Failure of Sandwich Beams

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Abstract. An investigation was conducted on failure of composite sandwich beams under three-point bending and in cantilever beams under end loading. The beams consisted of unidirectional carbon/epoxy facings and a variety of core materials, including aluminum honeycomb, PVC closed-cell foams, polyurethane foam and balsa wood. The constituent materials were fully characterized and in the case of the core materials, failure envelopes were developed for biaxial states of stress. Deformation and failure mechanisms include core shear failure and compression facing wrinkling. Results were obtained for stress (strain) distributions in the linear and nonlinear/plastic range of the core, critical failure loads due to shear core failure and compression facing wrinkling and their dependence on geometrical dimensions, material parameters and loading conditions.

Introduction

Sandwich structures consisting of strong and stiff facings and light weight cores offer improved stiffness and strength to weight ratios compared to monolithic materials. Under flexural loading the facings carry almost all of the bending, while the core takes the shear loading and helps to stabilize the facings. Facing materials include metals and fiber reinforced composites. The latter are being used in advanced applications due to the large strength-to-weight ratio. The core materials mainly include honeycombs, foams and wood. Foam cores are widely used in sandwich construction. They include a large selection of foamed plastic materials with a variety of densities and shear moduli.

The overall performance of sandwich structures depends not only on the properties of the facings, but also on those of the core and the adhesive bonding the core to the skins, as well as on geometrical dimensions. Sandwich beams under general bending, shear and in-plane loading display various failure modes. Their initiation, propagation and interaction depend on the constituent material properties, geometry and type of loading. Failure modes and their initiation can be predicted by conducting a thorough stress analysis and applying appropriate failure criteria in the critical regions of the beam. Possible failure modes include tensile or compressive failure of the facings, debonding at the core/facing interface, indentation failure under localized loads, core failure, wrinkling of the compression face and global buckling. Following initiation of a particular failure mode, this mode may trigger and interact with other modes and final failure may follow another failure path. A general review of failure modes in composite sandwich beams was given by Daniel et al. [1]. Wrinkling failures in sandwich columns and beams were studied by Gdoutos et al. [2].

In the present work failure modes of composite sandwich beams under three-point bending and cantilever beams under end load were studied. A common failure of sandwich construction is the so-called "core shear failure," in which the core fails when the shear stress reaches its critical value. However, although the shear stress is usually the dominant stress, there are situations in which the normal stress in the core is of comparable magnitude or even higher than the shear stress.

Such situations occur when the bending component at the point is high (long span beams) and in the vicinity of applied loads and reactions. Under such conditions a material element in the core is subjected to a multiaxial state of stress. Thus, it is important to characterize the core material under multiaxial states of stress and determine the core failure envelops.

A number of core materials, including aluminum honeycomb, various types of closed-cell PVC foams, a polyurethane foam, foam-filled honeycomb and balsa wood, were characterized under uniaxial and biaxial states of stress. Gdoutos et al. [3] characterized Divinycell H250 under multiaxial states of stress and showed that the failure surface of the material can be described by the Tsai-Wu failure criterion.

In the present work, failure modes including shear core and compression facing wrinkling were investigated experimentally in composite sandwich beams under three-point bending and in end-loaded cantilever beams. Results were obtained for the critical failure load as a function of beam span for various core materials.

Analytical background

Stress Field in Sandwich Beams

Consider a sandwich beam of rectangular cross section with facings and core materials displaying linear elastic behavior, subjected to a bending moment, M, and shear force, V. The in-plane maximum normal stress, σ_c, and shear stress, τ_c, in the core, and the normal stress, σ_f, in the facings for a low stiffness core and thin facings are given by

$$\sigma_c = \frac{PL}{C_1 b d^2}\left(\frac{E_c}{E_f}\right)\frac{h_c}{h_f} \qquad \tau_c = \frac{P}{C_2\, b h_c} \tag{1a}$$

$$\sigma_f \cong \frac{M}{b h_f \left(h_f + h_c\right)} \tag{1b}$$

where

$$M = \frac{PL}{C_1}, \quad V = \frac{P}{C_2} \tag{2}$$

P = applied concentrated load
L = length of beam
E_f, E_c = Young's modulus of facing and core material, respectively
h_f, h_c = thickness of facings and core, respectively
d = distance between centroids of the facings
b = beam width
C_1, C_2 = Constants depending on loading configuration
(C_1= 4, C_2= 2 for three-point bending; C_1= C_2= 1 for cantilever beam)

The maximum normal stress, σ, for a beam under three-point bending occurs under the load, while for a cantilever beam under end loading it occurs at the support. The shear stress, τ, is constant along the beam span and through the core thickness, as verified experimentally [1].

