ADVANCED ENGINEERING MATERIALS

RESEARCH NEWS

Sandwich Panel Design Using Aluminum Alloy Foam

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Metal foams may replace polymer foams in applications where multi-functionality is important. For example it acts as a structural component in a sandwich panel but also as a cooling system or acoustic damper. Associated with sandwich panel geometry and change in loading one observes three failure modes: face sheet yield, core shearing and indentation under the loading roller.

1. Introduction

Polymer foam core sandwich panels are successful engineering structures for many applications.[1–3] Recently, attention has turned to replacing the polymer foams with metallic foams. Metal foams may replace polymer foams in applications where multi-functionality is important. For example it acts as a structural component in a sandwich panel but also as a cooling system or acoustic damper.

Here we explore the failure modes of aluminum skin-Alporas foam core sandwich panels and construct maps dependent on the sandwich panel geometry. Simple analytical models have been used to determine the stresses in the core and face sheets and a failure map has been developed. Since structural components can expect to be loaded repeatedly, fatigue testing has been done to determine the endurance limit of the panels in a given failure regime. The fatigue limit of the sandwich panels is closely related to that of the constituent materials. A fatigue failure map for sandwich panels was constructed using fatigue data for the skins and the Alporas foam core.

2. Sandwich Panel Theory and Design

Sandwich panels are made up of two face sheets or skins adhered to a core to improve flexural rigidity without sacrificing weight as shown in Figure 1. The following equations

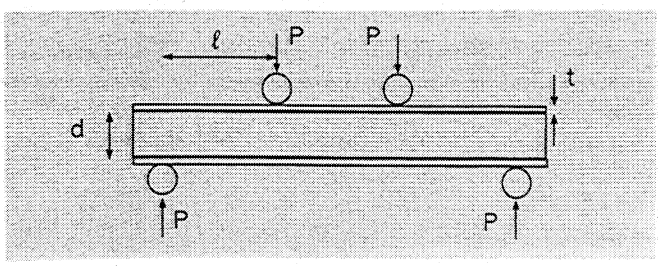

Fig. 1. Sketch of sandwich panel, of unit depth.

for the stresses in the core and skin of the sandwich panels are based on the assumptions that the skins are much thinner than the core and the modulus of the skins is much greater than that of the core. Perfect bonding is assumed. The result of these assumptions is that the skins carry the bending moment as longitudinal tensile and compressive stresses and the core the transverse shear force.

The flexural rigidity is approximated by

$$D = \frac{E_f t d^2}{2} \tag{1}$$

and is a result of the interaction of the face and the core. E_f is the elastic modulus of the face sheet, t is the thickness of the face sheet and d is the foam thickness. The longitudinal stress in the face sheet is given by

$$\sigma = \frac{M}{td} \tag{2}$$

where M is the bending moment. The shear stress in the core τ_c due to the shear force P on the section is given by

$$\tau_c = \frac{P}{d} \tag{3}$$

If the stress in the face sheets reaches the yield strength of the face sheet material then failure will be in the face sheets and if the shear stress in the core reaches the shear yield strength of the core material, failure will be in the core. Indentation is a third failure mode. A simple model has been suggested to approximate the indentation failure load. The skins form a fully plastic hinge under the roller and the foam exerts

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an upward pressure on the skin equal to its plastic flow strength σ_c. Given a roller force P on the surface of a panel, then the indentation force is

$$P = t\sqrt{2\sigma_c\sigma_f} \tag{4}$$

where σ_f is the yield strength of the faces. In four point bending the bending moment between the two inner rollers is a maximum and is constant with a value of Pl The shear force equals P between the inner and outer roller and equals zero between the inner rollers. The load necessary for face yield is

$$P = \pm\frac{\sigma_f td}{\ell} \tag{5}$$

and for core shear is

$$P = \tau_c d \tag{6}$$

A theoretical failure map has been produced for a sandwich panel with aluminum skins of yield strength 100 MPa and an Alporas aluminum alloy foam core with a relative density of 11 % under four point bending. The map is given in terms of t/l and d/l in Figure 2.

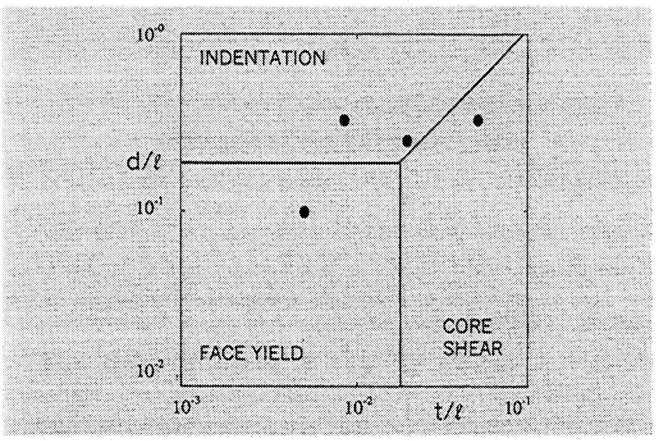

Fig. 2. Theoretical failure mode map for aluminum skin–aluminum foam core. Relative density is 11 %.

