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The influence of core density on the blast resistance of foam-based sandwich structures

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ABSTRACT

This paper investigates the influence of varying core density on the blast resistance of sandwich panels based on crosslinked PVC cores and aluminium alloy skins. Initially, the findings of a series of compression and single edge notch bend and shear tests are presented in order to characterise the strength and toughness characteristics of the foams and generate data for input into the finite element models.

Experimental blast tests employing a ballistic pendulum are then reported, where it is shown that damage within the sandwich panels becomes more severe as the density of the foam core is increased. Indeed, panels based on the lowest density foam (60 kg/m^3) did not exhibit any fracture or debonding over the range of impulses considered, instead absorbing energy through plastic deformation in the metal skins and compression of the foam core. In contrast, significant damage, in the form of Mode I core cracking and debonding at the skin–core interface, was apparent in the higher density core systems. A finite element analysis has been employed to model the blast response of the sandwich structures. The FE models successfully predicted the post-test deformed shapes of the panels. These analyses were also used to determine the individual contributions of the skin and core to the energy-absorbing capacity of the various sandwich structures. Here, it was shown that the foam core absorbs more than fifty percent of the overall energy dissipated during the test.

1. Introduction

As a result of their low weight and superior flexural properties, sandwich structures, based on strong, stiff skins bonded to low density cores are finding increasing use in a wide range of engineering structures. In a bid to take advantage of their attractive dynamic properties and overall light weight, engineers have been investigating the energy-absorbing characteristics of sandwich structures when subjected to blast loading [1–10]. To date, much of this work has focused on the effect of underwater blast loading on the response of sandwich panels [1–6]. However, a number of workers have investigated the response of sandwich panels to conditions associated with air blast [7–10]. For example, Hoo Fatt and Palla [8] developed analytical solutions for the transient response and damage development in foam core sandwich panels subjected to air blast loading. The predictions of the analytical models agreed well with the responses offered by an associated finite element analysis. Nurick et al. [10] studied the response of sandwich panels based on unbonded steel plates placed on an aluminium honeycomb core. Various phases of interaction in the sandwich structures were identified, including deformation, contact, crushing and the tearing of the constituents. The compromises between load transfer through the core and improved energy absorption were discussed [10]. Theobald et al. [11] investigated the influence of core type and skin thickness on the air blast resistance of unbonded sandwich panels with steel surface plates. The performance of the panels was compared with that exhibited by a monolithic steel plate with a comparable areal density. Metal foam sandwich structure with thinner face sheets offered a superior blast resistance to that of a plain steel plate, with aluminium honeycomb panels offering the best performance over the range of impulses examined. Shukla et al. [12] studied the blast resistance of sandwich panels with stepwise graded cores. Two graded core structures, with an identical areal density, were subjected to shock wave loading using a shock tube. A configuration based on a low/middle/high density foam greatly outperformed a system based on a middle/low/high density foam. Significant core compression was observed in the former, whereas the latter

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disintegrated under the effect of the blast. To date, there has not been any systematic study to investigate the influence of core density on the blast resistance of foam-based sandwich structures. The work presented herein therefore attempts to address this by investigating the influence of core density on the air blast resistance of sandwich panels based on aluminium skins and a cross-linked PVC core. Initial attention focuses on characterising the fracture properties of the foams. The failure modes of the sandwich panels are discussed based on evidence from polished cross-sections. The final part of this study attempts to model the dynamic response of the plates through a series of finite element analyses. The finite element analysis is used to assess the relative importance of the skins and the core by determining the energy absorbed by each constituent during the blast process.

2. Experimental procedure

Five crosslinked PVC foams, having nominal densities ranging between 60 and 200 kg/m^3, were investigated in this study, details of which are given in Table 1. Prior to conducting the blast tests, a series of compression and fracture tests were undertaken in order to establish the influence of density of the mechanical properties of the foams. It should be noted that the terms Mode I and Mode II relate to the commonly used fracture modes and not the failure modes associated with blast-loaded plates as identified, for example, by Nurick et al. [13].

2.1. Mechanical tests

Compression tests were undertaken at a crosshead displacement rate of 10 mm/min on foam cubes with a side length of 20 mm. Tests were conducted on an Instron 4045, in which the test samples were positioned between two steel plattens and loaded until the onset of densification.

The Mode I (i.e. opening mode) fracture toughness properties of the foams were characterised by conducting single edge notch bend (SENB) tests on notched beams with length, depth and thickness dimensions of 150 $\times$ 20 $\times$ 30 mm respectively, Fig. 1a. The length of the crack was equal to half the depth, i.e. 15 mm. The SENB samples were supported on 10 mm diameter steel cylinders positioned 120 mm apart and loaded directly above the pre-crack by a 10 mm diameter bar. Tests were conducted at a crosshead speed of 10 mm/min. The fracture toughness of each foam was characterised by determining the work of fracture (in J/m^2) from the area under the load–displacement trace divided by the area of the fractured ligament.

