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# The energy-absorbing behaviour of foam cores reinforced with composite rods

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ABSTRACT

This paper investigates the energy-absorbing characteristics of composite reinforced PVC foam cores for use in lightweight impact-resistant sandwich structures. Compressive tests have been undertaken on crosslinked PVC foam cores with densities ranging from 40 to 200 kg/m$^3$, reinforced with carbon fibre and glass fibre rods with nominal diameters of 2, 3 and 4 mm. It has been shown that the compression strength of the reinforced foams can be optimised through the correct selection of rod arrangement and foam density.

A limited number of drop-weight impact tests were also conducted on selected samples to investigate their dynamic performance. Here, it was shown that increasing the volume fraction of rods above 2.5% has little effect on the measured SEA of the two types of reinforced foam. Finally, a theoretical analysis has been undertaken to predict the peak load and the corresponding compressive displacement of the reinforced PVC foam cores.

## 1. Introduction

Sandwich structures, based on strong, stiff skins bonded to low density cores are finding increasing use in a wide range of aerospace, maritime and automobile structures. The advantages associated with these structures include low weight, superior flexural stiffness and high energy absorption. In recent years, engineers have been investigating the energy-absorbing characteristics of sandwich structures subjected to a wide range of loading conditions, such as those associated with quasi-static [1–6], impact [7–12] and blast loading [13–22]. The overall mechanical response of a sandwich structure is largely dependent on the properties of the skin, the stiffness and strength properties of the core, as well as the strength of the bond between the skin and the core. The need to strengthen the core and control its subsequent crushing characteristics is crucial to maximising energy absorption in sandwich structures. A number of approaches have been used to develop sandwich cores with a greater compression strength and superior energy absorption characteristics, including z-pinning, through-the-thickness stitching and rod reinforcement.

Extensive research has been undertaken to investigate the effect of z-pinning on the compression properties of composite materials [23–29]. Mahfuz et al. [28] investigated the low velocity impact response of sandwich structures based on foam cores reinforced with titanium pins. For the energy levels considered, they showed that reinforcing the foam with z-pins served to constrain the level of impact damage within the test samples. Zhang et al. [29] investigated the effect of z-pinning on the low velocity impact resistance of composites and observed reductions in the level of damage of between 19% and 64%, depending on the impact energy level and laminate thickness. Childress and Freitas [30] observed reductions of up to 50% in the level of damage sustained following hailstone impacts on z-pinned laminates. The authors showed that reduction in damage was associated with increased bridging traction forces, which in turn increased the delamination resistance of the composite. Research on z-pinned sandwich structures subjected to shock loading is relatively limited, however, *Z*-directional pins have been used to modify the core and improve overall response of sandwich structures under high strain rate impact loading [31].

A number of studies have been undertaken on stitched sandwich structures subjected to bending, shear and compressive loads [32–35]. Raju and Tomblin [32] investigated the energy absorption characteristics of sandwich panels containing through-thickness stitches, subjected to edgewise compression. The static crush tests showed that the average crush load increased with reducing stitch spacing, resulting in an increase in the total energy absorbed. The effect of stitch density and thread thickness on

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damage progression and failure in stitched composites subjected to out-of-plane loading has been investigated by Tan et al. [36]. The impact resistance of foam-based sandwich structures can also be enhanced by through-thickness stitching. Novel stitch-bonded sandwich composite structures have been developed using a closed cell core and a woven broadcloth, and then subjected to increasing impact loads [37]. Lascoup et al. [38] evaluated the low velocity impact resistance of sandwich structures based on a stitched foam core and glass fibre face-sheets. They found that the impact resistance of the sandwich structure was greatly improved by the presence of the stitches, with the global impact behaviour being influenced by the principal stitching parameters. Fan and Wu also studied the impact response of sandwich structures with through-thickness stitching [39]. Compared to the unstitched samples, they showed that the maximum cracking width of the stitched samples decreased by 67% following a 25 J impact.

Work investigating the energy absorption capability of foam cores with embedded composite rods or tubes is limited [40–45]. Cartie and Fleck [40] investigated the effect of pin reinforcement on the through-thickness compressive strength of foam-cored sandwich panels. In their study, titanium and carbon fibre pins were inserted into a polymethacrylimide foam core in a sandwich panel, with carbon fibre face sheets, to enhance the through-thickness strength characteristics. It was shown that the foam core served to stabilise the pins against elastic buckling. In addition, the authors demonstrated that the core offered strength and energy absorption characteristics that exceeded the individual contributions from the foam and the unsupported pins. Marasco et al. [41] measured the out-of-plane mechanical properties of two z-pinned PMI foam sandwich panels, reinforced with carbon fibre pins. It was observed that out-of-plane shear failure occurred mainly at the core-face interface. Mouritz [42] investigated the influence of volume fraction and pin size on the compressive behaviour of z-pinned PMI core sandwich panels. It was found that the both modulus and strength of the sandwich structures increased with increasing pin volume fraction for a fixed pin diameter.

