Study of Thermal-Expansion-Molded, Graphite-Epoxy Hat-Stiffened Sandwich Panels

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Abstract

MINIMUM weight configurations for two types of graphite-epoxy, hat-stiffened, compression-loaded panels fabricated by the thermal-expansion-molding (TEM) manufacturing process were evaluated analytically and experimentally. Optimal structurally efficient TEM panels are compared to commercially available aluminum aircraft structures.

Content

Thermal-expansion molding (TEM) can be used to build hat-stiffened panels made of laminated graphite-epoxy plies and foam core and may be more cost-effective than conventional methods for manufacturing hat-stiffened panels since it simplifies the tooling and does not require an autoclave. Foam is easy to work with, relatively inexpensive, and can be left inside hat stiffeners or removed from the finished product.

Panel configurations involving an open hat or a foam-filled hat, each with a sandwich skin, which could be constructed using the TEM manufacturing process, were evaluated by comparing optimum structurally efficient TEM panels to commercially available aluminum aircraft wing components. The computer code PASCO[1] was used to size and evaluate the optimum panels for compressive loading in one direction.

The configurations evaluated consist of graphite-epoxy laminates containing 0, ±45, and 90 deg plies. Panel dimensions were specified to be 76.2 cm long and approximately 61 cm wide. All dimensions of the hat stiffeners were variables. Simply supported boundary conditions on the loaded edges and free boundary conditions on the unloaded edges were assumed. Restrictions on ply thicknesses, safety margins, etc., are discussed in Ref. 2. The optimization study was performed based on typical material properties of graphite epoxy (E_1 = 127.6 GPa, E_2 = 11.3 GPa, G_{12} = 6 GPa, μ_{12} = 0.3, and ρ = 165 kg/m^3) and Rohacell 71 foam ($E_1 = E_2$ = 0.092 GPa, G_{12} = 0.03 GPa, μ_{12} = 0.53, and ρ = 70 kg/m^3).

The structural efficiency of the optimum panels (minimum weight design) is shown in Fig. 1 in the form of a weight index W/AL (where W is the panel weight, A is the panel area, and L is the panel length) vs a load index N_x/L (where N_x is the compressive stress resultant). Both configurations yield optimum designs that are 20 to 40% more structurally efficient than commercially available aluminum aircraft components for all load levels considered. Optimum panels contain a minimum thickness of ±45-deg plies and 90-deg plies as well as foam in the skin. All optimum panels contain 12 stiffeners in the 61 cm required width. Critical constraints are dependent upon the panel configuration and the load level. The filled hat-stiffener configuration is more efficient than the open-hat configuration for all load levels because the foam inside the hat prevents the webs of the hat stiffeners from buckling.

A panel with foam-filled hat stiffeners made from Hercules Incorporated AS4-3502 and Rohacell 71 foam was designed based on the PASCO analysis and constructed using the TEM process. Small changes, such as adjusting each layer thickness to contain an integral number of plies, were made in the optimum design to allow the panel to be built. The panel was ultrasonically evaluated before testing by using a bondascope and was determined to have no defective regions. Four test specimens with dimensions 30.48 cm long and 25.4 cm wide were cut from this panel. Each specimen contained eight stiffeners. Stiffener geometry is shown in Fig. 1. The stacking sequence of the sides of the hats was $[\pm 45]_T$, of the top of the hats was $[-45/0_6/\pm 45/0_6/45]_T$, and of the skin was $[\pm 45/\text{foam}/\pm 45/0_7/\mp \rfloor \lesseqgtr \rceil_T$. A finite element analysis of the test specimen using the Structural Analysis of General Shells (STAGS)[3] computer code was conducted to verify the results obtained from the Panel Analysis and Sizing Code (PASCO) analysis using the configuration with foam-filled hat stiffeners.

The ends of the specimens were potted in an epoxy material and ground flat and parallel to assure uniform loading. The specimens were then instrumented with axial and lateral back-to-back strain gauges. An axial compressive load was slowly applied to each test specimen until failure. Details of the test results are presented in Ref. 2 and are summarized herein.

All TEM panels tested experienced several failure events that were indicated by all strain gauges, caused a redistribu-

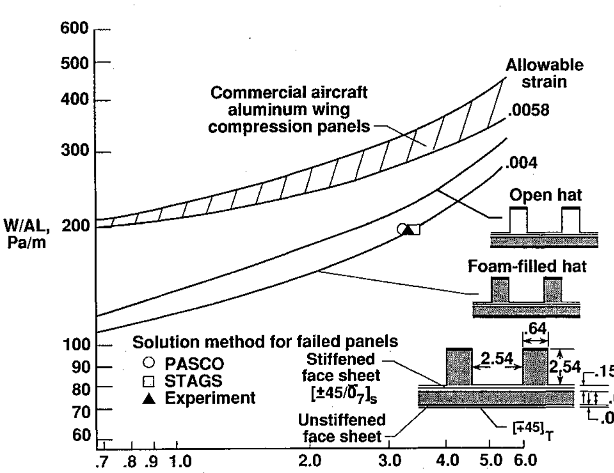

Fig. 1 Structural efficiency of thermal-expansion-molded panels using AS4-3502 properties (all dimensions in cm).