3. Experimental

3.1. Test Method

Four point bend, rather than three point bend, was chosen as the method of testing to take advantage of the area of constant bending moment and zero shear force between the center rollers. This decouples the failure mechanisms to allow for simplification in experimental observations: face yield occurs between the center rollers, core shear between the outer and inner roller and indentation directly under the rollers.

Fatigue tests with a ratio of maximum applied load to maximum static load, $R = |P_{max}| / |P_{pl}| = 0.1$ were done. Static tests and fatigue tests were performed using freely rotating rollers to apply the load.

3.2. Materials

The construction of the sandwich panels is shown in Figure 1. The sandwich panel skins were half-hard commercially pure aluminum sheets and the cores were foamed aluminum (trade name Alporas) with a closed cell structure and relative density of $\rho = 11$ %.

Four geometries were used here in order to vary the failure mode observed in experiments. Three extreme geometries were chosen to study face yield, core shear and indentation and a fourth, reflecting an geometry optimized for strength, lies on the boarder of indentation and core shear. This involved changing both the thickness of the skin t, the thickness of the core, d, and the distance between the inner and outer rollers l. The skins were adhered to the surface of the foam using an epoxy contained in a nylon mesh carrier known by the trade name Redux 322 made by Hexcel Composites. The adhesive is of thickness 0.1 mm and of shear strength 20 MPa: we can neglect its effect on the structural response. The aluminum skins were degreased then abraded before cutting the sheet epoxy to size. The panels were assembled and air cured for 1 h at 175 °C then slowly cooled.

The monotonic and fatigue behaviors of 11 % Alporas in compression have been summarized in the literature.[4] Alporas exhibits crush-band formation at random locations under uniaxial compression; in compression–compression fatigue, a single crush-band forms and broadens with additional fatigue cycles and the specimen progressively shortens. In monotonic and cyclic shear Alporas fails by distributed cracking along a shear plane on the center line of the specimen.

4. Experimental Results

4.1. Static Test

Measured load versus displacement curves are shown in Figure 3 for sandwich panels which fail by face yield, core shear, and indentation. Indentation begins with the face sheet following the roller profile but at larger deformations the face sheet loses contact with the roller and forms a triangle in which the roller sits. Face yield occurs in the tensile face sheet directly beneath the inner rollers. Core shear begins as individual cracks tilted at an angle of approximately 45° to the neutral axis. With continued loading more dispersed fine cracks appear until at failure the microcracks join to form a macroscopic crack along the neutral axis of the core. The ends of the final crack terminate at the rollers. This is in contrast to a single crack at 45° to the neutral axis as Burman and Zenkert[1] observed in polymer foam cores. The optimized sandwich panel (t = 1.6 mm, d = 20 mm, l = 80 mm) failed by indentation under static loading. The failure map suggests that this panel sits just inside the indentation regime.

