International Journal of Impact Engineering 37 (2010) 638–651

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Fracture of aluminium foam core sacrificial cladding subjected to air-blast loading

G.S. Langdon [a,*], D. Karagiozova [a,b], M.D. Theobald [a], G.N. Nurick [a], G. Lu [c,d], R.P. Merrett [a]

[a] Blast Impact and Survivability Research Unit (BISRU), Department of Mechanical Engineering, University of Cape Town, Private Bag, Rondebosch 7701, South Africa
[b] Institute of Mechanics, Bulgarian Academy of Sciences, Acad. G. Bonchev Street, Block 4, Sofia 1113, Bulgaria
[c] Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, Hawthorn, Vic 3122, Australia
[d] School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

ARTICLE INFO

Article history:
Received 8 December 2008
Received in revised form
14 July 2009
Accepted 14 July 2009
Available online 22 July 2009

Keywords:
Sacrificial cladding
Blast
Aluminium foam
Structural response
Fracture

ABSTRACT

The effect of core density and cover plate thickness on the blast response of sacrificial cladding panels has been investigated through blast loading experiments and finite element modelling on structures with steel cover plates and aluminium foam cores. A range of foam core densities were examined, with 10%, 15% and 20% nominal relative densities. The cover plate thickness greatly influenced the response of the sacrificial cladding. Cover plates that were 2 mm thick exhibited significant permanent deformations and variable percentage crush across the section, whereas the 4 mm thick cover plates were more rigid causing the core to compress uniformly. Considerable fracture of the foam was observed after blast testing, particularly for the lower density foams. The effect of bonding the cover plate to the core was also examined. Numerical simulations of the experiments were performed using ABAQUS/Explicit to provide insight into the response mechanism. It was shown through the finite element simulations that tensile fracture of the foam occurred during the unloading phase of response and that adhesion of the cover plate to the foam caused higher levels of cracking. This was consistent with the experimental observations.

1. Introduction

The blast response of sandwich structures has been attracting research interest recently, as it appears sandwich constructions may offer improved resistance compared to equivalent mass monolithic metal structures [1]. A sandwich panel comprises of a deformable core sandwiched between (at least) two faceplates. In cladding structures, the back faceplate does not deform, whereas in sandwich panels, both faceplates are able to deform. Many core topologies are available, including lattices [2–4], polymeric foams [5], aluminium honeycomb [5–7], and metal foams [8–11]. Choice of core material is critical to the performance of the sandwich as the core properties control the energy absorption and magnitude of the force transfer through the structure. Many cellular materials subjected to quasi-static compression are characterised by a relatively constant plateau stress region over a large range of plastic strains prior to densification, which is the key to the ability of the cellular material to mitigate a blast load. An idealised model of a foam material is shown in Fig. 1 [5]. The general principle is as follows, for the situation of a core sandwiched between two plates: the front plate (the outer cover plate exposed to the blast) deforms into the cellular core and the core reduces in thickness via a cell collapse mechanism. During quasi-static core compression, the stress transmission through the core to the back plate is limited by the plateau stress up to the relatively high (typically 70–75%) densification strain.

The high pressure loading incident on the structure should be converted into a lower magnitude load with a much longer duration (due to conservation of momentum) and hence the core should provide predictable and constant load transfer up to densification. Once densification occurs, the loads increase and the advantages of the cellular material are lost. Previous work on aluminium foam sacrificial cladding subjected to blast loading was reported by Hanssen et al. [10]. Two sets of tests were performed: one set with the blast loading impinging directly onto the aluminium foam and a second set employing aluminium cover plates in front of the foam. Without the protective cladding extremely large pressures are generated by the blast which were directly experienced by the structure. With the use of foam cladding, the pressure experienced by the protective structure is applied over a longer duration with a smaller magnitude. Aluminium foam was considered to be an ideal structure for absorbing energy under blast loads as it was already readily available in various forms and had properties that should be less directionally dependent than aluminium

* Corresponding author. Tel.: +27 (0)21 650 4810; fax: +27 (0)21 650 3240.
E-mail address: genevieve.langdon@uct.ac.za (G.S. Langdon).

0734-743X/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijimpeng.2009.07.006

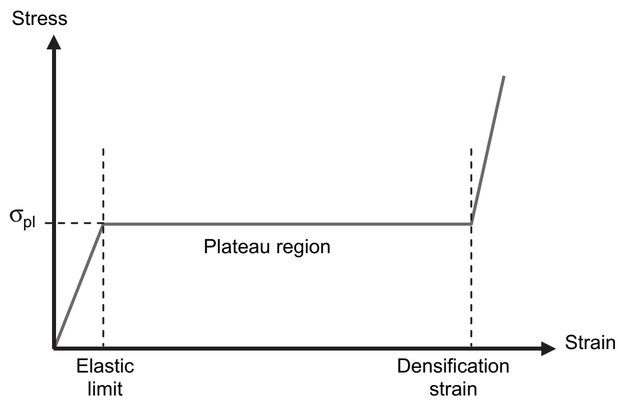

Fig. 1. Typical idealised stress–strain curve for a cellular material subjected to quasi-static compression.

honeycomb. However, using foam in cladding structures requires thick cores to absorb the energy due to high pressure pulses. A reflected compaction wave from the stationary boundary can occur if the foam thickness is not sufficiently large and the magnitude of the reflected stresses can be larger than the magnitude of the incident wave due to the foam properties at densification.

