Composites: Part B 64 (2014) 24–32

Contents lists available at ScienceDirect

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

Response of aluminium foam-cored sandwich panels to bending load

Kaveh Kabir *, Tania Vodenitcharova, Mark Hoffman

School of Materials Science and Engineering, The University of New South Wales, Sydney, NSW 2052, Australia
ARC Centre of Excellence for Design in Light Metals, The University of New South Wales, Sydney, NSW 2052, Australia

ARTICLE INFO

Article history:
Received 29 November 2013
Received in revised form 27 March 2014
Accepted 2 April 2014
Available online 19 April 2014

Keywords:
A. Foams
A. Laminates
B. Mechanical properties
D. Mechanical testing

ABSTRACT

The response of aluminium sandwich panels comprising thin foam cores and thin face sheets of low and high yield strength was investigated under three-point bending load. The effect of skin strength, bending span and core thickness on the failure modes and loads was investigated. While the lower strength face sheet is associated with lower failure loads, that decrease is not proportional to the yield strength due to the additional failure mode of face yielding. Theoretical models enabled prediction of the failure loads and elucidated the contribution of each failure mode. Failure maps were subsequently constructed which can be used for the design of foam-cored sandwich panels with very thin face sheets.

1. Introduction

Light weight, high strength sandwich panels of low density metallic foam cores and thin face sheets provide extraordinary energy absorption capability [1]. The bending strength and stiffness of metal foams dramatically increases with the adhesion of stiffer skins to the top and bottom surfaces, with only a slight weight increase. In many applications, such as in marine industry (e.g., hulls and decks in cruise ships and high speed ferries) and the automotive and aviation industries, large strength/stiffness to weight ratios are critical in the designing of the sandwich panels. During exploitation, the sandwich panels are subjected to various types of mechanical loads, which lead to deformation and even failure. The efficient design of the sandwich structures necessitates that the failure modes and load bearing capacities under various loading conditions are well known.

In the last two decades, a number of research reports have been published on the mechanical response of sandwich panels under various mechanical loads. The response to three-point bending was investigated in a number of studies [1–10] which discuss various failure modes depending on the geometrical and material properties of the sandwich panels (Table 1): (i) face yielding, (ii) core shearing, (iii) indentation, (iv) face wrinkling and (v) skin-core delamination.

Core shear was reported as the failure mode of sandwich panels comprising thick high-strength face sheets and thin cores – in particular, sandwich panels with foam core thickness less than 30 mm and 0.79 mm thick face sheets of 263 MPa yield strength [2], and panels fabricated with 0.8 mm thick face sheets of 268 MPa yield strength, and 5 mm and 10 mm thick foam cores [3]. Core shear was also found in sandwich panels fabricated with low-strength but thick face sheets – in particular, of 6 mm thick face sheets of 92 MPa yield strength, and cores thinner than 21 mm [6]. Three collapse mechanisms of core shear have been observed in sandwich panels with closed-cell foam cores, when flat punch loading fixtures were used [1–4]: (1) *Mode A* corresponds to forming four plastic hinges at the loading point at the mid-span (two in each face sheet at the corners of the loading punch) and shearing of the foam core outside the plastic hinges [2]. (2) *Mode B* corresponds to forming eight plastic hinges at both mid-span and supports (four in each face sheet) and limiting core shearing to the section of the core located between the supports [2]. (3) *Mode AB* is related to half of the beam deforming in *Mode A* and the other half in *Mode B* [4]; thus, plastic hinges are developed at the mid-span and above one of the supports and the core shears outside the mid-span hinges (excluding outside the hinges formed above one of the supports).

Crupi and Montanini [5] and Yu et al. [6] observed failure modes similar to *Mode AB* using cylindrical roller fixtures on sandwich panels fabricated with thick low-strength face sheets and relatively thin cores (10–20 mm) [6], and panels with 1 mm thick low-strength face sheets and 10 mm thick ALULIGHT foam core [5]. However, loading using cylindrical roller fixtures resulted in only two plastic hinges (one in each face sheet), which were formed under the loading roller at the mid-span, due to the geometry of the loading fixture.

* Corresponding author. Tel.: +61 2 9385 7580.
E-mail address: z3169748@zmail.unsw.edu.au (K. Kabir).

http://dx.doi.org/10.1016/j.compositesb.2014.04.003
1359-8368/

Table 1
Comparisons between mechanical and geometrical properties of face sheets and cores of metallic foam-cored sandwich panels. σ_{yf} and σ_{yc} are yield strengths of the face sheets and core, respectively. c, t and L are the core thickness, face sheet thickness and bending span length, respectively.

References	σ_{yf} (MPa)	σ_{yc} (MPa)	c (mm)	t (mm)	L (mm)
McCormack et al. [2]	263	1.52	23–40	0.5–3.98	125–410
Barth-Smith et al. [3]	80	1.52	5, 10	0.4	40, 80, 160
	268			0.8	
Kesler and Gibson [4]	140	1.52	6–34	0.3–2.22	76–440
Crupi and Montanini [5]	100	1.4	10	1	55–135
	180	2			
Yu et al. [6]	92	6	10–50	0.5, 3, 6	250

Failure in indentation was found in sandwich panels with high-strength face sheets, in thick cores and thin face sheets – in particular, in sandwich panels with cores thicker than 30 mm and face sheets thinner than 0.79 mm [2]. This mode of failure was also found in panels fabricated with low-strength face sheets, when thick foam cores (20–50 mm) and thin face sheets (0.5 and 3 mm) were utilised [6]. Indentation was associated with formation of plastic hinges in the face sheet and crushing of the foam core beneath the loading point. Bart-Smith et al. [3] reported that decreasing the span length from 80 mm to 40 mm changed the failure mode from core shearing to indentation, when 0.8 mm thick high-yield strength face sheets (268 MPa yield strength) and 10 mm thick core were utilised.

