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A Study of the Structural Efficiency of Fluted Core Graphite-Epoxy Panels

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Abstract

The structural efficiency of compression-loaded graphite-epoxy sandwich panels with fluted cores is studied to determine their weight saving potential. Graphite-epoxy equilateral triangular elements are used to construct the fluted cores for the sandwich panels. Two panel configurations are considered. One configuration has two layers of triangular elements in the fluted core and the second configuration has only one layer of triangular elements in the core. An optimization code is used to find the minimum weight design for each panel configuration. Laminate ply orientations are limited to $\pm 45°$, $0°$, and $90°$. A constraint on the axial stiffness is included in the design process so the panel will conform to typical constraints for aircraft wing structures. Minimum thickness requirements for each laminate and maximum allowable strains are also included. A comparison is made of the calculated structural efficiency of the fluted core panels to the structural efficiency of aluminum transport aircraft structures and simple blade-stiffened graphite-epoxy panels. Limited experimental results are also included for comparison with the analytical predictions and to identify the critical failure mechanisms of graphite-epoxy fluted-core sandwich panels.

Introduction

Since laminated composite materials have low density and high stiffnesses compared to aluminum, they offer the potential for constucting aircraft components with better structural efficiency than those that can be made from metals. However, panel configurations which are structurally efficient and inexpensive in metallic structures are not necessarily optimal configurations if these panels are made from composite materials. New concepts must be developed and evaluated to determine whether they represent more efficient structures than the typical metallic aircraft structures available today. One concept which may provide a practical alternative to some aluminum wing structural components is the fluted core panel made of graphite-epoxy material. The present paper presents the results of a structural efficiency study of two fluted-core sandwich panel configurations. The results of the study are compared with conventional aluminum panel results and blade-stiffened graphite-epoxy panel results. Limited experimental results are also included to identify the critical failure mechanisms of fluted-core graphite-epoxy panels.

Panel Configurations

Optimal (minimum weight) cross-sections for various load levels for two graphite-epoxy fluted-core sandwich panel configurations are determined and evaluated in the present study using the computer code PASCO (ref. 1). Since composite materials provide more of an opportunity to tailor a structure to its specific use than metallic structures, design variables such as ply orientation and geometric dimensions must be taken into account in any structural efficiency comparison. The first configuration, shown in figure 1, consists of two layers of equilateral triangular core elements made of $\pm 45^\circ$ laminates sandwiched between face sheets consisting of $\pm 45^\circ$, 0°, and 90° plies. An inner laminated sheet separates the two layers of triangular core elements. The second configuration, shown in figure 2, consists of one layer of triangular core elements sandwiched between the outer face sheets.

Each panel configuration was optimized for four axial-compression load levels that range from 3000 lb/in. to 24,000 lb/in. The panels are 30 inches long and approximately 30 inches wide. The actual panel width varies since the total width must be an integral multiple of the optimum side length of the triangular core element. The loaded ends of the panels are assumed to be simply supported in the PASCO analysis. The unloaded edges are assumed to be either unrestrained or simply supported. The material properties used are shown in Table 1.

The optimum stacking sequence for a given panel is dependent upon the design load level since the thickness of all plies are design variables. The length of a side of the triangular core element is also a design variable.

The panels are designed to withstand a specified axial compressive load before buckling. No lateral loading or shear loading was considered. The minimum thickness required in the triangular core elements and in each face sheet was the thickness of a $[\pm 45]_s$ laminate. This requirement specified $\pm 45^\circ$ plies as the outer plies of each laminate. The minimum thickness requirements for the triangular core elements are based on the restrictions in the process currently used to manufacture these elements. The face sheets and inner core separator sheet could contain any number of 0° and 90° plies. There was no upper limit on the number of plies of any orientation. For the purposes of optimization, integer ply thicknesses were not required, but a minimum thickness of a 45° or -45° layer was taken to be .005 inches. The triangular core elements and face sheets have the same constraints in the one- and two-layer configurations. The top and bottom face sheets are required to be the same for any given panel. This requirement forces the panels with two layers of triangular elements to be symmetric about the inner core separator sheet. A maximum allowable extensional strain of .006 and an allowable shear strain of .01 were included. Constraints on the overall axial stiffness of the panels were also included. The value of the minimum allowable overall axial stiffness is dependent on the load level and is described in reference 2.

