The collapse response of sandwich beams with aluminium face sheets and a metal foam core in three-point bending

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Plastic collapse modes of simply supported and clamped sandwich beams have been investigated experimentally and theoretically, for aluminium face sheets and Alporas foam core. The effect of clamped boundary conditions is to induce axial stretching after the initial yield mechanism. Hence, face sheet ductility dictates the level of energy absorption of the beam. Numerical and analytical predictions are validated by the available experimental evidence.

1. Introduction

In practical applications such as ship hulls, sandwich structures are supported by an underlying array of reinforcement beams. Consequently, it is important to explore the collapse modes for two extremes of support conditions: simply supported and clamped. In this study the quasi-static load-deflection response of simply supported and clamped sandwich beams are measured, for the choice of aluminium faces and Alporas aluminium alloy foam core. Three possible initial collapse modes are identified and a collapse mechanism map is developed from analytical models. Additional predictions are given by detailed finite element simulations.

2. Analytical models

We begin by summarising analytical formulae for the initial collapse load, and the post-yield behaviour of clamped sandwich beams, assuming that the face sheets and core can be considered as elastic–perfectly plastic materials. The analogous formulae for the initial collapse of simply supported beams have been given previously by Chen *et al.*[1]. Consider a sandwich beam of length l and width b, comprising two identical face-sheets of thickness t, bonded to a metal foam core of thickness c, as shown in Fig. 1a. A frictionless flat-bottomed punch of width a is used to load the beam as shown. In the following, we will use the suffixes f and c for the face sheets and core material, respectively. Thus, E_f, σ_f and E_c, σ_c denote the Young's modulus and yield stress of the faces and core, respectively.

It is convenient to express the geometry, material properties, load F and mid-point deflection δ non-dimensionally as

$$\bar{c} = \frac{c}{l}; \bar{t} = \frac{t}{c}; \bar{a} = \frac{a}{l}; \bar{\delta} = \frac{\delta}{l}; \bar{\sigma} = \frac{\sigma_c}{\sigma_f}; \bar{F} = \frac{F}{bl\sigma_f} \tag{1}$$

The extensive study of Ashby *et al.* [2] has identified several competing collapse modes for sandwich beams with ductile faces and cores. For aluminium faces and a metal foam core, the three dominant collapse mechanisms are *face yield*, *core shear* and *indentation*, as sketched in Fig. 1. The following upper-bound analysis is used to calculate the initial collapse load by each mechanism, for the choice of clamped beams.

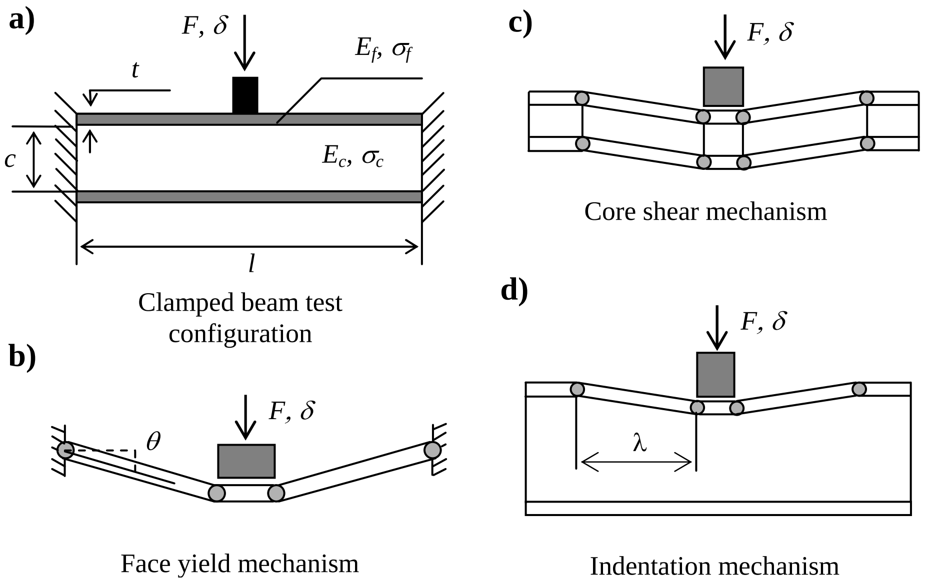

Fig. 1: a) geometry of a clamped beam in three-point bending. b) initial collapse by face yield. c) initial collapse by core shear. d) initial collapse by indentation.

