., and Lagace, P. A., 1989, "Transient Response of Graphite/Epoxy and Kevlar/ Epoxy Laminates Subjected to Impact," *AIAA Journal*, Vol. 27, No. 11, pp. 1590-1596.

4. Christoforou, A. P., and Swanson, S. R., 1991, "Analysis of Impact Response in Composite Plates," *International Journal of Solids and Structures*, Vol. 27, No. 2, pp. 161-170.

5. Joshi, S. P., and Sun, C. T., 1985, "Impact Induced Fracture in a Laminated Composite," *Journal of Composite Materials*, Vol. 19, January, pp. 51-66.

6. Liu, D., and Malvern, L. E., 1987, "Matrix Cracking in Impacted Glass/Epoxy Plates," *Journal of Composite Materials*, Vol. 21, July, pp. 594-609.

7. Morton, J., and Godwin, E. W., 1989, "Impact Response of Tough Carbon Fibre Composites," *Composite Structures*, Vol. 13, pp. 1-19.

8. Qian, Y., and Swanson, S. R., 1990, "Experimental Measurement of Impact Response in Carbon/Epoxy Plates," *AIAA Journal*, Vol. 28, No. 6, pp. 1069-1074.

9. Ambur, D. R., and Starnes, J. H., Jr., and Prasad, C. B., 1993, "Influence of Transverse-Shear and Large-Deformation Effects on the Low-Speed Impact Response of Laminated Composite Plates," *NASA Technical Memorandum* 107753, April.

10. Ramkumar, R. L., and Thakar, Y. R., 1987, "Dynamic Response of Curved Laminated Plates Subjected to Low Velocity Impact," *Journal of Engineering Materials and Technology*, Vol. 109, January, pp. 67-71.

11. Palazotto, A., Perry, R., and Sandhu, R., 1992, "Impact Response of Graphite/Epoxy Cylindrical Panels," *AIAA Journal*, Vol. 30, No. 7, pp. 1827-1832.

12. Lin, H. J., and Lee, Y. J., 1990, "Impact-Induced Fracture in Laminated Plates and Shells," *Journal of Composite Materials*, Vol. 24, November, pp. 1179-1199.

13. Budiansky, B., and Roth, R. S., 1962, "Axisymmetric Dynamic Buckling of Clamped Shallow Spherical Shells," *NASA TN*, D-1510.

14. Simitses, G.J., 1965, *Dynamic Snap-through Buckling of Low Arches and Shallow Sperical Caps*, PhD Dissertation, Stanford University.

15. Simitses, G.J., 1990, *Dynamic Stability of Suddenly Loaded Structures*, Springer-Verlag, New York.

Material	E_x (GPa)	E_y (GPa)	G_{xy} (GPa)	G_{yz} (GPa)	ν_{xy}
AS4/3502	137.8	8.96	5.99	3.51	.30

Table 1: Lamina 0^0-ply material properties

Case	Plies	Rad. Curv. (m)	Impact Energy (N-m)
1	8	0.381	1.02
2	8	0.381	1.36
3	8	1.524	1.02
4	8	1.524	1.36
5	8	1.524	1.69
6	16	0.381	1.36
7	16	0.381	2.71
8	16	0.381	3.39
9	16	0.381	4.07
10	16	1.524	3.39