Failure mode transition

When the normal stress in the core is small relative to the shear stress, it can be assumed that core failure occurs when the shear stress reaches a critical value. Furthermore, failure in the facings occurs when the normal stress reaches its critical value, usually the facing compressive strength. Under such circumstances we obtain from Eqs. (1a) and (1b) that failure mode transition from shear core failure to compressive facing failure occurs when

$$\frac{L}{h_f} = C\,\frac{F_f}{F_{cs}} \tag{3}$$

where

F_f = facing strength in compression or tension
F_{cs} = core shear strength
C = constant ($C = 2$ for a beam under three-point bending; $C=1$ for a cantilever beam under an end load)

When the left hand term of Eq. (3) is smaller than the right hand term, failure occurs by core shear, whereas in the reverse case failure occurs by facing tension or compression. Failure mode transition according to Eq. (3) is shown in Fig. 1 for a beam under three-point bending and a cantilever beam under end load. In the above discussion it is assumed that the beam is adequately reinforced locally at the points of load application and supports, to suppress premature failure due to indentation.

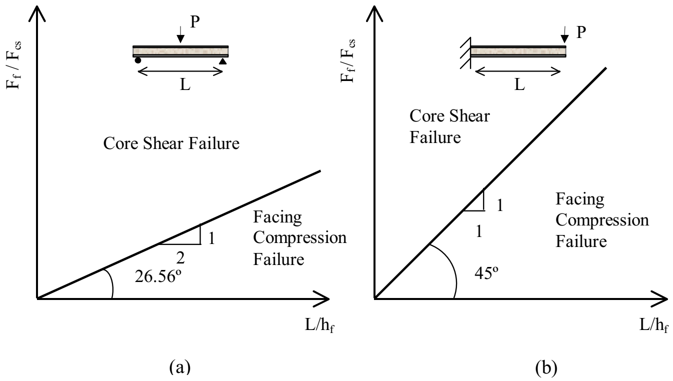

Fig. 1 Failure envelopes for (a) a beam under three-point bending and (b) a cantilever beam under end loading

Experimental procedure

Materials and specimens

The sandwich beams were fabricated from 8-ply unidirectional carbon epoxy (AS4/3501-6) facings and various core materials. They include four types of a closed-cell PVC foam (Divinycell H80, H100, H160 and H250, with densities of 80, 100, 160 and 250 kg/m^3, respectively), an aluminum honeycomb (PAMG 8.1-3/16 001-P-5052, Plascore Co.), a polyurethane foam, a foam-filled honeycomb and balsa wood. All core materials were characterized in uniaxial tension and compression along the in-plane and through-the-thickness directions and under in-plane shear. The core materials (honeycomb or foam) were provided in the form of 25.4 mm (1 in.) thick plates. The honeycomb core was bonded to the top and bottom facings with FM73 M film adhesive and the assembly was cured under pressure in an oven following the recommended curing cycle for the adhesive. The foam cores were bonded to the facings using a commercially available epoxy adhesive (Hysol EA 9430). Beam specimens 25.4 mm (1 in.) wide and of various lengths were cut from the sandwich plates.

Failure envelopes

Two core materials, Divinycell H100 and H250 were fully characterized under multiaxial stress condition [3]. A series of biaxial tests were conducted including constrained strip specimens in tension and compression with the strip axis along the through-the-thickness and in-plane directions; constrained thin-wall ring specimens in compression and torsion; thin-wall tube specimens in tension and torsion; and thin-wall tube specimens under axial tension, torsion and internal pressure. From these tests and uniaxial results in tension, compression and shear, failure envelopes were constructed. It was shown that the failure envelopes were described well by the Tsai-Wu criterion [4].

For a beam loaded under combined bending and shear, the foam is subjected to longitudinal normal stress, σ_1, and in-plane shear stress, τ_5 (τ_{13}). The Tsai-Wu criterion for this case takes the form

$$f_1 \sigma_1 + f_{11} \sigma_1^2 = 1 - k^2 \tag{4}$$

where

$$f_1 = \frac{1}{F_{1t}} - \frac{1}{F_{1c}}, \quad f_{11} = \frac{1}{F_{1t} F_{1c}}, \quad f_{55} = \frac{1}{F_5^2}, \quad k = \frac{\tau_5}{F_5}$$

F_{1t}, F_{1c} = tensile and compressive strengths in the in-plane (1, 2) direction.
F_5 = shear strength on the 1-3 plane.