This paper presents the results from air-blast loading tests on sacrificial cladding comprising Cymat® aluminium foam cores and steel cover plates. Foam cores with (nominal) relative densities of 10, 15 and 20% were employed. Photographs of the foam cross-sections are shown in Fig. 2. The 15 and 20% cores were nominally 25 mm thick and the 10% foams were 50 mm thick. This article also examines the influence of bonding and cover plate thickness on the response of the sacrificial cladding. Numerical modelling of the blast loading tests on the cladding is also reported to provide insight into the response mechanism and the reason behind the fracture of the foam.

2. Panel construction

All the cladding structures used aluminium foams as core, obtained from the Cymat Corporation. The foam was manufactured by injecting gas into molten aluminium which is cast into a continuous sheet [12]. This resulted in cells which were randomly distributed and of varying size within a foam sheet.

Each cladding structure comprised a 105 by 105 mm square steel cover plate, a rigid rear plate and an aluminium foam core, as shown in the photograph in Fig. 3. Two different thicknesses of cover plates, 2 mm and 4 mm, were used during the cladding panel construction. The results from standard tensile tests on the cover plate material indicated that the steel had an average yield stress of 244 MPa.

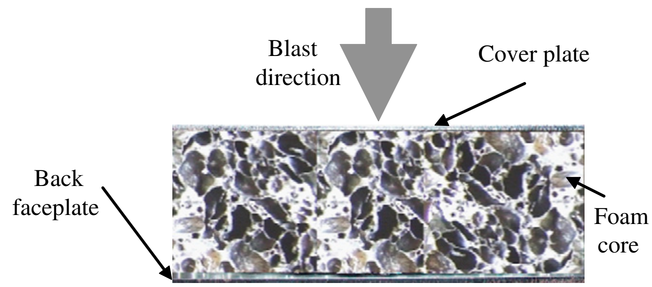

Fig. 3. Photograph of the cladding structure cross-section.

In one series of tests, the foam of all three densities was bonded to both the cover plate and the rear plate using a cold curing two-part epoxy resin (Spabond 345, commercially available) and allowed to cure for 24 h. A second series of tests were performed on the 10% relative density foam core cladding structures with the plates not bonded to the foam.

3. Material characterisation of the foam

Many foam materials show little or no hardening within a large strain interval and are, therefore, well approximated by the model shown in Fig. 1 – where the initial yield stress of the foam is identical to the plateau stress of the foam. There have been a number of approaches to characterising the dependence of the plateau stress upon relative density. Based on the deformation mechanism of a regular structure, Gibson and Ashby [13] developed a formula for closed cell, plastic foams that relates the plateau stress to the relative density of the foam given by

$$\frac{\sigma_{pl}}{\sigma_{ys}} \approx 0.3\left(\varphi\frac{\rho_f}{\rho_s}\right)^{3/2} + (1-\varphi)\frac{\rho_f}{\rho_s} + \frac{p_0 - p_{atm}}{\sigma_{ys}}, \quad (1)$$

where σ_{pl} is the plateau stress of the foam, σ_{ys} is the yield strength of the parent material, φ is the fraction of solid in the cell edges of the foam, ρ_f is the density of the foam, ρ_s is the density of the parent material, P_0 is the internal cell gas pressure and P_{atm} is atmospheric pressure.

Eq. (1) includes membrane stresses and a contribution from accumulation of gas pressure within the cells due to the reducing cell volume under compression and cell collapse. While Eq. (1) was developed for regular closed cells, the commercially available foams have rather irregular structures exhibiting usually lower strength compared to the theoretical prediction. Therefore, different dependences of the plastic strain on the relative density were proposed.

Ruan et al. [14] remark that, for man-made foams such as Cymat aluminium foam, P_0 is usually equal to atmospheric pressure effectively negating the influence of the third term in Eq. (1) and the response of the Cymat foam can be adequately described by

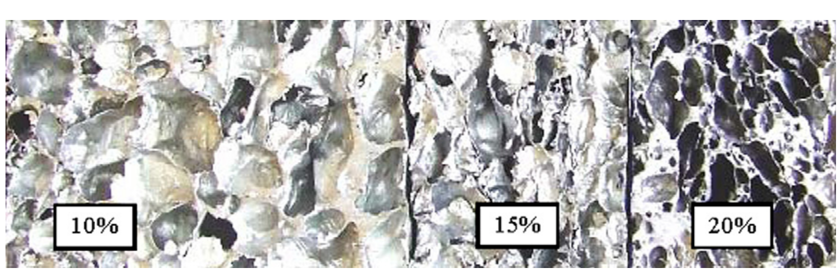

Fig. 2. Cross-sectional view of the Cymat® foam types, showing the different cell sizes and morphologies. [The numbers correspond to the nominal relative density.]