Face yield. Assume plastic collapse by four plastic hinges at the indenter edges and the outer supports, as shown in Fig. 1b. Then, an upper bound work calculation gives

$$\overline{F}_{FY} = \frac{2\overline{c}^2}{1-\overline{a}}\left(4\overline{t}\left(1+\overline{t}\right)+\overline{\sigma}\right) \tag{2}$$

Core shear. When a sandwich panel is subjected to a transverse shear force, the load is carried mainly by the core, and plastic collapse by core shear can result, involving the formation of plastic hinges as sketched in Fig. 1c. The non-dimensional collapse load is

$$\overline{F}_{CS} = 4\overline{c}\left(\frac{\overline{c}\ \overline{t}^2}{1-\overline{a}}+\frac{\overline{\sigma}}{3}\right) \tag{3}$$

Indentation. Sandwich beams with thin faces and a narrow indenter (compared with core thickness) are likely to start collapsing by a local indentation phenomenon. Four plastic hinges form near the indenter edges and on the top face at a distance λ from them, and the core crushes beneath the indenter. A limit load analysis gives

$$\overline{F}_{IN} = 2\overline{t}\ \overline{c}\sqrt{\overline{\sigma}}+\overline{a}\,\overline{\sigma} \tag{4}$$

2.4 Large deformation of clamped sandwich beams

After the initial collapse has taken place, the subsequent response is sensitive to the choice of boundary conditions. Simply supported beams collapse at a nearly constant load and deflection proceeds until the structure fails by fracture of the face sheets or of the core. If the beam is clamped, axial stretching dominates when the transverse deflection is comparable to the beam thickness. Upon neglecting the core contribution to the axial strength of the beam, simple equilibrium considerations give

$$F = \frac{4N_0}{l-a}\delta \qquad for \quad \delta \geq H \tag{5}$$

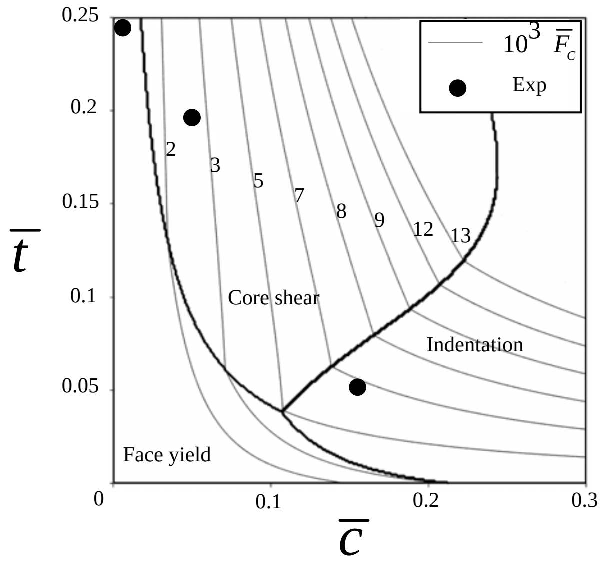

Fig. 2: Initial collapse mechanism map for clamped sandwich beams comprising aluminium face sheets and an Alporas foam core ($\overline{\sigma} = 0.034$ and $\overline{a} = 0.2$). Contours of non-dimensional initial collapse load, and tested geometries as denoted by 'Exp', are marked on this figure.

where $N_0 = 2tb\sigma_f$ and $H = c + 2t$.
The response of the sandwich structure can be thought as consisting in three phases: (i) Initial collapse: the beam fails by the dominant mechanism, (ii) Transition: a stretching effect takes place due to finite deflections, and the stress distribution within the beam sections deviates from the one associated with the initial collapse load towards a pure membrane distribution when the deflection of the beam is equal to its height, (iii) Membrane state: the beam behaves as a string and the face sheets yield in tension, until they eventually tear leading to the ultimate failure of the structure.

3. Experimental investigation

Clamped and simply supported beams comprising an aluminium foam core and aluminium faces were tested in bending to underpin the analysis detailed above.
Material characterisation. In order to determine the mechanical properties of the constituent materials a series of tests was performed on both the composite face sheets and the foam core. Commercially pure, annealed aluminium sheet was used for the faces, whereas the core was a closed-cell aluminium alloy foam, with trade-name Alporas; its relative density (density of the foam divided by the density of the cell wall material) was $\hat{\rho} = 11\%$, and the average cell size was 3 mm. The aluminium face-sheets were degreased and abraded, and were then adhered to the foam core using Redux 322 epoxy adhesive on a nylon carrier mesh. The sandwich beams were air cured at 180˚C for 1 hour, and bonding was facilitated by imposing a dead load. The mechanical properties of the face sheets material were measured by testing specimens of dog-bone geometry, and measuring strains via $120\,\Omega$ strain gauges and laser extensometers.