It was assumed that the failure behavior of all core materials is described by the Tsai-Wu criterion. Failure envelopes of all core materials constructed from the values of F_{1t}, F_{1c} and F_5 are shown in Fig. 2. Note that the failure envelopes of all Divinycell foams are elongated along the σ_1-axis, which indicates that these materials are stronger under normal longitudinal stress than in-plane shear stress. Aluminum honeycomb and balsa wood show the opposite behavior. For all materials, the most critical combinations of shear and normal stress fall in the second and third quadrants (the failure envelopes are symmetrical with respect to the σ_1-axis).

Sandwich beams

The deformation and failure mechanisms in the core of sandwich beams in three-point bending and cantilever beams under end load were studied by means of moiré gratings and photoelastic coatings. Figure 3 shows moiré fringe patterns in the core of a sandwich beam under three-point bending for an applied load that produces stresses in the core within the linear elastic range. The moiré fringe patterns corresponding to the u (horizontal) and w (through-the-thickness) displacements away from the applied load consist of nearly parallel and equidistant fringes from which it follows that

$$\varepsilon_x = \frac{\partial u}{\partial x} \cong 0, \quad \varepsilon_z = \frac{\partial w}{\partial z} \cong 0, \quad \gamma_{xz} = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} = \text{ constant} \tag{5}$$

Thus, the core is under nearly uniform shear stress, which is in agreement with the linear theory of sandwich beams.

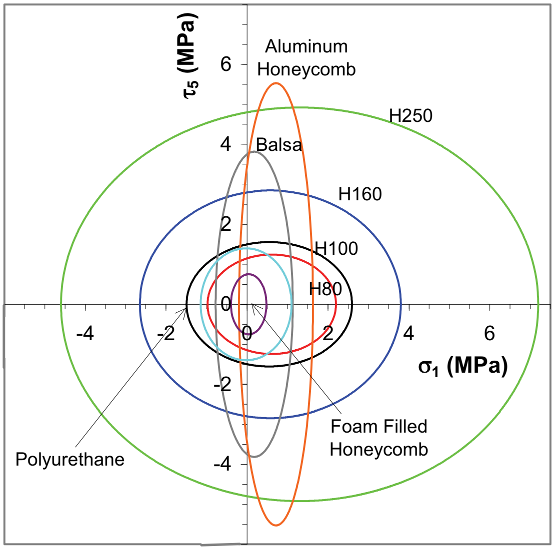

Fig. 2 Failure envelopes for various core materials based on the Tsai-Wu failure criterion for interaction of normal and shear stress

Figure 4 shows isochromatic fringe patterns in the birefringent coating for a beam under three-point bending for various values of applied load P. The shear strain γ_{xz} is related to the fringe order by

$$\gamma_{xz} = f_e N \tag{6}$$

where f_e is the photoelastic constant of the coating material of thickness 1 mm (0.042) in.) and N is the fringe order. Note that the fringe patterns for applied loads less than 3.3 kN (740 lb) are almost uniform, indicating that the shear strain (stress) in the core is constant. For this load the average shear stress in the core is 2.55 MPa (370 psi), which is close to the proportional limit of the shear stress-strain curve of the core material (Divinycell H250). For higher loads the core begins to yield and the shear strain becomes highly nonuniform peaking at the center.

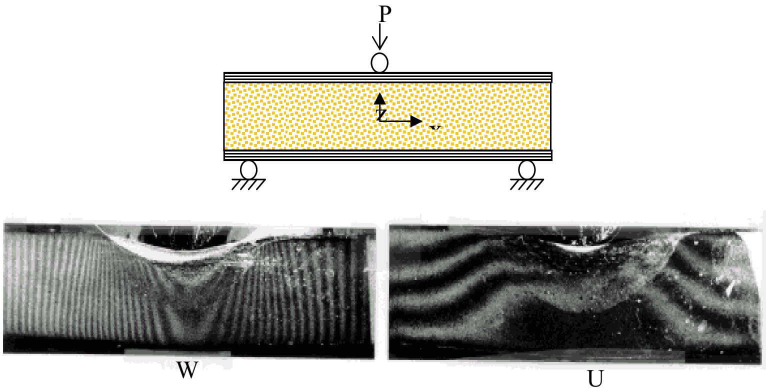

Fig. 3 Moiré fringe patterns corresponding to horizontal and vertical displacements in sandwich beam under three-point bending (12 lines/mm, 300 lines/in; Divinycell H250 core)

From Figure 2 it is shown that the most critical situation for core failure is a combination of compressive and shear stresses. Analysis of horizontal displacements by the moiré and birefringent coating methods shows that, for nonlinear deformation, the neutral axis is no longer located at the mid-plane of the core, but moves towards the tension side of the beam. This is due to nonlinear behavior of the core and facings. If most of the bending moment is taken up by the facings, the distance of the neutral axis from the tensile side of the beam is given by

$$x = \frac{h_c}{1+\frac{\varepsilon_c}{\varepsilon_t}} \tag{7}$$

where ε_c and ε_t represent the average compressive and tensile strains of the facings, respectively.

