Composite Structures 97 (2013) 370–377

Contents lists available at SciVerse ScienceDirect

Composite Structures

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

The impact response of graded foam sandwich structures

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ARTICLE INFO

Article history:
Available online 12 November 2012

Keywords:
Graded foam
Perforation
Finite element
Impact
Progressive failure
Sandwich

ABSTRACT

Low velocity impact tests have been undertaken on sandwich structures based on cores fabricated by bonding foams of different densities together. Here, a range of linear PVC, crosslinked PVC and PEI foams were bonded together to produce a three layer core. Carbon fibre skins were then bonded to the core and the structures were loaded by a drop-weight impact carriage with a hemispherical head. It has been observed that the majority of the panels failed in a through-thickness shearing mode, leaving a clear cylindrical hole in the multi-layered core. A limited number of structures also exhibited cone cracking on the exit surface, due to failure in a mixed tensile/shear mode. The impact response of the graded sandwich structures was modelled by finite element analysis and the predicted load–displacement responses and failure modes compared. Agreement between the FE model and the experimental data was good across the range of structures investigated, with the model accurately predicting the impact responses and failure characteristics observed within the panels. It has also been shown that graded core structures can out-perform their monolithic counterparts. Finally when normalised by their unit cost, significant differences in the perforation resistances of the structures have been observed.

1. Introduction

Although a considerable of experimental work has been undertaken to study the impact and blast response of sandwich beams and panels, few attempts have been made to simulate the perforation behaviour of such structures under impact loading. Lin and Hoo Fatt [1] developed an analytical model to predict the low velocity impact response of glass/epoxy-aluminium honeycomb panels. A three-stage perforation model was used that considered failure of the top composite skin, the honeycomb core and the lowermost composite skin. The perforation model predicted the perforation velocity of the panel under low velocity impact conditions. Buitrago et al. [2] used finite element techniques to model the impact perforation process in sandwich panels based on carbon fibre/epoxy skins and an aluminium honeycomb core. They showed that most of the incident energy of the projectile was absorbed by the 2 mm thick composite skins, with the core absorbing between ten and twenty percent of the impact energy. Zhou et al. [3] investigated perforation failure in foam-based sandwich panels using the finite element analysis technique. The FE analysis accurately predicted the impact load–displacement responses and the perforation energies of both the plain foams and the sandwich panels. The FE analysis was used to investigate the effect of oblique loading on sandwich structures and also to study the impact response of sandwich panels on an aqueous support.

A number of numerical studies have been undertaken to investigate the dynamic response of functionally-graded foam sandwich structures. Cui et al. [4] proposed a functionally-graded foam model and investigated its energy-absorbing characteristics using the finite element method. It was shown that functionally-graded foams are superior in their energy-absorbing capability than plain foams and that convex gradients performed better than concave systems. It was found that the performance of such foams could be further improved if the density difference between each layer was increased. Other studies have investigated functionally-graded foam sandwich beams subjected to various forms of dynamic loading [5–8].

Theoretical analyses and numerical modelling studies have also been undertaken on various functionally-graded sandwich structures subjected to static and dynamic loading. This includes continuously, piece-wise, layer-wise and exponentially functionally-graded cores [9–15]. Etemadi et al. [9] developed a 3-D finite element model to simulate sandwich panels with functionally-graded cores subjected to low velocity impact loading. Using validated models, they studied the effect of varying the projectile velocity and kinetic energy, as well as the influence of beam dimensions on the impact behaviour and associated indentation and displacement histories. Avila [10] developed a failure criterion to model piece-wise functionally-graded sandwich composites and successfully predicted the failure mechanisms that were obtained

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http://dx.doi.org/10.1016/j.compstruct.2012.10.037

in the experimental data. The most impressive performance was exhibited by a beam configuration in which the highest density core was located directly below the upper face-sheet. Sburlati [11] presented an elastic bending analysis for circular sandwich panels with exponentially-graded material cores. The solution, and associated sensitivity analyses, highlighted the advantages of graded cores in reducing interfacial stresses, thereby decreasing the likelihood of failure. An axisymmetric bending and stress analysis was also performed on circular functionally-graded sandwich plates subjected to transversely-distributed loads [12]. Comparisons with numerical results (ABAQUS software) showed that even for thick sandwich plates with soft cores, the accuracy of the results was comparable to predictions offered by three dimensional elasticity theory. Icardi and Ferrero [15] attempted to optimise the performance of sandwich panels with functionally-graded core and faces. In their study, the distribution of properties through the thickness (core) and in-plane (face sheets) that minimise the interlaminar stresses at the interface with the core were determined.

This paper investigates the impact behaviour of graded/layered foam-based sandwich structures made with carbon fibre resin plastic (CFRP) face sheets and a range of PVC and PEI foam cores. The low velocity impact response of the sandwich panels is simulated using three dimensional non-linear finite element models to investigate the influence of core properties and configurations on the perforation resistance of the sandwich structures. Attention is given to identifying the fundamental parameters that govern the impact response of these layered structures.

