THE ENERGY-ABSORBING BEHAVIOUR OF POLYMER FOAMS REINFORCED WITH COMPOSITE TUBES

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Abstract

This work presents the findings of a research study investigating the energy-absorbing characteristics of polymer foams reinforced with composite tubes. The specimens were tested under quasi-static tests at a loading rate of 1mm/minute. Initial attention focused on establishing the influence of tube diameter on the specific energy absorption (SEA) and the failure characteristics of the tubes. In the next stage of the investigation, the tubes were embedded in a range of polymer foams in order to establish the influence of foam density on the crush behaviour of these lightweight structures.

1. Introduction

Research and development are extensively carried out to improve the efficiency, cost and reliability of composite materials. Composite materials are recognized as possess superior specific energy absorption properties and have been widely used for many purposes. Application of composite materials as energy absorber structures in automotive or aerospace industry will not only optimise the safety of passengers, but will also greatly reduce the vehicle weight and simultaneously improve the fuel efficiency. Experimental investigations have shown that composite materials, such as carbon fibre and glass fibre reinforced epoxies can offer impressive values of specific energy absorption (SEA) [1-2]. Previous researchers have reported that the main factors affecting the energy absorption performances are constituent materials, fabrication conditions, tube geometries and testing conditions. A number of studies have studied the influence of tube geometry on energy absorption [3,4]. Thornton and Edwards concluded that for a given fibre stacking sequence, glass, carbon and Kevlar fibre reinforced circular tubes out-perform their square and rectangular counterparts [3]. Mamalis et al [4] studied the crushing characteristics of a range of glass fibre reinforced composite structures with circular, square and conical cross-sections. They found that circular tubes offered the highest values of energy-absorption, with the crashworthiness of conical structures decreasing with increasing cone angle. Farley [5] investigated the influence of specimen size on the energy-absorbing capability of carbon and Kevlar reinforced epoxy cylindrical tubes and observed that the ratio of the inner diameter of the tube to that of its thickness, (D/t), greatly influences the specific crushing stress (SCS) of the tube. It was shown that the value of SCS increased by approximately 180% as the value of D/t was decreased from 120 to 3.8. This increase in crushing response at lower values of D/t was attributed to a reduction in interlaminar cracking.

Here, it was argued that the buckling load of the fibre bundles increases with a reduction in the number and length of these interlaminar cracks [5]. Given that the SEA of composite tubes increases significantly with reducing D/t ratio, it is likely that structures based on an array of small tubes in a low density foam could represent an attractive option in the search for new, lightweight energy-absorbing structures. Since they are based on simple cylindrical tubes that are widely available in the market place, tubular-reinforced sandwich structures should offer a number of potential benefits, including a relative ease of fabrication of complex and curved structures, superior energy-absorbing characteristics and a relatively low cost. Such structures could also offer other attractive characteristics, such as an ability to control the crushing load during compression, e.g. through the use of embedded tubes of different length, as well as the possibility to produce curved core geometries for more complex structures. This paper investigates the characteristics and properties of composite tubes reinforced foams for use in lightweight energy-absorbing structures.

2. Experimental Procedure

2.1. Materials

The commercially-available composite tubes used for this investigation were obtained from Easy Composites Ltd. They were made out of a total of five pre-preg layers consisting of three layers of T700 unidirectional pre-preg carbon fibre reinforced epoxy oriented at 0^o direction and alternated by two layers of unidirectional E-Glass oriented at 90^o. The tubes with the fiber weight fraction of about 60% were produced by using a roll-wrapping procedure starting by placing a layer of carbon pre-preg layer around a mandrel. The crosslinked PVC foams were selected as the core materials since they offer relatively high compression strength and stiffness properties to weight ratio. The foams were prepared by introducing gas bubbles into liquid monomer or hot polymer and it solidifies by cross-linking or cooling. The crosslinked (C70) PVC closed-cell foams of various densities were used during the course of the research were manufactured and supplied in the form of 20 mm thick flat panels by Alcan Airex AG.

Figure 1. The set-up for quasi-static tests.

2.2 D/t ratio of CFRP Tubes

Initially, the effect of the tube D/t ratio on specific energy absorption was investigated. The characteristic types of progressive crushing modes were also distinguished between different D/t ratios of tubes. Five different sizes of tubing were investigated, with outer diameters ranging from approximately 10.2 mm to 50.40 mm and values of the ratio of internal diameter to thickness (D/t) ranging from 6.3 to 28.0. Prior to testing, the tubes were cut to a length of 20 mm and ground at one end in order to introduce a forty-five degree chamfer for triggering the crushing process as shown in Figure 2a. This will initiate a stable crushing process throughout the tubes and will yield a relatively low initial peak load. Crushing tests were conducted on the plain composite tubes using an Instron 4505 universal test machine as represented in Figure 1. The tests were undertaken at a crosshead displacement rate of 1 mm/minute and interrupted when the crosshead had travelled at least 15 mm. The specific energy absorption of the tubes was determined from the energy under the load-displacement trace and the initial mass of the specimen.

