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The energy-absorbing properties of composite tube-reinforced aluminum honeycomb

A. Al Antali [a], R. Umer [a,b], J. Zhou [c,*], W.J. Cantwell [a]

[a] Aerospace Research and Innovation Center, Khalifa University of Science and Technology (KUST), 127788 Abu Dhabi, United Arab Emirates
[b] Centre for Future Materials, University of Southern Queensland, Toowoomba, Queensland 4350, Australia
[c] School of Engineering, University of Liverpool, Liverpool L69 3GH, United Kingdom

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ABSTRACT

This paper investigates the energy-absorbing characteristics of a lightweight honeycomb core containing embedded carbon fibre reinforced plastic (CFRP) tubes. Initial tests are undertaken on the plain aluminum honeycomb material in order to characterize its specific energy absorption (SEA) capability and to identify the prevailing failure mechanisms. Tests are then conducted on honeycomb cores reinforced with increasing numbers of composite tubes in order to establish the influence of varying the density of the tubular array on the measured SEA. Finally, a series of drop-weight impact tests are conducted in order to characterize the dynamic response of these materials and assess their overall rate-sensitivity.

Tests on the plain aluminum honeycomb cores resulted in the characteristic plastic wrinkling of the cell walls, yielding an average value of SEA of 14 kJ/kg. Embedding CFRP tubes into the honeycomb served to greatly enhance the energy-absorbing properties of the core, with quasi-static values of SEA reaching as high as 105 kJ/kg. An examination of the failed samples indicated that the previously-observed wrinkling mode of failure was largely absent, with the composite tubes being reduced to fine debris. Increasing the areal density of tubes in the honeycomb to relatively high values proved to be counterproductive, due to unwanted interactions between the individual tubes.

Dynamic tests on the tube-reinforced honeycombs yielded SEA values that exceeded the quasi-static results with values reaching 112 kJ/kg for a moderately-reinforced core. Given the simplicity of the preparation process, it is believed that these lightweight structures represent an attractive cost-effective energy-absorbing material for use in dynamic applications.

1. Introduction

It is now well-established that when correctly designed and loaded under well-defined conditions, composite materials can offer outstanding energy-absorbing characteristics over a wide range of strain-rates [1–10]. Work by Farley [11] showed that when loaded in compression, carbon fibre reinforced epoxy tubes fail in splaying and fragmentation modes, leading to significant energy dissipation and measured values of specific energy absorption (SEA) up to 80 kJ/kg [1,2]. Hull [12] proposed a unified approach to progressive crushing of composite tubes based on brittle fibers and matrices. He also argued that the crushing process occurs by splaying of the fibers as well as by fragmentation. He suggested that the micro-mechanisms of crush and the resulting load-bearing capacity of the tube could be changed by varying the distribution of fibers within the structure. Increasing the percentage of hoop fibers in the tube reduces the ease of splaying, whilst serving to increase the likelihood of shear fracture and increased fragmentation.

A number of investigations have established the importance of the tube geometry in determining the energy-absorbing characteristics of a composite tube [13–15]. Thornton and Edwards tested a number of tube geometries based on carbon, Kevlar and glass fibre reinforcements and showed that circular tubes exhibit a superior energy-absorbing capacity relative to rectangular and square tubes [15]. Mamalis et al. [14] conducted crushing tests on samples with square, circular and conical cross-sections based on a glass fibre reinforced epoxy composite and established that circular tubes exhibited the most impressive energy-absorption characteristics. Farley [13] conducted tests on a range of Kevlar and carbon fibre reinforced epoxy tubes with different diameters and thicknesses and showed that the D/t ratio (tube inner diameter/thickness) determines the specific crushing stress (SCS). Farley showed that

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* Corresponding author.
E-mail address: jinzhou@liv.ac.uk (J. Zhou).

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the value of this parameter almost doubled as D/t was decreased from approximately 120 to 3.8 and linked this to a decrease in interlaminar cracking.

A number of workers have investigated the potential benefits of filling composite tubes with traditional core materials, such as metal foams and aluminum honeycombs [16,17]. Liu et al. [16] introduced an aluminum honeycomb filler into square CFRP tubes and showed that the peak load and absorbed energy increased by more than ten percent relative to the plain composite tubes. In contrast, Sun et al. [17] observed that incorporating an aluminum honeycomb into empty circular CFRP tubes resulted in a slight decrease in SEA, although the authors did note that these modified composite tubes still outperformed their metallic counterparts at quasi-static rates of strain. Similar conclusions were drawn by Hussein et al. following tests over a range of strain rates on square CFRP tubes filled with aluminum honeycomb [18]. For example, the authors recorded values of SEA of 64 kJ/kg at a very low strain-rates for a plain CFRP tube and 55 kJ/kg for a filled tube, tested under the same conditions.