This aforementioned work has highlighted the potential offered by sandwich structures based on cores reinforced with composite pins. This paper presents an experimental investigation into the crushing characteristics of composite rod reinforced PVC foam cores. Quasi-static and dynamic compression tests on both carbon and glass individual rods and reinforced PVC foam panels have been undertaken to evaluate their energy absorption characteristics and their overall crush resistance. In addition, a theoretical analysis has been undertaken to predict the peak load and the corresponding compressive displacement of the reinforced PVC foam cores.

## 2. Experimental procedure

Prior to their insertion into the foams, individual 4 mm diameter carbon and glass fibre rods were subjected to axial compressive loading at a crosshead displacement rate of 1 mm/min using a universal testing machine (Instron 4045). Load–displacement traces were recorded during the test and the compressive modulus and strength properties of the rods were determined. Three tests were conducted on each type of rod. In addition, three-point bend tests were carried out in order to determine the flexural modulus and strength of both the carbon and glass fibre rods. Here, the length of the rods was 70 mm and the span between the supports was 50 mm. The crosshead displacement rate was also set to 1 mm/min.

The crosslinked PVC polymer foams investigated in this study were supplied by Airex A.G. The mechanical properties of the four foam materials, with nominal densities of 40, 80, 130 and 200 kg/m$^3$, were determined in an earlier study [46] and details are given in Table 1. The PVC foam specimens were cut to a size of 50 × 50 × 20 (thickness) mm using a band saw. Nine holes were then drilled into the square foam samples as shown in Fig. 1a. The diameters of the holes were exactly equal to those of the rods that were inserted into them. The ends of rods were polished to ensure uniform loading when in contact with the loading platens. Tests were also undertaken on plain foam samples (i.e. without composite rods) having similar dimension to those of their reinforced counterparts.

Carbon and glass fibre rods with diameters of 2, 3 and 4 mm were inserted into the pre-drilled holes in the foam panels. A total of 24 material configurations were prepared, details of which are given in Table 2. Here, C200C3 corresponds to a 200 kg/m$^3$ crosslinked PVC foam reinforced with 3 mm carbon fibre (C) rods. Similarly C130G4 refers to a 130 kg/m$^3$ crosslinked PVC foam reinforced with 4 mm glass fibre (G) rods. Fig. 1b shows typical a carbon fibre rod reinforced foam sample.

Compression tests on the reinforced PVC foam panels were carried out using the aforementioned Instron 4045 universal testing machine. The panels were placed between two stainless steel plates and subjected to loading at a crosshead displacement rate of 1 mm/min. The load–displacement traces were recorded to obtain the compression strength and energy absorption characteristics of the reinforced foam panels. The dynamic response of the reinforced foams was investigated through a series of drop-weight impact tests on 80 and 130 kg/m$^3$ foams reinforced with 2, 3 and 4 mm diameter CFRP and GFRP rods. The 50 × 50 × 20 mm test specimens were supported on a steel base and compressed by a circular steel platen attached to a falling carriage. The force and displacement were measured using a piezoelectric load cell and a high speed video camera respectively.

## 3. Results and discussion

### 3.1. Compressive tests of individual composite rods

Compressive tests on individual composite rods were conducted to characterise their basic mechanical properties and to establish their individual energy-absorbing capability. The resulting mechanical properties of the carbon and glass rods are summarised in Table 3. Fig. 2 shows load–displacement traces following compressive tests on individual 4 mm diameter, 20 mm long carbon and glass fibre rods. An examination of the trace corresponding to the carbon fibre rod indicates that the force rises in a linear fashion up to approximately 2500 N before dropping slightly and subsequently stabilizing at approximately 2300 N. In contrast, the load–displacement trace for the GFRP rod drops sharply following the peak at 2100 N to a much lower plateau value of 650 N. It is worth noting that the Euler buckling loads for the 4 mm CFRP and GFRP rods were approximately 25 and 13.3 kN, i.e. much higher

**Table 1**
Mechanical properties of the foams used in this study.

| | C40 | C80 | C130 | C200 |
|---|---|---|---|---|
| Density (kg/m$^3$) | 40 | 80 | 130 | 200 |
| Tensile modulus (MPa) | 28 | 66 | 110 | 175 |
| Tensile strength (MPa) | 0.7 | 2.0 | 3.8 | 6.0 |
| Compressive modulus (MPa) | 37 | 97 | 160 | 280 |
| Compressive strength (MPa) | 0.45 | 1.3 | 2.6 | 4.8 |
| Compressive fracture strain | 0.65 | 0.7 | 0.7 | 0.7 |
| Shear modulus (MPa) | 13 | 30 | 47 | 75 |
| Shear strength (MPa) | 0.5 | 1.2 | 2.3 | 3.5 |
| Shear fracture strain | 0.08 | 0.23 | 0.30 | 0.30 |
| Poisson's ratio | 0.32 | 0.32 | 0.32 | 0.32 |
| Work of fracture in tension (kJ/m$^2$) | 0.21 | 0.44 | 0.76 | 1.33 |
| Work of fracture in shear (kJ/m$^2$) | 4.5 | 12.6 | 27.6 | 44.2 |