(a) (b)

Figure 2. Samples before testing under quasi-static tests (a) A 45 degree chamfer at one end of 10.2 mm CFRP tube and (b) top view of a CFRP tube embedded in a 50 x 50 x20 mm panel of 224 kg/m^3 PVC foam.

2.3 Foams with Embedded CFRP Tubes

A range of crosslinked PVC foams of densities between 56 to 224 kg/m^3 as shown in Table 1 were used as cores. Foams were cut in the form of 50 mm x 50 mm x 20 mm panels with one hole of 10.2 mm diameter was drilled at the centre of the foams. Individual chamfered tubes, with an outer diameter of 10.2 mm, were then embedded without applying adhesive in a range of crosslinked PVC foams as shown in Figure 2b. The samples were then loaded to failure in uniaxial compression at a crosshead displacement rate of 1 mm/minute. For all of the above, tests were conducted on at least four repeat samples to yield an average value. The crushing characteristics, deformation patterns and the corresponding load–displacement histories of all the composite tube/foam specimens are presented. A total of 40 tests have been conducted to study the crushing performance of the individual composite tubes and composite tubes embedded in core materials.

3. Results and Discussion

3.1 The effect of the tube D/t ratio on SEA

The deformation patterns and the corresponding load–displacement histories of all the composite tubes under quasi-static axial compressive loading condition were studied. In order to compare the crushing characteristics of D/t ratios of CFRP tubes, Figure 3 representing the typical load-displacement traces of tubes with a diameter of 10.2 mm (D/t = 6.3) and 40.9 mm (D/t = 22.4) was constructed. The initial stage of the crushing of 10.2 mm diameter tube showed a progressive crushing of the triggered end where the force increased constantly up to 6kN at displacement of 2mm. The 10.2 mm diameter tube then continued to crush in a stable manner at an approximately constant loading of 6kN until compacted. The failure characteristics observed highlighted a similar failure mode as described by Farley and Jones [6]. They quoted that the combination of lamina bending and transverse shearing are causing the CFRP to undergo brittle fracturing. The small fragments as shown in Figure 4a indicated that a large number of fibres had been fractured during the crush process. In contrast, the load-displacement curve for larger D/t ratio which is the 40.9 mm diameter tube showed a different response pattern. Immediately after the crushing of the triggering profiles, the load drops rapidly from 35kN to 23 kN at displacement of 12 mm. Due to the sudden growth of the axial cracks observed along its length, the composite tube had lost its load bearing capacity in the later stage of crushing. During the crushing process, interlaminar fracture caused the The relatively large plate-shaped structures from crushing of 40.9 mm diameter tube can be clearly noticed from Figure 4b. Figure 5 shows the variation of SEA with D/t for the CFRP. The highest value of SEA is 93.3 kJ/kg comprising the smallest tube tested with D/t of 6.3. From the figure, it is apparent that the SEA of CFRP tube increases with decreasing D/t. It is evident that those CFRP tubes that failed into small fragments absorb significantly more energy than those that fail in a macroscopic manner.