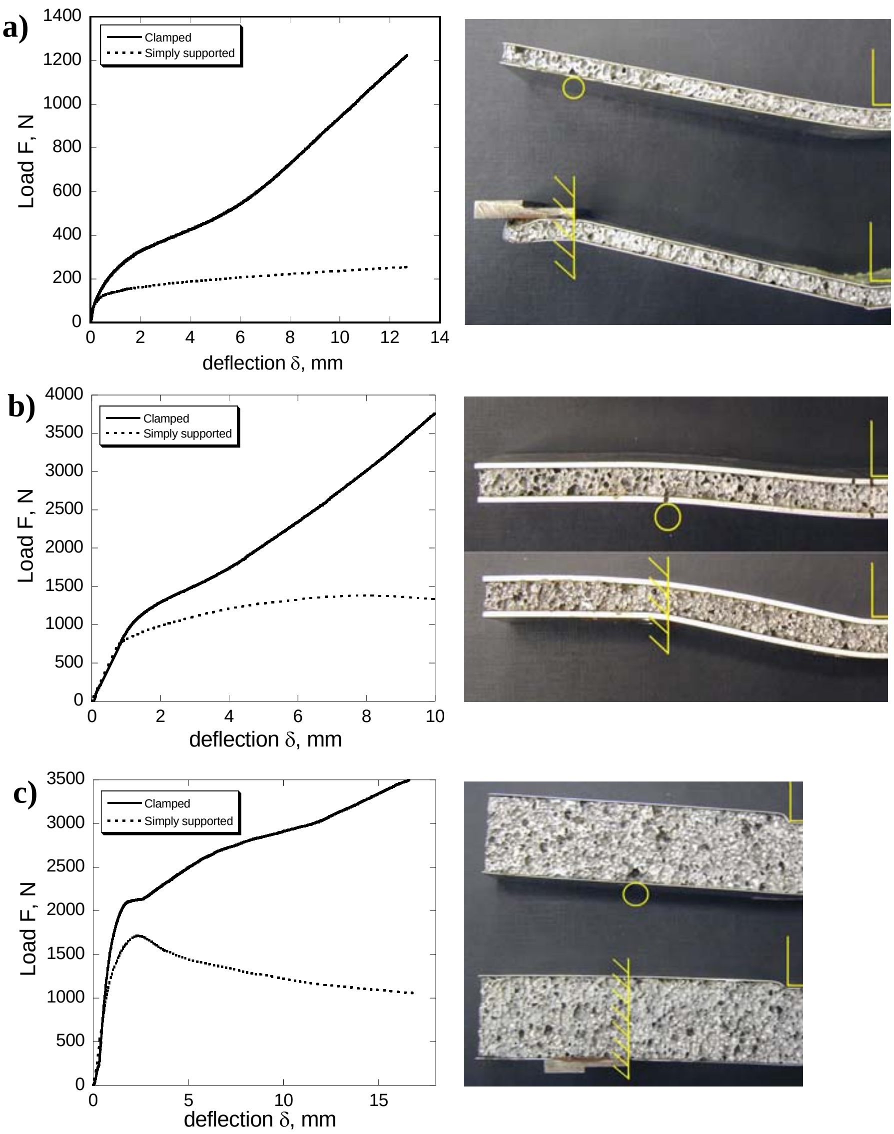

Fig. 3: Load versus deflection curves and video captures for the three selected structural geometries, tested in simply supported and clamped conditions. a) face yield specimens. b) core shear specimens. c) indentation specimens.

The associated tensile stress-strain curves have been used to characterise the face sheet material, which had a Young's modulus of E_f = 65-70 GPa, a Poisson ratio of $\nu_f = 0.33$, a yield stress of 65 MPa and a tensile ductility of about 45%. The uniaxial compressive response of the Alporas foam has also been measured. Cuboidal specimens of dimension 35 mm x 35 mm x 50 mm were compressed between two metal plates at a nominal strain rate of 10^{-4} s^{-1}, and a laser extensometer was used to measure the axial strain. The Alporas foam has a Young's modulus E_c =1.06 GPa, a compressive strength of about 2 MPa, and a densification strain of 40-50%.

