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The compressive properties of sandwich structures based on an egg-box core design

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ABSTRACT

Lightweight cores, based on an egg-box core design, have been manufactured using a simple compression-moulding technique. Two types of composite prepreg were used to manufacture the core materials, these being a woven carbon fibre reinforced epoxy and a woven glass fibre reinforced epoxy. The resulting cores were of a high quality, exhibiting little or no wrinkling following the manufacturing procedure. Subsequent compression tests at quasi-static rates of loading showed that the compression strength of the core depended strongly on the level of constraint applied during testing, with sandwich panels based on composite skins bonded to an egg-box core offering a load-bearing capability that was more than double that of its unconstrained counterpart. The quasi-static compression strength of the carbon-based cores has been shown to be slightly higher than the glass fibre systems, particularly at higher core densities. Local splitting damage at cell joining regions and crushing of the cell of the egg-box structure was identified as the primary failure mechanism in the sandwich panels.

Impact tests, conducted using a drop-weight impact tower, have shown that the compression strength of the egg-box cores is higher at dynamic rates of loading than at quasi-static rates. Here again, the local splitting and crushing was the primary mode of failure in the sandwich structures. Finally, the finite element technique has been used to model the mechanical response of these core designs under both quasi-static and impact loading testing conditions. Here, agreement between the predicted and observed responses was found to be good for both extremes of loading-rate.

1. Introduction

Sandwich structures consisting of a low density core material bonded to strong, stiff outer skins are finding increasing deployment across a broad range of engineering applications [1,2]. Such structures offer many unique advantages, most particularly when subjected to out-of-plane loading, such as that associated with the application of bending or flexural loads. Although sandwich technology is now well-established, there have been many attempts in recent years to develop new and novel core designs that can greatly expand the design envelope. Examples include the development of advanced lattice designs that seek to exploit the tensile deformation modes when loaded in compression as well as corrugated structures that offer increased levels of ventilation in humid environments [3–8]. Kazemahvazi et al. [9] investigated the compression behaviour of a corrugated system based on a carbon fibre reinforced epoxy resin. The resulting panels exhibited a number of different failure modes as the geometry of the structure was varied. More recently, corrugated core materials, based on both glass and carbon fibre reinforced epoxy composites, have been developed and tested [10]. Here, the compression moulding technique, employing a steel mould with a triangular profile, was used to produce a range of systems with differing wall thicknesses. The mechanical response of the composite sandwich structures were compared to that offered by an all-aluminium system, where it was shown that the specific compression strength of a carbon fibre-based core exceeded that of its metallic counterpart [10].

Found et al. [11] performed quasi-static compression tests to investigate the energy absorption properties of a polyurethane foam sandwich panel with four fibre-reinforced plastic tubular inserts incorporated within the core. They reported that by ensuring progressive brittle failure of the structure, higher specific energy absorption values were obtained. As a result of variations in the fibre distribution within the inserts, the sandwich tended to collapse in a catastrophic failure mode, leading to lower specific energy values. The energy-absorbing characteristics of hierarchical woven lattice composites were evaluated by Zheng et al. [12]. The square interlocking structures were composed

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of a woven lattice to form the sandwich cell walls. They concluded that these novel cell walls successfully restricted rib buckling. As a result, the structure had a high compressive strength and a stable plateau region, thereby enhancing the specific energy absorption of the cellular material.

A potential new class of energy-absorbing structure based on aluminium egg box was introduced by Zupan et al. [13]. Experiments suggested that egg-box structures deform by either the rotation of a stationary plastic hinge or by a travelling plastic knuckle, depending upon the in-plane kinematic constraints imposed upon the egg-box. Chung et al. [14] fabricated composite egg-box structures and stated that its density, boundary conditions and geometry affected the energy absorption capability of the structure. Fibre reinforced composite structures were manufactured using vacuum bagging and autoclave curing techniques. The production of foam-filled egg-box sandwiches, via autoclave curing, was investigated by Yoo et al. [15]. It was found that such structures offered an impressive energy absorption capacity, involving a stable collapse response, resembling that of an ideal energy-absorbing material.

Although extensive work has been carried out to understand the effect of various sandwich geometries on energy absorption, there is limited work relating to the mechanical properties of contoured core sandwich panels (or the egg-box structure) based on composite materials. The present study investigates the properties of contoured core sandwich panels based on both carbon and glass fibre composites. The study initially focuses on the quasi-static and impact response of these panels as a function of the cell wall thicknesses and core density. Following this, a series of finite element models are developed to predict the mechanical response of these structures under compression loading.