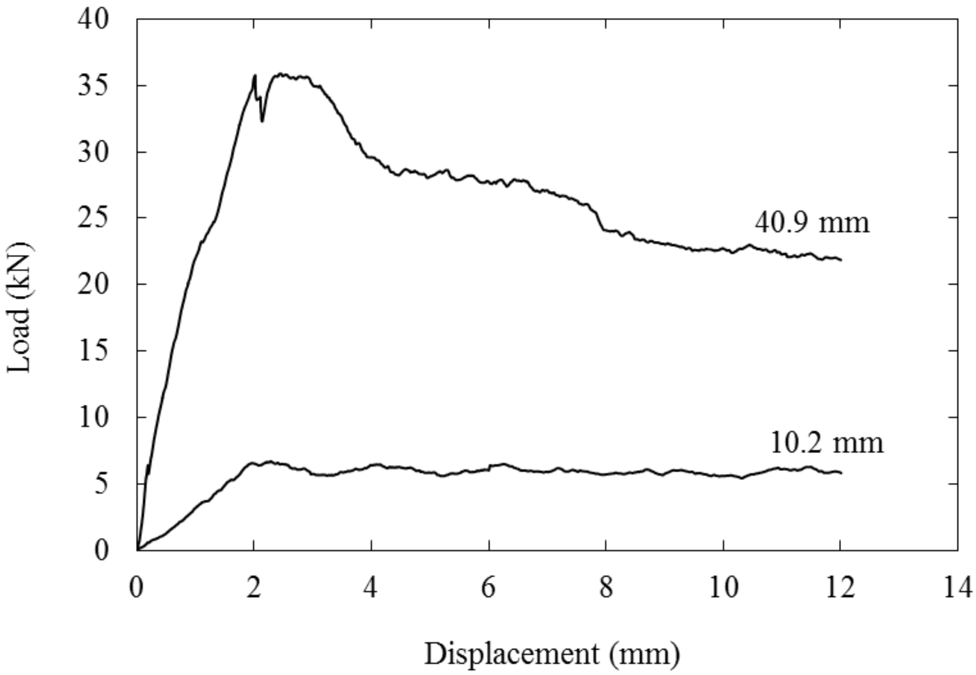

Figure 3. The load-displacement curves of 10.2 mm and 40.9 mm diameter CFRP tubes.

(a) (b)

Figure 4. Remnants of the composite tubes following quasi-static testing at 1mm/minute for tubes of (a) D_o = 10.2 mm (D/t = 6.3) and (b) D_o = 40.9 mm (D/t = 22.4)

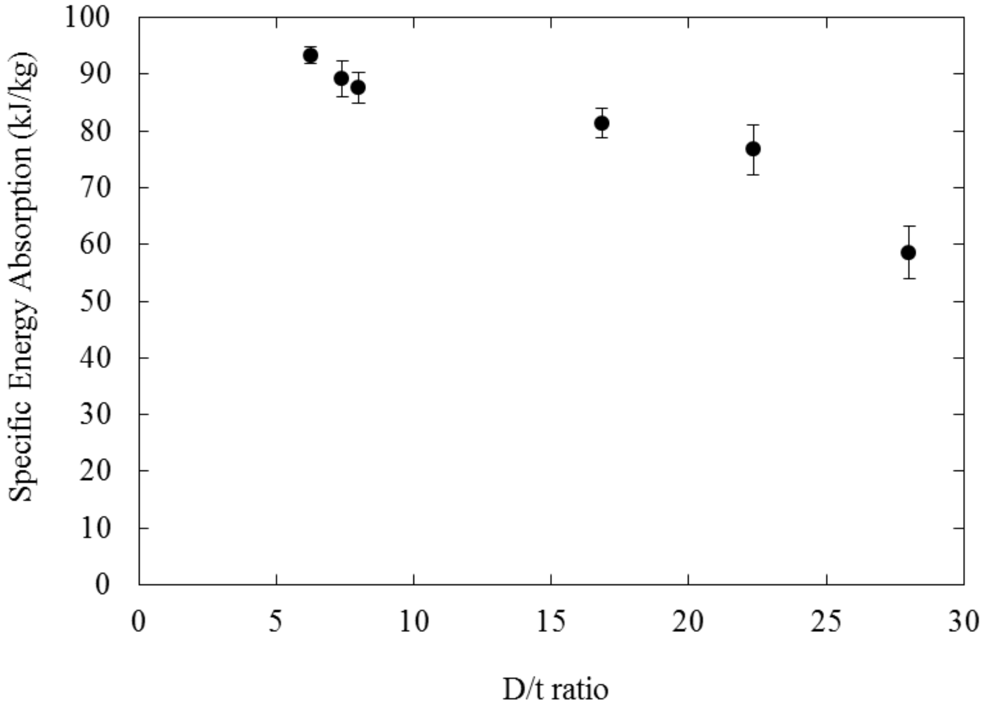

Figure 5. Variation of SEA at quasi-static rates of loading with D/t ratio for the 20 mm long CFRP tubes.

3.2 Effect of Embedding CFRP Tubes in Cores

The next stage of this research study investigated the behaviour of the composite tubes when embedded in a foam core. Here, 20 mm long CFRP tubes with a diameter of 10.2 mm were inserted in 20 mm thick PVC foams with densities ranging from 56 kg/m^3 to 224kg/m^3. Figure 6 shows the top view of crushed tube/foam combination and the remnants of tube after being removed from the core. A closer examination on figure 6(c) shows that the remnants fractured to finer particles when compared to small fragments of compression on an individual tube as can be observed in figure 4(a). The SEA values obtained are in an agreement with a finding by Farley [7] that the debris size of crushed materials represents the energy absorption efficiency. The area of the foam that was in contact with the tube as in figure 6(b) seems to experience a slight expansion but with no visible crack. This depicts that the foam serves to constrain the splaying process, possibly resulting in greater levels of crushing within the embedded tube.

