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Impact and Quasi-Static Response of Cylindrical Composite Shells

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Executive Summary

Although the impact resistance of composite plates has been explored extensively, virtually no work has ben done with composite shells. Actual aerospace structures of interest, such as wings and fuselages, are most accurately characterized as shells due to the inherent curvature of these structures. This exploratory experimental investigation was undertaken as a first attempt at determining basic response characteristics (including damage) of impacted composite shells. This work thus extends the current understanding of the impact response of composite plates to that of shells.

Experiments were conducted to investigate the impact response of composite shells over a range of impact events considered in the large-mass (1.60 kg), low-velocity (1 m/s to 4 m/s) regime. Both impact and quasi-static tests were conducted on various structural configurations including convex shells, concave shells, plates, and cylinders. A special test fixture was designed and built to provide boundary conditions of pinned/no in-plane sliding on the axial edges and free on the circumferential edges for the plates and shells. Specimens with a planar aspect ratio of 1 were constructed in [±45n/0n]s (n = 1, 2, 3) layups from Hercules AS4/3501-6 graphite-epoxy prepreg. Basic structural parameters (radius, span, and thickness) were varied via a scaling scheme to investigate the effects of these parameters and their ratios on the response. Impact response was characterized by recording specimen force-time histories while force-deflection and force-indentation data were taken during quasi-static testing. Damage states were characterized visually and with the dye-penetrant x-ray photography method and compared by defining damage metrics such as the average damage extent and damage extent ratio.

The response of many convex shells to impact was quite different than that of plates due to a snap-through type instability phenomenon which was identified in the response of many convex shells but was not noted for plates. The presence of the instability strongly affects the response parameters (e.g. peak force) and trends. The instability means that the load decreases and the deflection of the shell increases significantly (over 50 times the specimen thickness in some cases) between two stable equilibrium loading paths. Although the instability has many of the characteristics of a snap-through instability, a stable path is observed between the two equilibrium paths which for a true snap-through instability would not exist. The existence of this stable path means that impact tests of convex shell structures act like deflection-, rather than load-, controlled tests.

The effects of this instability on the damage resistance of composite structures have not been considered previously, but was found to be crucial to understanding the damage behavior. Many convex shells are noted to have less damage than corresponding plate specimens. This is explained by

considering the modes of energy consumption available to the two structures. Compared to plates, convex shells can consume more impact energy through large deformations (oftentimes through the instability region). As plates do not exhibit an instability, impactor energy is consumed through high peak forces and small (relative) deformations. Since damage to composite plates (also shells as found in this research) is known to scale with peak force, higher peak forces translate to increased damage. Thus, convex shells with an instability have increased impact damage resistance compared to equivalent plates. The instability gives convex shells a structural mechanism that leads to improved damage resistance.

Conversely, convex shells that do not undergo an instability can incur more damage than plates at a given force - thus leading to decreased damage resistance at the barely visible impact damage (BVID) level compared to plates. This damage behavior, which includes different damage distributions, is attributed to differences caused by compressive versus tensile membrane stresses, the latter which occurs in plates. These different membrane stress states occur due to the different equilibrium paths in the shell response; compressive on the first equilibrium path, and tensile on the second. The compressive membrane stresses can promote ply and sublaminate buckling leading to increased delamination. Such increased delamination extent was observed in convex specimens of this type. Thus, as discussed before, convex shells which show an instability can be more impact damage resistant than plates, but convex shells can also have increased damage extent at the BVID level if there is no response instability.

As is known for plates, the response of shell specimens (including plates) in impact and quasi-static tests were shown to be generally comparable. Force-deflection curves were noted to be identical for all types of specimens, including many examples of convex shells with instability regions. Damage states, including unsymmetric and atypical damage distribution, were also found to be the same when the peak forces between the impact and quasi-static tests were kept constant. This provides strong evidence that peak force is an excellent damage resistance metric in shells as it is in plates.

All structural parameters were shown to affect the response, including the shell height, although thickness was of particular importance. No nondimensional structural ratios were found that capture the behavior of convex shells over the entire range of data. However, the data does indicate that there are regimes where different ratios are important, especially the height-to-thickness ratio.

Other important observations were also made relating to the modeling and testing of real composite structures. Due to the highly nonlinear response (instability) of shell specimens, initial stiffness cannot be used to characterize the response of transversely loaded shells because it tells little about the response, especially after the critical snapping load has been reached. The Hertzian-type contact relation does not capture the local response of indented shells. This is attributed to many effects, including the observation that the indentation can actually become negative (through-thickness expansion) in the instability region where high compressive membrane stresses are present even though the contact force can drop off significantly. This is important in relation to modeling impact events because the Hertzian relation is oftentimes used in analyses. Full cylinders, often used to model impacted shells, were found to behave much differently (different impact response parameters and force-deflection histories) than corresponding half-cylinder specimens restrained in the test fixture. Thus, using full cylinders to model the response of real shell structures (with stiffeners etc.) is not appropriate. This indicates that boundary conditions play an important role in the impact response of shells and must be properly simulated in tests of structures, particularly scaled structures and (sub)elements.

The differences in plate and shell impact damage resistance are especially important because plate data is typically used in the design of structures which are better modeled by shells. Due to the noted differences in plate and shell response, especially damage, results from this work have important implications in the design of damage tolerant composite structures. However, many questions also remain unanswered. The importance of membrane stress on damage formation, specifics (extent and mode) of the damage state and parameters which affect it, and the effects of structural parameters on convex shell response (instability) are some of the areas which must be further analyzed and supplemented with additional experiments as required.