Specimens, Apparatus and Tests

A graphite-epoxy fluted core panel with two layers of triangular core elements with the cross section shown in figure 3 was constructed from braided triangular sections made from $\pm45^\circ$ plies and flat face sheets. The face sheets contained $\pm45^\circ$, 0° and 90° plies. The test section was 10 inches long and 6.25 inches wide. The loaded ends of the specimen was potted in an epoxy material and ground flat and parallel to assure uniform loading. The unloaded edges were unrestrained. The specimen was instrumented with strain gages and painted white to allow the use of moire interferometry to monitor out-of-plane displacements during testing.

The test specimen was loaded in axial compression to failure. Strain gage data, displacement measurements and moire patterns of out-of-plane displacements at various load levels were recorded during the test. These measurements are used to evaluate the structural response and failure characteristics of the specimens.

Results and Discussion

Optimum panels (minimum weight design) were designed for four load levels of axial compression for both panel configurations. The structural efficiency of these optimum panels is shown in figure 4 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) versus a load index N_x/L (where N_x is the compressive stress resultant). The more structurally efficient configurations are those represented by the lower curves on the plot. The shaded area represents typical aluminum aircraft panels. The solid curves represent the structural efficiency of the optimum fluted-core graphite-epoxy panel configurations and the data points represent the experimental and analytical results for the test specimen.

Two layer configuration.-The configuration containing two layers of triangular core elements has a structural efficiency comparable to that of aluminum structures for low load levels. For an axial compressive load of 3000 lb/in. applied to a panel with 30-inch-long unsupported unloaded edges, the weight index is $.77 \times 10^{-3}$ lb/in^3. However, for higher load levels, such as 24,000 lb/in. applied to a panel of the same length, the weight index only increases to $.98 \times 10^{-3}$ lb/in^3. As the load is increased, the structural efficiency of the panel is not reduced as much for the composite fluted core panels as it is for typical aluminum panels. The critical constraints change as design load level changes. For the lowest load level the optimum design is buckling critical. For intermediate load levels the critical constraint is the overall panel stiffness requirement. For the highest load level examined, the panel will fail by shearing in the sides of the triangular core elements when the design load is applied.

For all load levels examined, the optimum thickness of the 90° layers is zero and the optimum thickness of all $\pm 45^{\circ}$ layers is the minimum allowed. The primary change in the optimum cross section as the design load level is increased is an increase in the thickness of the 0° plies in the face sheets. For the lowest load level a total thickness of 0.024 inches of 0° plies is required in each outer face sheet and a thickness of 0.008 inches of 0° plies is required in the inner core separator sheet. For the highest load level considered, a total thickness of 0.07 inches of 0° plies is required in each outer face sheet and a thickness of .022 inches of 0° plies is required in the inner core separator sheet. The length of the sides of the triangular core elements changes slightly. The optimum side length is .866 inches for the 3000 lb/in. load level and .953 inches for the 24,000 lb/in. load level. The dashed curve in figure 4 represents the structural efficiency of a graphite-epoxy blade-stiffened panel. The blade-stiffened configuration is more structurally efficient than the two-layer fluted-core configuration for all load levels. The minimum gage constraints on the fluted-core components and on the face sheets and inner core separator sheet prevent the development of a lighter weight design.

The effects of simply supported or unrestrained unloaded edges on the structural efficiency were also evaluated. The boundary conditions on the unloaded edges have little effect on the structural efficiency or cross section of the two-layer core panel configurations for the width studied.

One layer configuration.-The configuration with one layer of triangular core elements has better structural efficiency than the configuration containing two layers of triangular core elements for all load levels. For an axial compressive load of 3000 lb/in. applied to a one-layer core panel with 30-inch-long unrestrained unloaded edges, the weight index is 30% lower than the weight index of the two-layer core panel configuration for the same load level. As the load level increases, however, the difference in structural efficiency of the one-layer and two-layer core configurations decreases. For a load of 24,000 lb/in., the difference in weight indicies is only 12% for a panel with unrestrained unloaded edges and 24% for a panel with simply supported unloaded edges. This comparison is shown in figure 4. For low and intermediate loads (up to 15,000 lb/in.), the critical constraint is the overall axial stiffness requirement. For the 15,000 lb/in. load level and above the optimum design is buckling critical. For the highest load level, the critical condition is the maximum allowable shear strain in the sides of the triangular core elements. The blade stiffened graphite-epoxy configuration is more structurally efficiency than the one-layer fluted-core configuration for all but the highest load levels. Minimum gage constraints prevent lighter weight fluted core panel designs.