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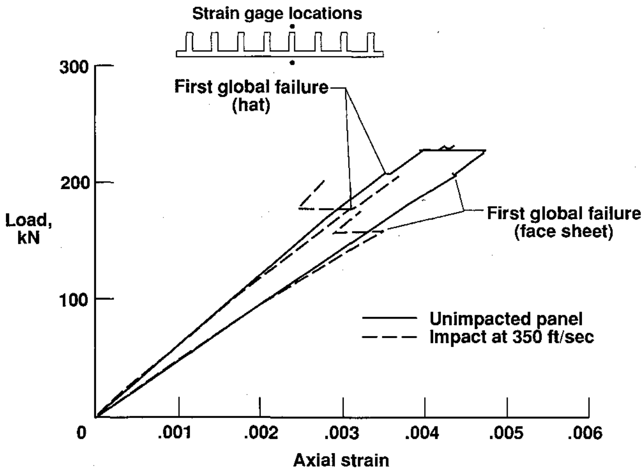

Fig. 2 Axial strain at the center of the panel.

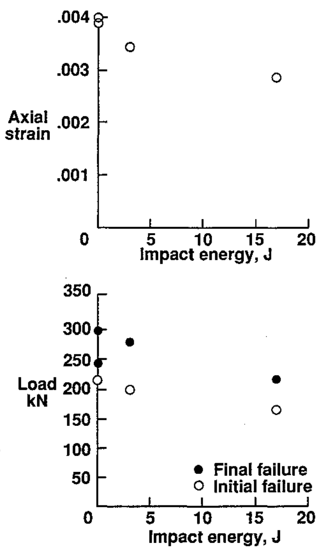

Fig. 3 Comparison of failure load and strain of impacted and undamaged panels.

tion of load, and changed the overall panel stiffness. Surface strain results indicate that the specimens behave linearly as the load is increased until the first failure event. The load-strain curves for all strain gauges show a discontinuity in slope at each failure event, as shown in Fig. 2 for two axial strain gauges at the lengthwise centerline of the undamaged panel and the panel impacted with energy of 17 J. The solid lines represent the strain of the unimpacted panel, and the dashed lines represent the strain of the impacted panel.

The failures in the undamaged panel involve delamination between the unstiffened face sheet and the foam core or the formation of a transverse crack in the foam in two corners of the panel, causing the unstiffened face sheet to buckle. Damage then propagates across the width of the panel. These initial failures may be related to boundary effects (as described in Ref. 4). At final failure, the regions with the previous failures unload, and a previously undamaged part of the panel fails across the entire panel width. The unstiffened face sheet buckles and delaminates from the foam core, and the foam core fails. The impact-damaged test specimen was impacted over a stiffener and midbay between two stiffeners on the unstiffened face sheet with impact energy of 17 J. These impacts induced damage through the entire skin thickness. The impacted panel failed at the impact locations upon being subjected to axial compressive loading. Examination of the failed panel reveals that the foam core in the skin delaminated from both face sheets. However, few cracks through the thickness of the core are evident.

The strains and loads of all four panels tested are shown in Fig. 3. The final failure loads of the undamaged panels and the panel impacted with energy of 3.1 J differ by 20%, whereas the final failure load of the panel impacted with energy of 17 J is 20% below these. The initial failure load of the panels impacted with energies of 3.1 and 17 J is 10% and 20% below the initial failure load of the unimpacted panels, respectively. However, the failure strains at initial failure range from 0.0040 to 0.0029. The amount of decrease in strain recorded in the unstiffened face sheet when the first failure occurs is approximately 0.001 in the undamaged panel but is 0.004 and 0.006 for the panels impacted with energies of 3.1 and 17 J, respectively. The strain gauges on the hats recorded the same increase in axial strain at the first failure for all panels.

The load-strain relationships predicted by PASCO and STAGS agree well with each other and with the experimental results (see Fig. 2) up to the first failure event when a failure mechanism occurs that these analysis codes do not predict.

Comparing the results of a PASCO analysis of the TEM panel tested and of a similar hat-stiffened panel without the unstiffened face sheet and foam core in the skin indicates that the presence of the foam core in the skin suppresses a buckling mode of 7 longitudinal half waves at 20% of the predicted buckling load of the test specimen. The test specimen failed at 36% of its predicted buckling load without buckling.

Acknowledgments

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