2. Experimental procedure

Core materials with varying through the thickness properties were manufactured by bonding three 10 mm thick foam sheets together using a fast-drying contact adhesive, as shown schematically in Fig. 1. Table 1 summarises the properties of the nine different foams investigated in this study. Four of the foams were based on crosslinked PVC foams with densities between 60 and 200 kg/m^3. The three linear PVC foams had densities between 60 and 140 kg/m^3 and the two PEI foams offered densities of 60 and 80 kg/m^3. Table 2 summarises the stacking sequences of the twelve configurations investigated here, in which the average core density varied from approximately 77 kg/m^3 to 113 kg/m^3. It should be noted that six of the twelve configurations were obtained by inverting the original stacking sequence, for example Core C2 was simply Core C1 turned upside down. Mode I (opening) and Mode II (shearing) tests on the foams were also conducted to determine the corresponding work of fracture energies, as shown in Table 3, to be used in the finite element modelling.

Prior to testing, carbon fibre reinforced epoxy (CFRE) skins were bonded to the cores using a two-part epoxy resin. The 0.35 mm thick skins were manufactured by curing two woven CFRE plies (EP121 C15-53 from Gurit Ltd.) in a hot press at 125 °C for 1 h.

Impact testing was conducted on 200 mm square panels using a drop-weight impact tower. The panels were placed on a cylindrical support with an internal diameter of 100 mm. The panels were impacted at their centres by a carriage with a 10 mm diameter hemispherical head. The mass of the impactor was 5.56 kg and the release height of the impact carriage was increased up to a maximum of 1.4 m. The displacement and impact force were recorded using a high-speed video camera and a piezoelectric load-cell respectively. The impacted panels were sectioned through the damaged region, ground, polished and photographed in order to highlight the failure mechanisms occurring during the impact process.

Table 1
Mechanical properties of the foams investigated in this study.

	C60	C80	C100	C200	L60	L90	L140	P60	P80
Density (kg/m^3)	60	80	100	200	60	90	140	60	80
Compressive modulus (MPa)	69	97	125	280	30	56	110	46	62
Compressive strength (MPa)	0.9	1.3	1.9	4.8	0.38	0.9	1.6	0.7	1.1
Compressive fracture strain	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Tensile modulus (MPa)	45	66	84	175	30	50	90	45	54
Tensile strength (MPa)	1.3	2	2.7	6	0.9	1.4	2.4	1.7	2.0
Shear modulus (MPa)	22	30	38	75	11	21	37	18	23
Shear strength (MPa)	0.8	1.2	1.6	3.5	0.5	1	1.85	0.8	1.1
Shear fracture strain	0.16	0.23	0.27	0.3	0.7	0.75	0.8	0.25	0.23

3. Finite element modelling

Finite element models were developed to simulate the dynamic behaviour of the graded foam sandwich panels subjected to low velocity impact loading. The following section discusses the modelling-approach adapted for the various components of the sandwich structures.

3.1. Modelling of the CFRP skin

Prior to damage initiation, the CFRP face sheets were modelled as an orthotropic elastic material. The elastic modulus values of the plain weave skins were assumed to be equal in the longitudinal and transverse directions. Damage initiation was modelled using Hashin's failure criteria [16] which assumes four damage initiation mechanisms, namely fibre tension, fibre compression, matrix tension and matrix compression. Using the longitudinal, transverse and shear effective stress tensor components within the plane of the CFRP, the damage initiation criteria can be determined [17].

The damage elastic matrix, which relates the stress and strain and controls degradation of the material stiffness, can be expressed as:

$$C_D = \frac{1}{D}\begin{bmatrix} (1-d_f)/E_1 & (1-d_f)(1-d_m)\upsilon_{21}/E_1 & 0 \\ (1-d_f)(1-d_m)\upsilon_{12}/E_2 & (1-d_m)/E_2 & 0 \\ 0 & 0 & (1-d_s)GD \end{bmatrix} \quad (1)$$

where G is the shear modulus and D is an overall damage variable, dependent upon the current state of fibre (d_f), matrix (d_m) and shear (d_s) damage, respectively.

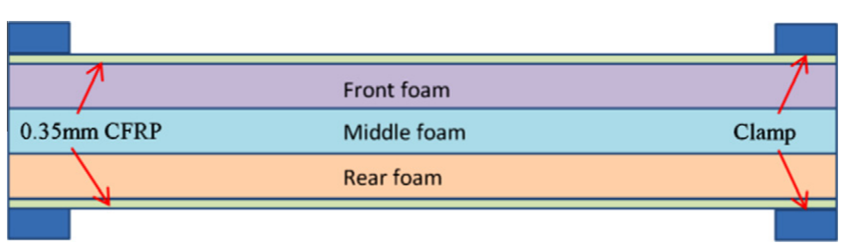

Fig. 1. Sketch of the stacking configuration of a graded foam sandwich panel.