As in the two-layer core configuration, the thicknesses of the 90° and 45° layers approach the minimum value allowed for all load levels examined. The total thickness of the 0° layers in each face sheet range from 0.043 to 0.085 inches as the load level changes from 3000 lb/in. to 24,000 lb/in. For the one-layer core configuration, there is no inner core separator sheet so all 0° plies must be in the outer face sheets. The triangular core element side length increases from 0.712 to 0.95 inches over the range of loads studied.

For high load levels, the one-layer core configuration has a slightly better structural efficiency than the two-layer core configuration. The fluted core panel's structural efficiency is better than that of aluminum aircraft components but the improvement is small. Only the structural efficiency of these panels have been considered in this study. To determine if these configurations are practical alternatives to aluminum aircraft components, an analysis of the cost and manufacturing difficulties would have to be completed. Improved structural efficiency could be obtained by reducing the minimum thickness constraint on the triangular core elements. To build panels with thinner triangular core elements, a material form or process other than braided graphite-epoxy material could be required.

Experimental Results

The initial failure of the panel tested was due to a shear failure in the sides of the triangular core elements. Immediately after the initial shear failure, the outer face sheets delaminated. The panel failed at a load level of N_x=13,500 lb/in. and had a weight index of 2.0 x 10^{-3} lb/in^3. The failure load predicted by a PASCO analysis of the test specimen and the data point representing the actual failure load are shown on figure 4. This panel is not an optimum design and so does not fall on the structural efficiency curves. In the PASCO analysis the braided elements were modeled as $\pm 45^{\circ}$ plies of the appropriate thickness. The analysis of the test specimen predicted a shear failure in the sides of the triangular core elements at a load within 10 percent of the actual failure load. A photograph of the failed panel is shown in figure 5.

Concluding Remarks

Optimal designs of fluted core graphite-epoxy panels were studied for panels subjected to axial compressive loads ranging from 3000 lb/in. to 24,000 lb/in. for square panels of length 30 inches. Fluted core panels made of laminated graphite-epoxy materials may provide an efficient alternative to aluminum aircraft wing components. For all load levels, a fluted core panel configuration with one layer of triangular core elements is more structurally efficient than a panel configuration with two layers of triangular core elements. The difference in structural efficiency of the one- and two-layer fluted core configurations is most significant at low load levels. Minimum gage constraints on ply thicknesses prevent lower weight design for the more lightly loaded panel designs.

In all cases studied, the optimal configuration contains the minimum number of 90° and $\pm 45^{\circ}$ plies. The thickness of the 0° layers is dependent upon the load level. The critical constraints are also dependent upon the load level. The structure tends to be limited by either a buckling constraint or an overall extensional stiffness constraint for lower loads and by an allowable shear strain constraint for higher loads. Limited experimental results confirm the critical shear strain failure mode for the fluted core panels designed for higher applied loads.

References

1. Anderson, Melvin S.; and Stroud, W. Jefferson: A General Panel Sizing Computer Code and Its Application to Composite Structural Panels. AIAA Journal, Vol. 17, No. 8, August 1979, pp. 892-897.

2. Williams, Jerry G; and Mikulas, Martin M., Jr.: Analytical and Experimental Study of Structurally Efficient Composite Hat-Stiffened Panels. Presented at the ASME/AIAA/SAE 16th Structures, Structural Dynamics, and Materials Conference, Denver, Colorado, May 1975. AIAA Paper No. 75-754.