In contrast to these studies, where a low density core material is embedded within the energy-absorber, a number of researchers have investigated the effect of positioning small tubular structures in a foam substrate [19–21] Alia et al. [19] conducted quasi-static and dynamic compression tests on PVC foams containing small aluminum and steel tubes and showed that the specific energy absorption does not vary with foam density, equaling approximately 69 kJ/kg for the former and 42 kJ/kg for the latter. The steel-based system exhibited a modest increase in SEA as the strain-rate was increased from quasi-static to dynamic rates, whereas the aluminum-reinforced cores were largely insensitive to strain-rate. This work was extended to investigate the energy-absorbing response of PVC foams containing an array of small diameter composite tubes [20]. Here, carbon fibre reinforced epoxy tubes with a range of D/t values were embedded in polystyrene and PVC foams with densities ranging between 15 and 225 kg/m^3. An examination of the failed tubes removed from the foam substrate, indicated that the crushing process had reduced the composite to fine debris. The resulting values of SEA exceeded 93 kJ/kg, although the dynamic values were slightly lower.

Honeycomb structures could potentially represent an excellent substrate for embedding composite tubes. Aluminum honeycombs on their own have been shown to offer attractive energy-absorbing characteristics under both quasi-static and dynamic loading conditions [22–24]. The aim of the work presented in this paper is therefore to investigate the potential offered by aluminum honeycomb core materials reinforced with carbon fibre reinforced epoxy tubes. Particular attention is given to assessing the effect of increasing the density of the tubular array in the honeycomb on the SEA when subjected to both quasi-static and dynamic rates of strain. The failure mechanisms occurring in both the embedded tubes and the surrounding honeycomb core are elucidated and discussed.

2. Experimental procedure

The reinforced cores investigated in this study were based on an aluminum honeycomb supplied by the Hexcel Corporation and a roll-wrapped carbon fibre reinforced plastic tube supplied by Easy Composites Ltd. The aluminum honeycomb, with a cell size of 6.35 mm, a wall thickness of 0.04 mm and a nominal density of 37 kg/m^3 (Hexweb CRIII based on a 5052 aluminum alloy), was supplied in the form of 20 mm thick sheets with length and width dimensions of 2 and 1 m, respectively. Square samples, with an edge length of 45 mm, were removed from the honeycomb sheets in preparation for testing. The majority of CFRP tubes tested here were manufactured using a roll-wrapping procedure to yield tubes with an outer diameter, D_o, of 6 mm, an inner diameter, D, of 4 mm and a nominal wall thickness, t, of 1 mm. The composite is based on a 2/2 twill weave, consisting of 3 k carbon fibre tows. The tubes were supplied in one metre lengths and cut to size using a bandsaw. Prior to insertion in the honeycomb, one end of the tube was chamfered using a grinding wheel and the other was ground flat using the same grinding process. A thin adhesive film was applied to the outside of the tubes to ensure that they remained in place once inserted into the aluminum core. Fig. 1a shows photographs of a sample containing eight tubes. In the initial part of this study, a limited number of tests were also conducted on unidirectional pultruded tubes with similar outer and inner diameters to their roll-wrapped counterparts. These tests were undertaken in order to ascertain which type of tube (wrapped or pultruded) would represent the most effective energy-absorbing reinforcement.

The energy-absorbing capability of the cores was initially investigated though a series of compression tests on an Instron 5969 universal test machine. The samples were placed between two circular steel plattens and compressed at a crosshead displacement rate of 10 mm/minute until the densification threshold was just exceeded. The load and crosshead displacement were recorded and subsequently used to determine the energy expended in crushing the cores. The specific energy absorption (SEA) of the samples was determined from the energy under the trace up to the onset of densification, divided by the mass of the sample. The effect of varying the areal density of the tubular array (equivalent to the percentage of cells occupied by tubes) on the SEA of the cores was subsequently investigated through a series of tests on 45 mm square samples containing between one and nine tubes (corresponding to an areal density of tubes, A_D, between 2.5% and 21%). Additional tests were conducted on a sample based on seventeen tubes ($A_D = 40\%$) in order to investigate the effect of enhanced reinforcement.

The possibility of controlling the force associated with the crushing process was investigated by conducting tests on samples containing nine tubes of differing length. Here, three core designs were investigated, details of which are given in Fig. 2. Core A contains four 20 mm long tubes positioned at the corners, four 10 mm tubes at the mid-points along the edges and one 15 mm tubes at the center. Core A has four 10 mm tubes at the corners, four 15 mm tubes along the edges and a full length tube at the center. Finally, Core C has 15 mm tubes in the corners, four full-length tubes at the mid-edges and a 10 mm tube at its center.

3. Dynamic crushing tests

The energy-absorbing properties of the tube-reinforced honeycomb and the plain core were investigated through drop-weight impact tests at impact velocities up to 3 m/s. The dynamic crushing tests were undertaken on square samples with an edge length of 45 mm, using an instrumented drop-weight impact rig. The test samples were placed on a steel platen located on a 100 kN load cell. The specimens were loaded by a falling carriage with a similarly-sized steel platten on its lowermost (contact) surface. The mass of the falling carriage was increased up to 47 kg and the release height up to 1.6 m in order to completely crush the samples during the test. The crushing force and the displacement of the carriage were recorded using a piezoelectric load-cell and a high-speed video camera, respectively.

4. Results and discussion

4.1. Energy absorption of the constituent materials

Crushing tests were initially conducted on individual 6 mm diameter composite tubes containing a small chamfer at one end. Fig. 3 shows a typical load-displacement trace following a