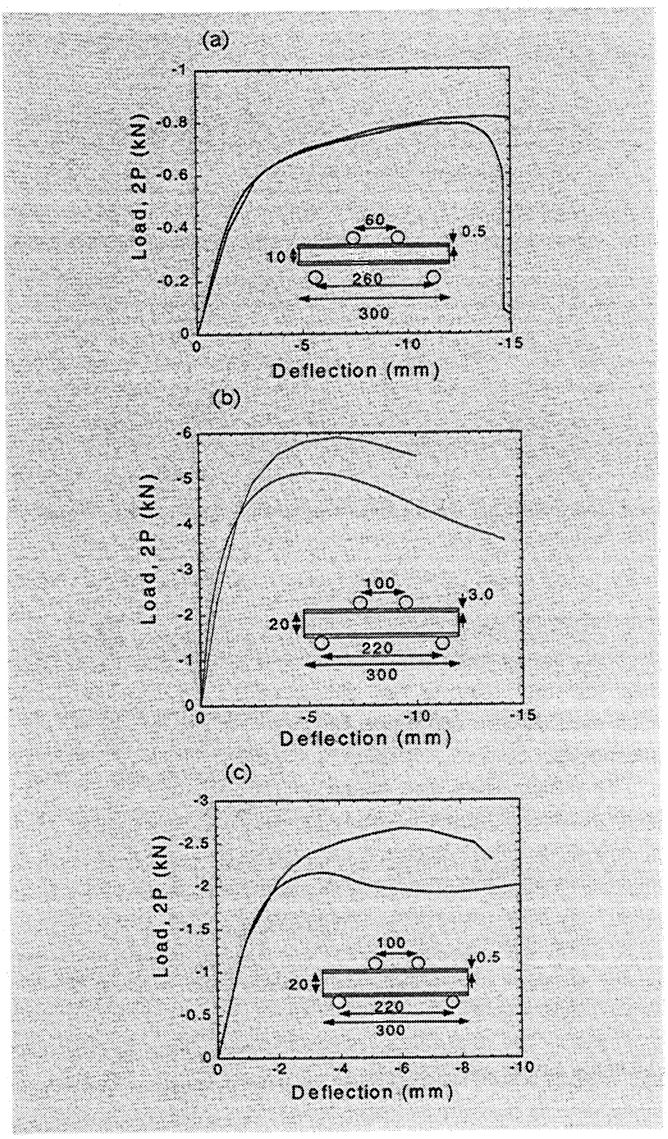

Fig. 3. Measured load versus displacement curves and geometry for sandwich panels which fail by a) face yield, b) core shear, and c) indentation. Repeat tests are reported in each case.

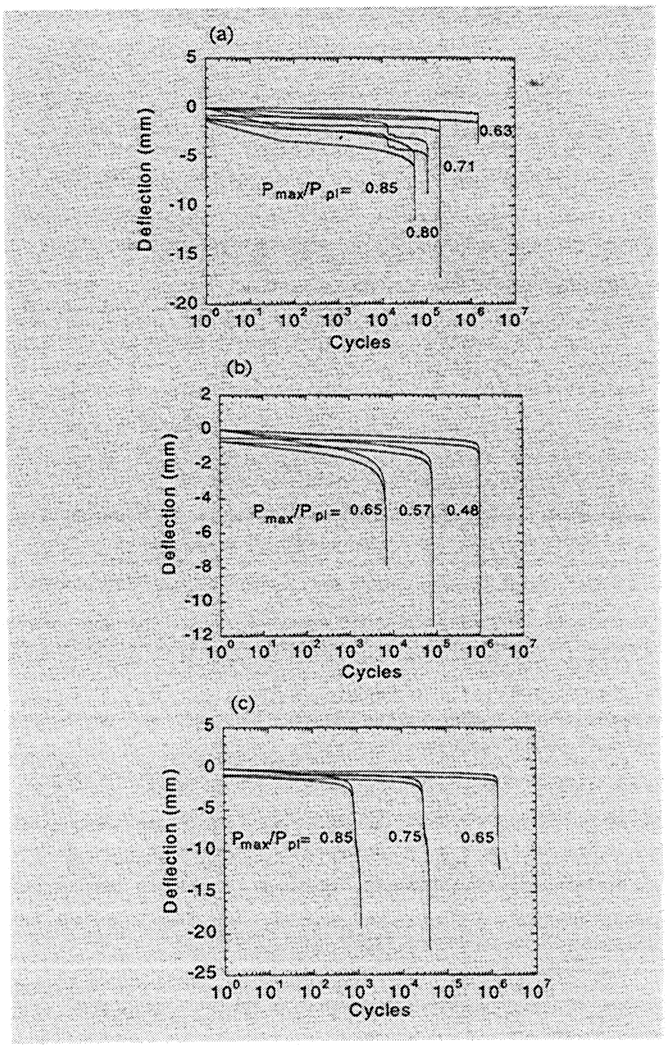

Fig. 4. Accumulated displacement versus number of cycles for sandwich panels which fail by a) face yield, b) core shear, and c) indentation. R = 0.1.

4.2. Fatigue Tests

Accumulated displacement versus cycles for the face yield, core shear and indentation specimens are shown in Figure 4 for $R = 0.1$. In all cases the curves show a long plateau region of little change in displacement followed by rapid failure. In core shear the first cracks are visible as the magnitude of the displacement begins to increase rapidly. Macroscopic crack development is the same as that observed in the static tests. Burman and Zenkert[1] observed a similar failure mode in polymer foam sandwich panels. Comparisons can be drawn between the indentation of sandwich panels and compression–compression fatigue of Alporas. In Alporas there is a incubation period, after which a crushband is initiated and broadens steadily until the material is consumed.[4] In indentation fatigue of sandwich panels the roller is pressed into the panel at a steady rate once indentation has initiated. The optimised panel shows evidence of both indentation and core shear damage.