Table I. Graphite-epoxy Properties

Young's modulus, E_1	18.5 Msi
Young's modulus, E_2	1.64 Msi
shear modulus, G_{12}	.87 Msi
Poisson's ratio, μ_{12}	.3
density, ρ	.057 lb/in.^{3}

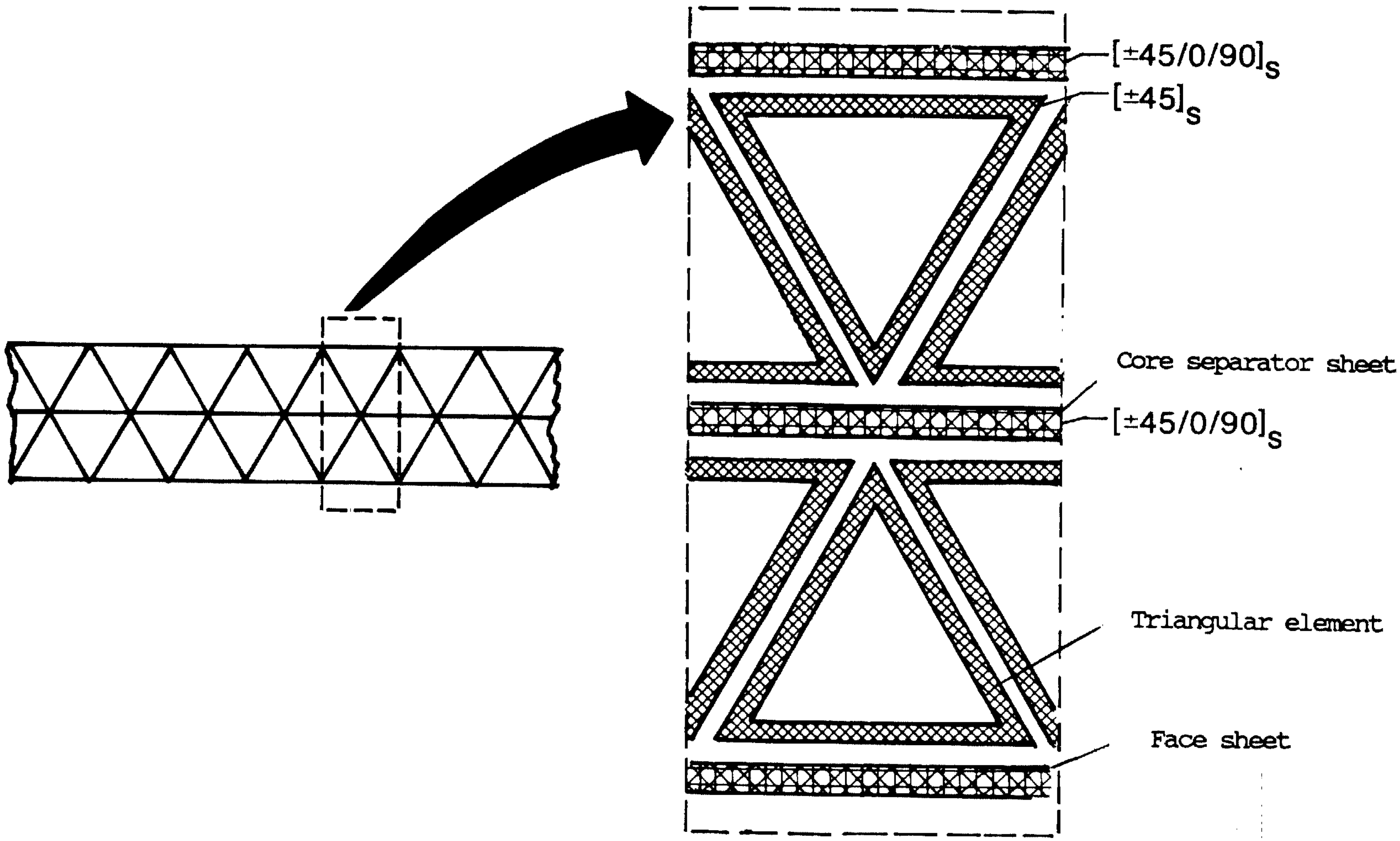

Figure 1. Configuration of Two-Layer Fluted Core Panel.