Failure loads

Failure modes of sandwich beams studied include compression facing wrinkling of the compression facing and shear core failure. Failure by compression or tension of the facings was not observed. A prediction of the critical facing wrinkling stress was given by Hoff and Mautner [5]:

$$\sigma_{cr} = c\left(E_{f1}\, E_{c3}\, G_{c13}\right)^{1/3} \tag{8}$$

where c is a constant usually taken equal to 0.5. In this relation the core moduli are the initial elastic moduli if wrinkling occurs while the core is still in the linear elastic range. This requires that the shear force at the time of wrinkling be low enough or, at least,

$$V < A_c\, F_{cs} \tag{9}$$

where A_c = core cross sectional area
F_{cs} = core shear strength

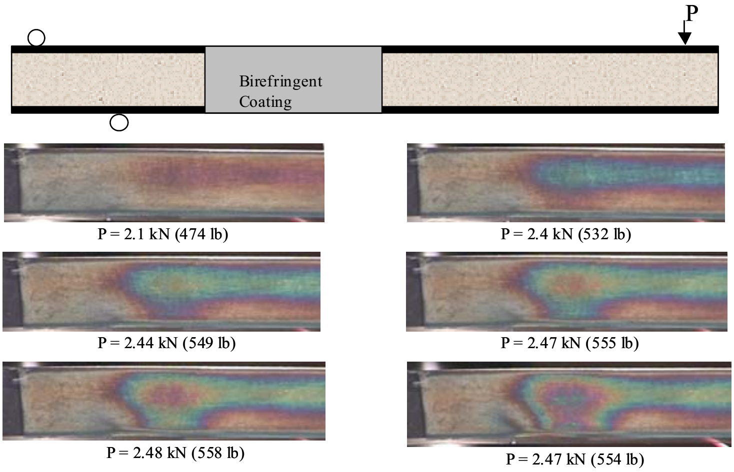

Fig. 4 Isochromatic fringe patterns in birefringent coating of sandwich beam under three-point bending

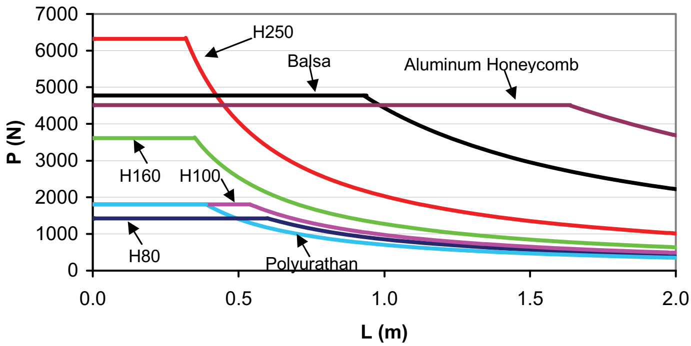

Fig. 5 Critical load for failure initiation versus length of a sandwich beam under three-point bending for a series of core materials

Fig. 5 shows curves of the critical load versus span length for initiation of the two failure modes discussed above for a variety of core materials. Their intersection defines the transition from core failure initiation to facing wrinkling initiation. For small values of the span length shear core failure takes place, while for higher values of the span length the sandwich beam fails by compression facing wrinkling.

CONCLUSIONS

Core failure modes were investigated for composite sandwich beams under three-point bending and cantilever beams under end loading. A number of core materials were characterized and their failure behavior under multiaxial state of stress was studied. Deformation and failure mechanisms were studied experimentally by means of moiré gratings and birefringent coatings. The main conclusions of the present study are the following:

1. In the linear elastic range the core shear stress (strain) is uniform through the thickness according to the bending theory of sandwich beams and as confirmed experimentally.
2. In the nonlinear/plastic range the core begins to yield and the shear strain becomes nonuniform peaking at the center.
3. In the nonlinear region the neutral axis is no longer located at the mid-plane of the core, but moves towards the tension side of the beam. This affects the shear and bending stress distributions in the beam.
4. Core failure is accelerated when compressive and shear deformations are combined.
5. Core yielding and stiffness loss reduce core support for the facings, precipitating facing wrinkling.
6. For small beam spans shear core failure takes place, while for larger spans failure takes place by wrinkling of the compression facing.
7. The dependence of the critical load for core failure initiation on the geometrical configuration, core and facing material properties and loading conditions of the sandwich beam was analyzed.

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