Given that core shear is another potential failure mode in dynamically-loaded sandwich structures, a series of shear tests were also undertaken in order to determine the Mode II values of the work of fracture. Here, 10 mm cracks were introduced at the mid-span of short foam beams with length, depth and thickness dimensions of 80, 30 and 20 mm respectively. The beams were clamped at one end and loaded directly above the pre-crack at a crosshead displacement rate of 10 mm/min by a steel traverse, Fig. 1b. The samples were loaded to failure and the work of fracture was again determined from the area under the load–displacement trace and the area of the fracture ligament.

Table 1
Summary of the properties of the foams investigated in this study. * =data taken from the manufacturers data sheets.

Foam	Nominal density (kg/m^3)	Compressive modulus* (MPa)	Tensile strength* (MPa)	Shear strength* (MPa)	Plastic collapse stress (MPa)
A	60	69	45	0.8	0.7
B	80	97	66	1.2	1.29
C	100	125	84	1.6	1.57
D	130	160	110	2.3	2.34
E	200	280	175	3.5	4.19

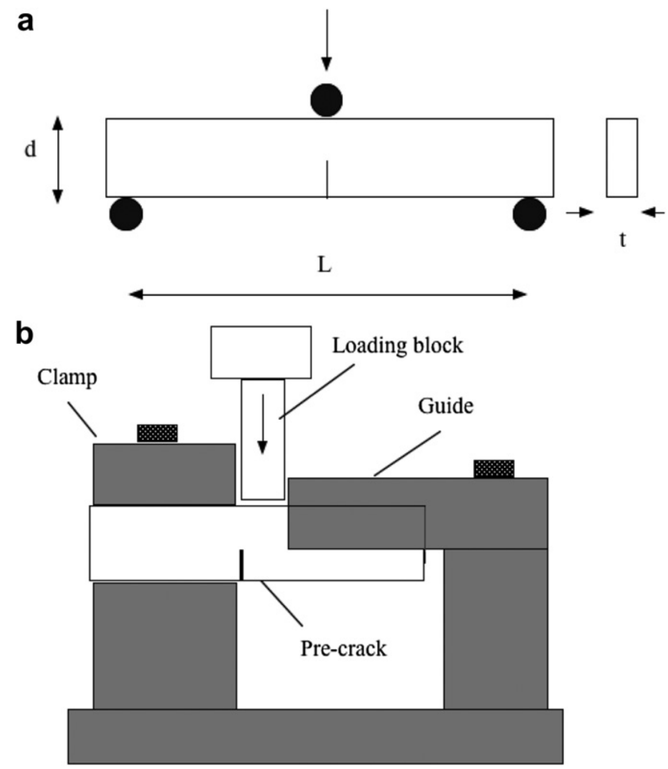

Fig. 1. (a) Single edge notch bend (SENB) geometry for measuring the work of fracture in Mode I. (b) Schematic of the test fixture for determining the work of fracture in shear.

2.2. Blast testing

Blast testing was conducted on sandwich panels based on four of the five foams in Table 1. Aluminium (2024-O) skins, with a thickness of 1.7 mm, were bonded to the cores using a fast-curing contact adhesive (Timebond). In preparation for testing, ten holes (10 mm in diameter) were drilled along a circular boundary with 114 mm in diameter and four holes (12.7 mm in diameter) in the corners of the 150 mm square sandwich panels to facilitate their attachment to a ballistic pendulum, Fig. 2. The panels were clamped between two steel frames, leaving a circular exposed area with a diameter of 90 mm. The bolts were manually nipped tight using a small Allen key to a torque that enabled the panels to be firmly gripped by the rig, without crushing the foam.

Blast loads were applied to the sandwich panels by detonating discs of PE4 explosive at a distance of 90 mm from the front surface of the panel. The PE4 explosive was moulded into a flat cylindrical (disc) shape and a detonator was attached to the centre of the disc

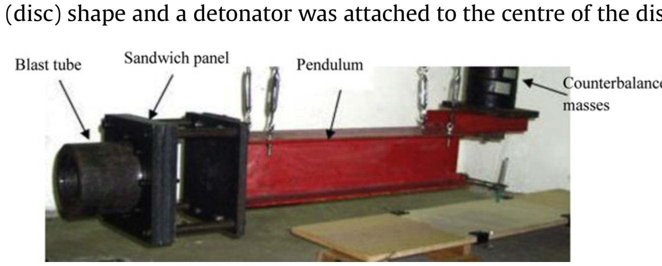

Fig. 2. The ballistic pendulum.