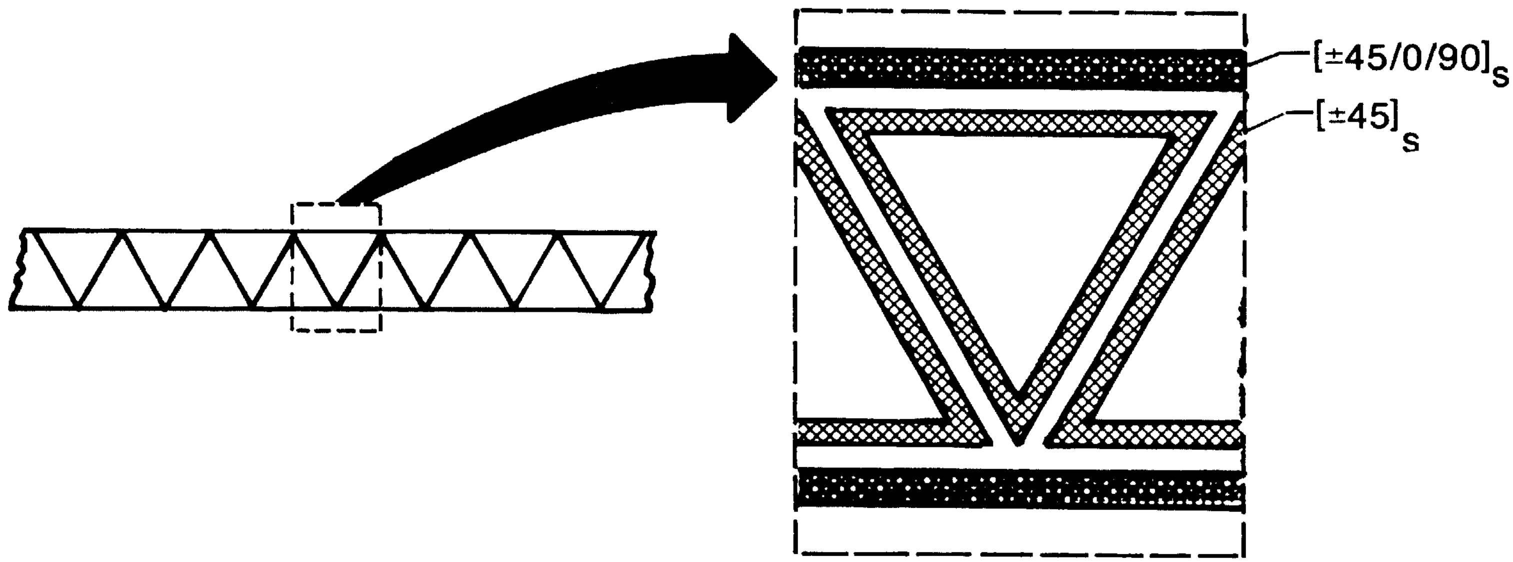

Figure 2. Configuration of One-Layer Fluted Core Panel.