(a) (b) (c)

Figure 6. A sample of a 10.2 mm diameter tube embedded in a 224 kg/m^3 foam (a) Top view of crushed tube/foam combination, (b) foam after removal of tube and (c) remnants of tube removed from the core.

Figure 7 shows typical load-displacement traces following quasi-static tests on a CFRP tube reinforced PVC foam (density of 224 kg/m^3). Also included in the figure is the corresponding trace for the plain (unreinforced) foam. An examination of the figure indicates that the stabilised crushing load for the CFRP tube-foam system is approximately 25 kN, suggesting that the reinforced foam structure offers a response that is significantly higher than the sum of its individual components (6.25 kN for the tube and 10 kN for the foam). This difference was more pronounced as the foam density was increased. Given that the composite is likely to be principal energy-absorbing material in these bi-material systems (particularly at low foam densities) the SEA of the embedded tubes was estimated by removing the energy absorbed by the foam from the combined tube/foam trace. Table 1 shows the resulting estimates for the SEA for tube as a function of foam modulus. By constraining the composite tube from splaying during crushing process, it is possible to improve the specific energy efficiency by up to about 50%. It is clear that increasing the density of the foam results in a greater absorption of energy of tube.

Sample	Core Density (kg/m^3)	Quasi-static SEA of tube (kJ/kg)
Tube without core	0	93.3
Tube in PVC foam C70.55	56.0	106.0
Tube in PVC foam C70.75	90.4	107.3
Tube in PVC foam C70.130	128.0	120.5
Tube in PVC foam C70.200	224.0	155.8

Table 1. Summary of the foam density and the specific energy absorbing following quasi-static tests.

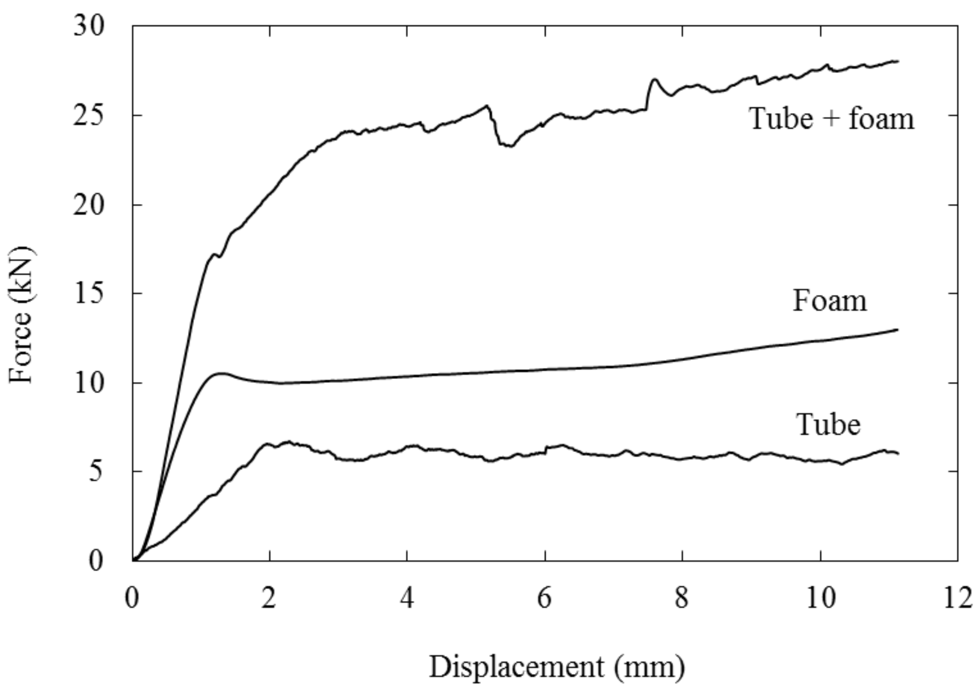

Figure 7. Load-displacement traces following tests on the tube-reinforced structures (tube diameter = 10.2 mm and foam density = 224 kg/m^3).

4. Conclusions

A range of tube-reinforced sandwich core structure has been developed in which CFRP tubes are embedded in low density core materials. Initial tests on plain tubes have shown that their specific energy absorption characteristics increase with decreasing inner diameter to thickness (D/t) ratio. Here, significant changes in failure mode have been observed in the CFRP systems, with larger diameter tubes failing in delamination by forming plate-shaped structures and smaller tubes were crushed into small fragments. This principle has then been applied to develop reinforced foams based on low D/t tubes. Compression tests on these modified foams have shown that the CFRP tubes absorbed greater levels of energy with increasing foam density, due to a change in the observed failure mode from small fragments to finer particles. Thereby, it is interesting to further develop a method that able to allow the CFRP tube embedded in a low density foam structure to crush into finer particles, subsequently resulting in high specific energy absorption.

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