Table 2: Test Matrix

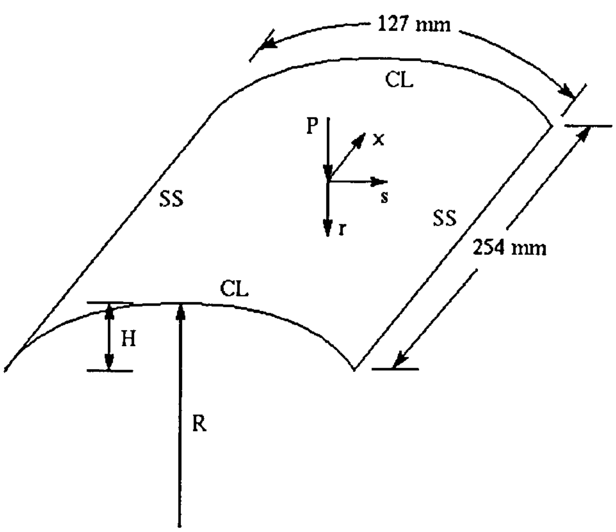

Figure 1

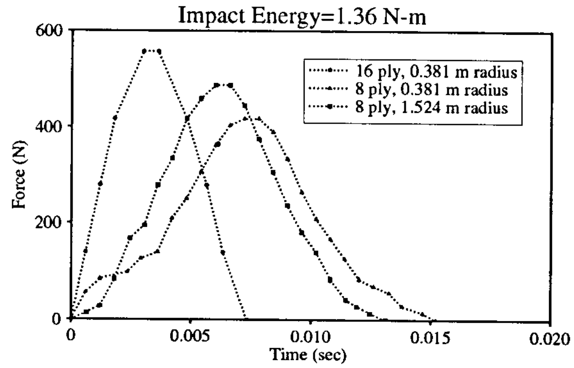

Figure 2(a)

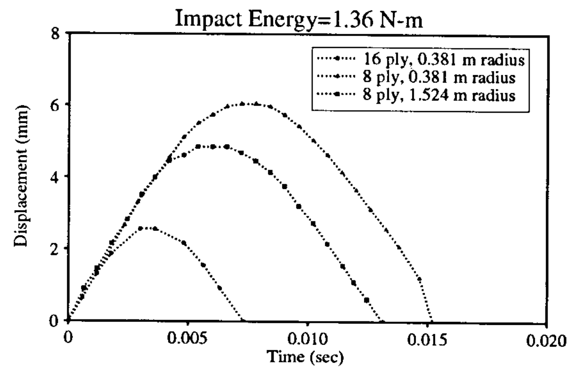

Figure 2(b)