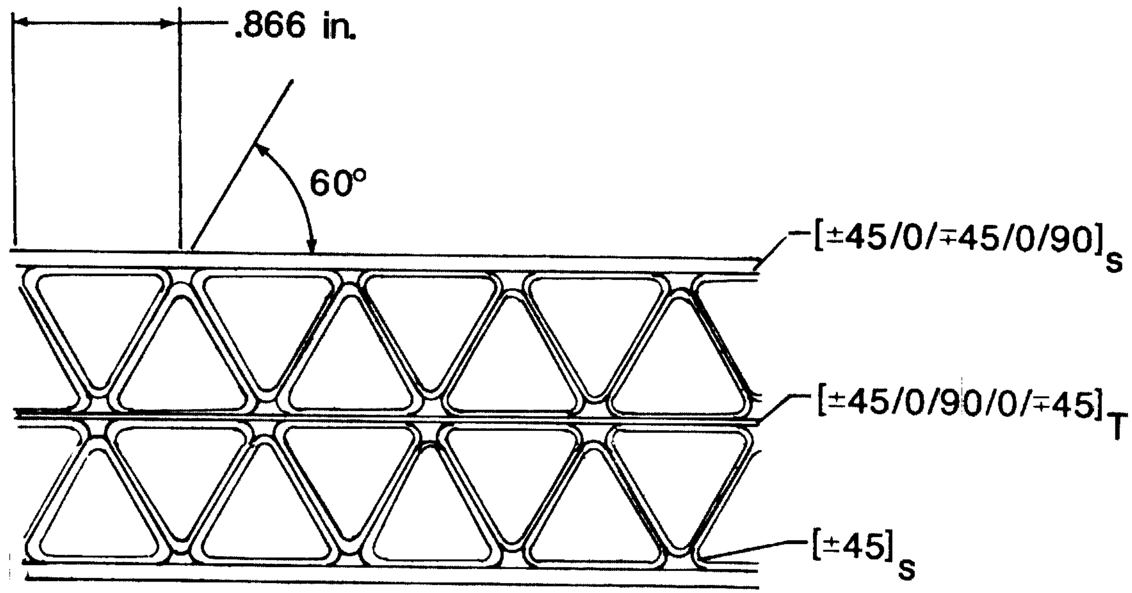

Figure 3. Cross Section of Test Specimen.