Failure by face yielding was noticed in thin face sheets of low strength and thin cores – in particular, in panels with 10 mm thick cores and 0.4 mm face sheets of 80 MPa yield strength [3]. Yu et al. [6] reported that decreasing the core thickness from 41 mm to 20 mm resulted in changing the failure mode from indentation to face yielding for the panels fabricated with 0.5 mm thick, low-strength face sheets (yield strength of 92 MPa). In previous studies, face wrinkling was not found to dominate the failure, although it was observed by McCormack et al. [2] in only a few specimens, which was explained by the foam variability and inhomogeneity beneath the loading fixture.

Crupi and Montanini [5] reported two combinations of failure modes in sandwich panels of high-strength face sheets (180 MPa yield strength) and 10 mm thick foam core, depending on the span length: (i) *Mode I*: a combination of indentation and core shearing for span lengths longer than 90 mm (ii) *Mode IIA*: a combination of compressive core yielding and core shearing in span lengths shorter than 80 mm. However, the reason for this behaviour remained unexplained.

As shown in Table 1, the influence of the strength of very thin face sheets (face thickness less than 0.5 mm) on the mechanical performance of thin metallic foam-cored sandwich panels has yet to be fully explained. Therefore, the aim of this study is to investigate the effect of very thin face sheets and to explain the significance of the strength of face sheet material on the structural integrity of the metal foam laminates in bending. Two types of aluminium for thin face sheets are considered: one of low yield strength and one of high yield strength. Additionally, the effects of core thickness and bending span length on the failure modes and loads are addressed. By considering the experimental results and a combination of failure models, failure maps for varying yield strength of the face sheet, core thickness and bending span length are created.

2. Materials and sample preparation

ALPORAS foam panels of two thicknesses ($c = 6$ and 12 mm) were employed in this study. Sheets of 0.32 mm thick aluminium alloys were used as reinforcing skins on both sides of the foam panels. To investigate the influence of the yield strength of the face sheet, two types of aluminium alloys were chosen: (i) AA 1100-O with low yield strength and (ii) AA 3104-H19 with high yield strength. The key mechanical properties of the alloys were investigated by conducting tensile tests on dog-bone specimens. The determined ultimate tensile strength, yield strength and elongation at break are listed in Table 2.

Table 2
Mechanical properties of the face-sheets: ε, σ, σ_y and E are the failure strain, tensile strength, yield strength and elastic modulus, respectively.

Face sheet material	ε (%)	σ (MPa)	σ_y (MPa)	E (GPa)
AA 1100-O	35.7 ± 2	79.8 ± 1	40 ± 0.4	69 ± 0.2
AA 3104-H19	3.8 ± 0.5	262 ± 4	236 ± 3	70 ± 0.1

The foam-only panels were cut from larger as-received panels to the required dimensions (150 mm × 35 mm, and 6 mm and 12 mm thickness, c) using a band saw equipped with a guide to ensure that the surfaces are plane-parallel. A guillotine was used to cut the aluminium sheets in the direction of rolling, providing a clean cut edge. To provide better adhesion, all surfaces of both the foam panels and aluminium sheets were degreased and abraded. The degreasing process was accomplished by immersing the aluminium sheets and the foam panels in two baths of acetone – they were washed in the first bath and rinsed in the second one. The contents of the baths were changed after they became visually contaminated. In addition, the surfaces to be bonded were cleaned using a brush and Scotchbrite® abrasive cloth. Since acetone enters into the voids during the degreasing process, the aluminium foam specimens were dried by temperature-assisted evaporation in an oven at 60 °C. After preparing the foam panels and the aluminium sheets, they were bonded using 1 mm thick epoxy film adhesive (Redux 322™, Hexcel Composites Ltd.) with shear strength and tensile strength of 20 MPa [11] and 5 MPa [12], respectively. Thus, the strength of the film adhesive is significantly higher than the shear strength of the foam core (1.6 MPa, maximum [13]) which explains why delamination was not observed at failure. A hot press machine equipped with an electronic controller was employed to cure the panels at 180 °C for 60 min with a heating rate of 2 °C/min. Subsequently, the fabricated panels were cooled down to the room temperature at a cooling rate of 3 °C/min. A uniaxial pressure of 0.1 MPa was applied to ensure that the skins bonded to the core material without collapsing the foam cells.

3. Experimental procedure

Three-point bending tests were conducted at room temperature, according to ASTM C 393-06. An Instron 1185 Universal Testing Machine equipped with a 5 kN load cell was used to conduct the bending tests with a loading rate of 6 mm/min. The tests were carried out with span lengths, L, of 50 mm and 100 mm, and loading rollers of 12.5 mm diameter. The loads, P, and the crosshead displacements, δ, were recorded, the P–δ curves were plotted for each test, and the failure loads were subsequently determined. Six specimens were provided for each test condition, and the density of the specimens was determined by dividing the mass of each specimen by its volume. The density of the foam specimens varied in the range of 0.22–0.35 g/cm^3 while the foam panels used to fabricate the sandwich panels had densities in the range of 0.16–0.36 g/cm^3. The evolution of foam cell deformation on the longitudinal plane of the specimens was investigated during the tests by video-recording and by taking a large number of still photos.