2. Experimental procedure

The egg-box composite cores investigated in this study were manufactured using either a woven glass fibre reinforced epoxy (GFRP) or a woven carbon fibre reinforced epoxy (CFRP). The nominal thicknesses of the GFRP and CFRP prepregs were 0.10 and 0.25 mm respectively. Details of physical properties of these two prepreg materials are given in Table 1. Prepreg sheets were cut to the required dimensions and placed between the two contoured aluminium moulds shown in Fig. 1a. Geometrical details of the mould design are given in Fig. 1b. The GFRP cores were manufactured by stacking 5, 10 and 15 prepreg sheets in the mould, and the thicknesses of the resulting cores were 0.5, 1.0 and 1.5 mm respectively. CFRP cores having similar thicknesses were produced by stacking 2, 4 and 6 prepreg sheets in the mould. A release agent (CIL Release 1711E, from Cilchem) was sprayed on both sides of the mould to ensure easy demoulding at the end of the cure cycle. The aluminium moulds were then placed in a hot press and the structure cured according to the processing parameters given in Table 1. Here, the panels were heated to 125 °C at a heating rate of 1.5 °C/minute. This temperature was then maintained for 90 min, before switching off the press and allowing the samples to cool to room temperature. The panels were then removed from the press and cut into 100 × 100 mm test samples, as shown in Fig. 2a.

Table 1
Details of the glass fibre and carbon fibre reinforced epoxy composites.

Prepreg	GFRP	CFRP
Fibre type	E-Glass	3 k HTA
Weave style	Satin	Plain
Resin content (% wt)	40 ± 3	53 ± 3
Curing temperature (°C)	125	125
Dwell time (minutes)	90	90
Laminate density (kg/m^3)	1780	1300
Nominal thickness of ply (mm)	0.10	0.25

To manufacture the bonded samples, skins were bonded to the core using a two-part epoxy resin (Araldite 420 A/B) in the ratio 10:4. All of the cores were bonded to 0.50 mm thick skins based on either CFRP or GFRP. The adhesive was applied to the core using a syringe. After bonding, the panels were cured in an oven at 120 °C for 1 h. The manufactured sandwich panels are shown in Fig 2b. An examination of the panels showed that they were free of defects, such as wrinkling or warping, suggesting that the weaves offered sufficient drapability to cope with the relatively complex mould design.

In the initial part of this investigation, unbonded plain core specimens (i.e. without skins) were subjected to quasi-static compression using an Instron 4505 universal test machine. Tests were conducted on two by two (100 × 100 mm) egg-box panels. Following this, a series of compression tests were performed on sandwich panels with similarly-sized cores and corresponding skins. In a number of tests, the lateral movement of the base of the cores was restricted to investigate the influence of boundary conditions on the compression response. All of the quasi-static compression tests were undertaken at a crosshead displacement rate of 1 mm/min. The crosshead movement was interrupted when the panel was fully crushed between the loading platens. The load-displacements response was converted to nominal stress-strain curves by normalising the applied load by the planar area of the specimen and dividing the crosshead displacement by the original specimen height, respectively. Table 2 summaries the sandwich structures investigated under quasi-static compression loading, which includes ply number, sample dimensions and core density. Here, in specimen ID 'GF' represents glass fibre and 'CF' represents carbon fibre.

The compression tests were repeated at dynamic rates of loading using a drop-weight impact tower. A flat square impacter (100 mm × 100 mm) with a mass up to 15 kg was dropped onto panels supported on a steel base. The resulting impact force was recorded using a 10 kN piezo-electric load cell (Kistler 9321A) positioned under the steel base. The cell was connected to a charge amplifier (Kistler 5011) using an insulated coaxial cable in order to amplify the resulting voltage signal. The recorded signal was then converted from an analogue to a digital format using a DAQ device (Measurement Computing, USB 1208HS) and then converted to a force. A high speed camera (MotionPro X4, model X4CU-U-4) was used to capture the displacement and velocity of the impactor. The camera was placed in the front of the impact rig to track the impactor and record displacement during the dynamic event, as shown in Fig. 3. Table 3 summarises the key parameters used in this part of the study, which include number of ply, cell wall thickness, sample dimensions, core density, drop height and impactor mass.

3. Numerical procedure

Numerical models were developed to simulate the compression response of the sandwich structures under quasi-static and dynamic loading. The composite was modelled using user-defined Hashin's 3D failure criteria for an anisotropic composite material. Fig. 4 shows the finite element mesh of an egg-box core with the top skin removed. Here, the core was meshed using six-noded triangular solid elements, while the composite skins were modelled using eight-noded brick elements, with an interface defined between the former and the latter. The loading platens above and below the panel were meshed using discrete rigid elements. The size of the core corresponds to that used in the experimental study (i.e. 100 × 100 mm). Mesh sensitivity was investigated by varying the mesh density within the plane and through-thickness directions of the composite sheet. Following this study, a mesh size based on element with a size of 1 mm within the plane and two elements through-the-thickness of the composite layer was used. A number of interfaces were considered in the model, including those between the face sheets and the loading platen, those between the composite core and the face sheets, as well as possible self-contact between the inclined faces of the egg-box core. A modified 3D failure