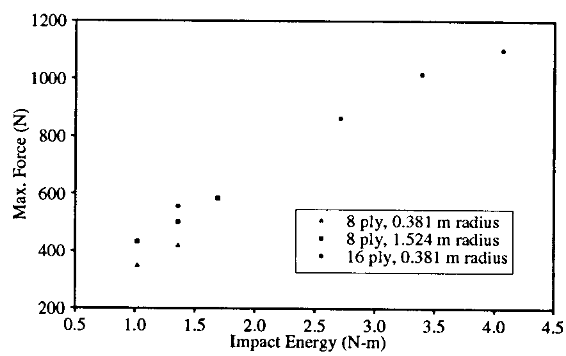

Figure 3

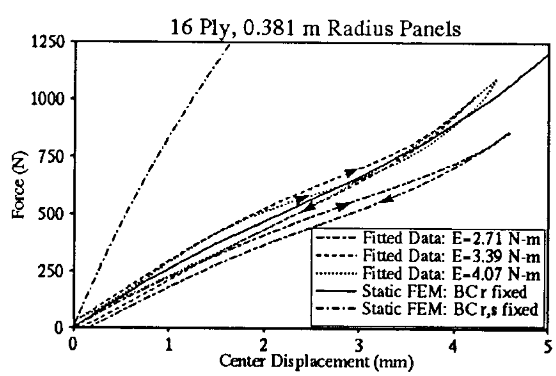

Figure 4

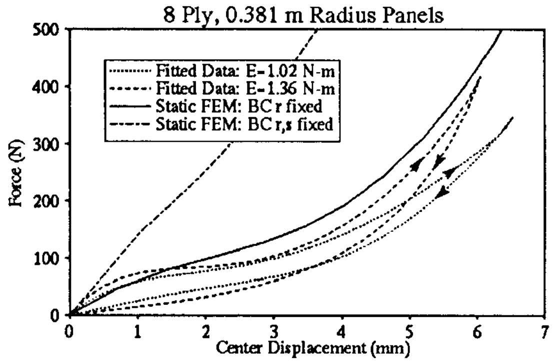

Figure 5

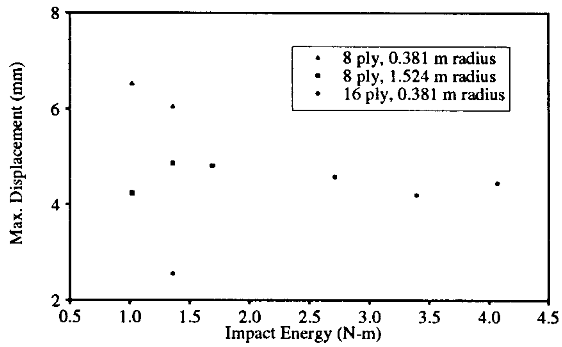

Figure 8

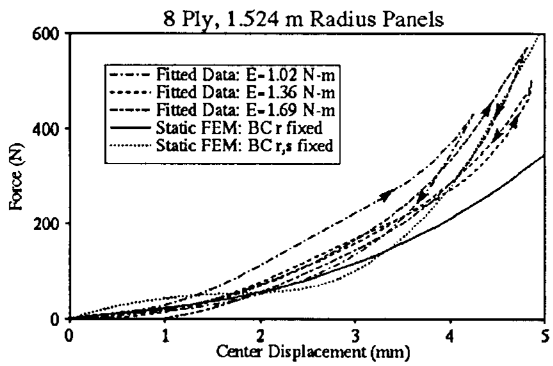

Figure 6

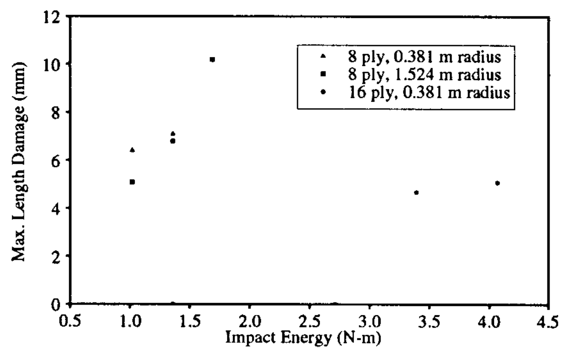

Figure 9

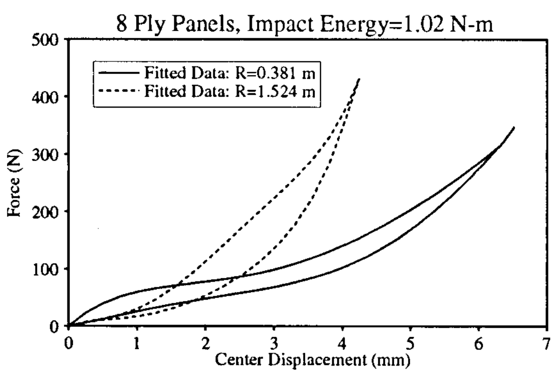

Figure 7(a)

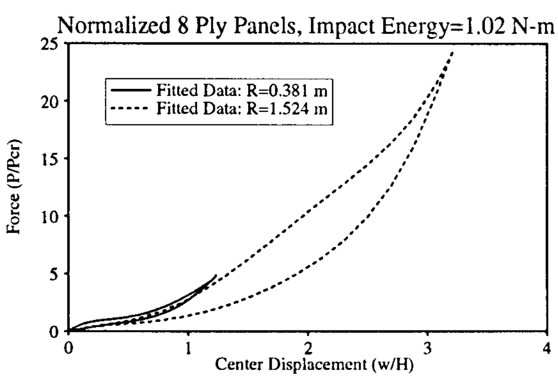

Figure 7(b)