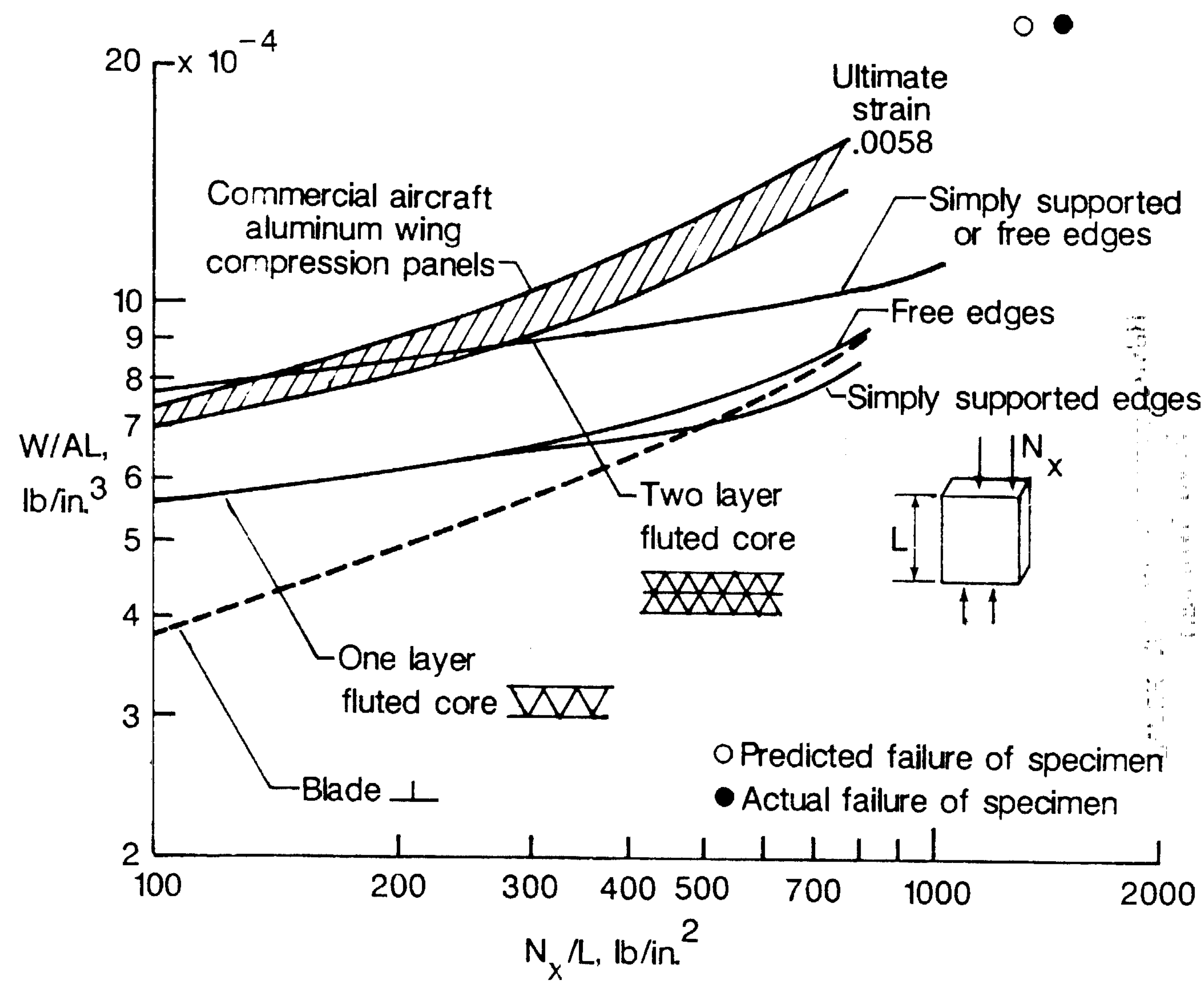

Figure 4. Structural Efficiency of Fluted Core Panels.

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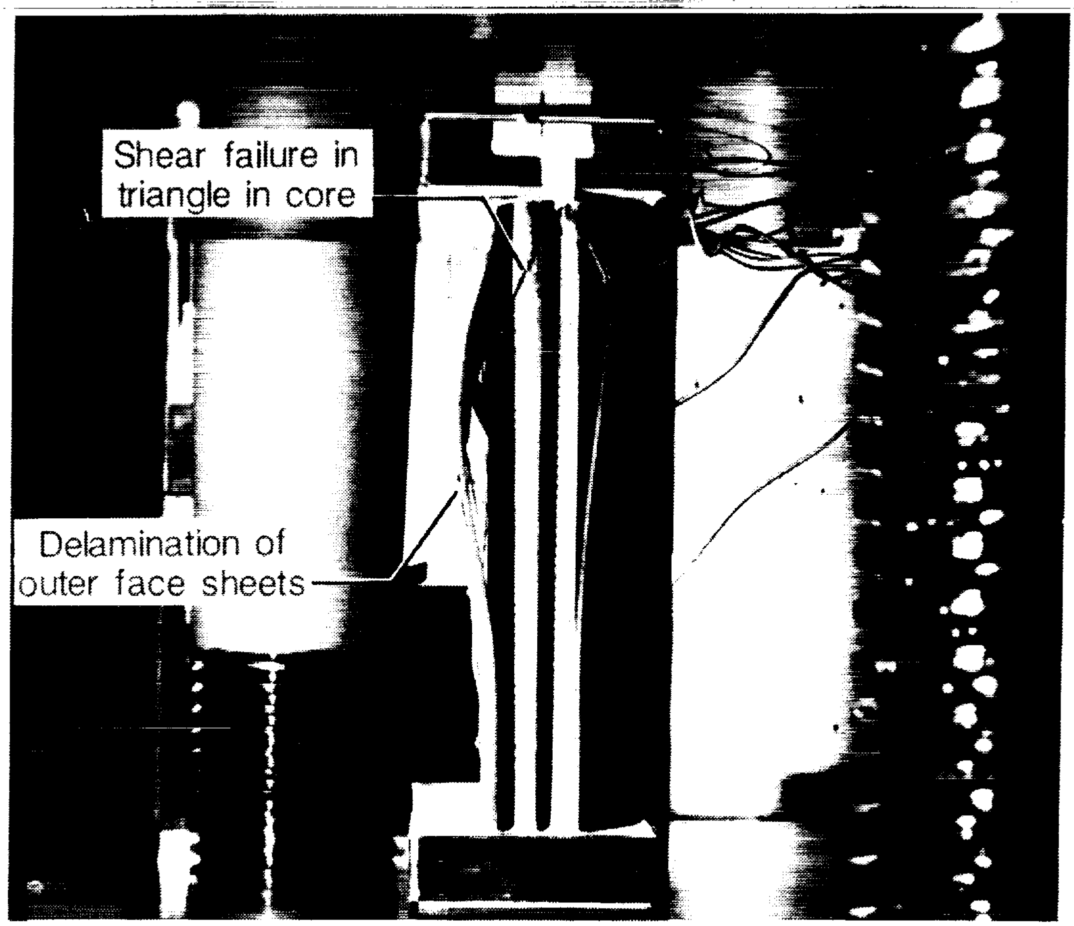

Figure 5. Failed Fluted Core Test Specimen.

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15. Supplementary Notes

16. Abstract

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