Test method for sandwich beams. In order to guide the choice of sandwich beam geometry, an initial collapse mechanism map for simply supported and clamped sandwich beams has been constructed from the analysis detailed in Section 2. An initial collapse mechanism map for clamped beams comprising aluminium face sheets and an aluminium foam core is shown in Fig. 2 for a choice of material and geometrical parameters $\overline{\sigma} = 0.034$ and $\overline{a} = 0.1$, in line with the measured material properties; the map is dominated by the core shear and indentation regimes. Contours of the non-dimensional initial collapse load index $\overline{F}_C$ are included in the map. Three structural geometries have been selected, each one lying clearly in a different region of the initial collapse mechanism map, and the associated sandwich beam were tested in both simply supported and clamped conditions. Beams of width 50 mm have been manufactured and loaded in three-point bending by means of flat punches of different sizes. The clamped boundary conditions were achieved by gluing the beams into a stiff supporting steel structure. The beams were instrumented with longitudinal strain gauges at mid-span of the bottom face sheet and the relative vertical displacement between the face sheets was measured with a laser extensometer.

4. Effect of boundary conditions upon the collapse response

In order to investigate the effect of boundary conditions on the response of sandwich beams, it is instructive to plot on the same graph the load versus deflection curves for two specimens with the same structural geometry but different boundary conditions.

Fig. 3a presents the measured responses for beams initially failing by face yield, together with photographs of the specimens after test. The two beams initially collapse at different load levels; the collapse load for a clamped beam is about twice that for a simply supported beam, as predicted analytically. After the initial collapse, the simply supported beam deflects at an almost constant load, whereas for the clamped beam, as the deflection rises, face sheet stretching becomes the main deformation mechanism. The load starts increasing and the stress distribution in the beam approaches a pure membrane state.

Fig. 3b shows results from experiments conducted on sandwich beams initially collapsing by core shear. For the simply supported beam, the peak load is due to shear fracture of the core. In the clamped beam case, face and core stretching causes the load to rise above the initial collapse strength.

Fig. 3c refers to a structural geometry lying within the indentation region in the initial collapse map. After an initial collapse phase that is approximately the same for the two specimens, the two responses diverge. The simply supported beam displays a softening behaviour after initial indentation, due to a progressive reduction in cross- section. In the clamped beam experiment the indentation mechanism is inhibited by the build-up of membrane loading. Failure of the beam is set by tearing in tension of the face sheets.

5. Accuracy of the predictions

The response of the clamped sandwich beams has been modelled by the commercial finite elements code Abaqus. Due to symmetry, only half the length of the sandwich structure has been modelled. Eight-nodes rectangular elements have been used to discrete the sandwich core and the aluminium skins. The aluminium faces are modelled by the measured uniaxial response and the foam core behaviour is described by the constitutive model by Deshpande and Fleck [3] and is implemented in Abaqus by Chen and Fleck [4].

It is instructive to plot on the same graph results from experiments, simulations and predictions; in Fig. 4 we show such a plot for a clamped beam whose initial mechanism of

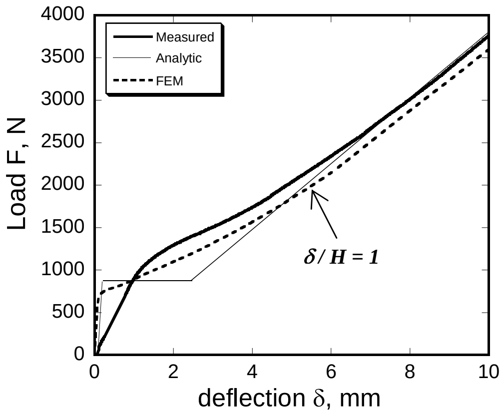

Fig. 4: comparison between the measured, FE and analytical predictions of the load versus deflection response of a clamped beam whose initial collapse mechanism was anticipated to be core shear.

collapse is core shear. Both finite elements and analytical models give good predictions for the initial collapse load. After the transition phase, when the deflection is equal to the height of the beam, the three curves overlap, confirming the accuracy of the membrane idealization.

7. Concluding remarks

This study focused on the effect of clamped boundary conditions on the flexural behaviour of sandwich beams comprising aluminium faces and an aluminium foam core, although its results can be easily extended to any sandwich configuration with metal faces and a ductile lightweight core. The differences between the three-points bend and the stretch-bend tests have been experimentally investigated and it has been concluded that the mechanism that governs deformation in the clamped test is face stretching, independently on the initial collapse mode. Rigid-plastic calculations have been developed for the initial collapse and the post-yield response, and predictions have been validated by experimental evidence and finite elements simulations.

Acknowledgements

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