5. *S–N* Curves and Failure Map

The goal here is to develop a failure map for aluminum skin–Alporas-cores in fatigue. It can be shown that the failure of the sandwich panels in fatigue is closely related to the fatigue behavior of its constituent parts. The *S–N* curves for Alporas in compression and shear with $R = 0.1$ are given in Figure 5a. It is important to note that the endurance ratio τ_{max}/τ_{pl} for Alporas in shear is much lower than the ratio σ_{max}/σ_{pl} in compression. The fatigue ratio for aluminum alloys lies between 0.6 and 0.75, for tension tests with $R = 0.1$. τ_{pl} and σ_{pl} are the peak values in a monotonic test.

The *S–N* curves for all of the sandwich panels tested are included in Figure 5b. The fatigue ratio P_{max}/P_{pl} for face yield

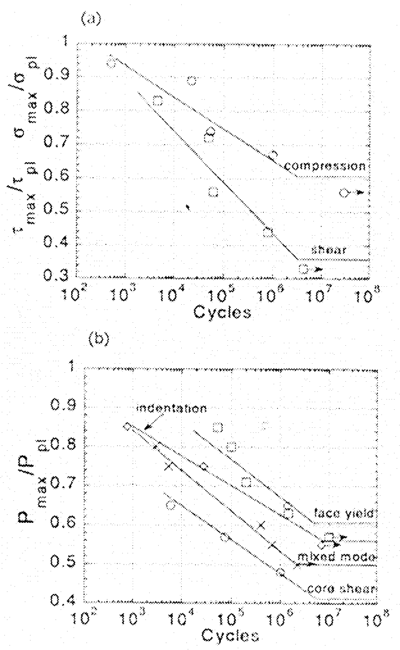

Fig. 5. S–N curves for a) 11 % Alporas in shear and compression and b) sandwich panels under four point bending. R = 0.1.

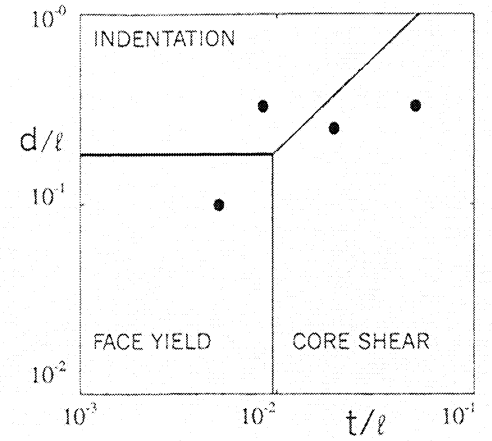

Fig. 6. Theoretical failure map for aluminum skin–Alporas core sandwich panel subjected to four pt. bend fatigue.

is the highest, followed by indentation and core shear. P_{pl} is the peak load observed in the monotonic test. This is expected given the *S–N* curves for Alporas. The optimized sandwich panel fails by indentation at high loads but near the fatigue limit core shear dominates. The *S–N* curve lies between the pure core shear and indentation curves.

A failure map has been constructed by using knock-down factors in Equations 4 to 6 to account for the endurance limit of the materials. A knock-down factor of 0.65 was used for the yield strength of the face sheets, 0.6 for the crushing strength of Alporas, and 0.35 for the shear strength of Alporas. A revised failure map is shown in Figure 6 along with experimental data. We can see that the boundary between indentation and core shear has been shifted so that the optimized panel now sits within the core shear regime.

6. Conclusions

In this work half-hard aluminum skins and Alporas foam cores were used for sandwich panels. They were tested in four point bend in order to examine the failure modes associated with change in loading and sandwich panel geometry. Three failure modes were observed: face sheet yield, core shearing and indentation under the loading roller. A failure map for static loading was constructed using simple sandwich panel theory and it was successful in predicting the failure modes.

The panels were also loaded in fatigue and *S–N* curves were produced for each failure mode. These were compared to *S–N* curves for Alporas in compression and shear. It was found that lower fatigue limit for shear loading is reflected in sandwich panel behavior: the fatigue limit for core shear is lower than that for indention. By using knock-down factors for the strength of Alporas in compression and shear and for the face sheet material a new failure map has been produced for fatigue. The core shear regime is more dominant for fatigue than monotonic loading.

[1] M. Burman, D. Zenkert, *Int. J. Fatigue* **1997**, *19(7)*, 551.
[2] P. D. Soden, *J. Strain Anal.* **1996**, *31(5)*, 353.
[3] T. C. Triantafillou, L. J. Gibson, *Mater. Sci. Eng.* **1987**, *95*, 37.
[4] A.-M. Harte, N. A. Fleck, M. F. Ashby, *Acta Mater.* **1999**, *47*, 2511.