**The Energy-Absorbing Behaviour of Composite Tube-reinforced Foams**

J. Zhou1,3 \*, Z. Guan1 and W.J. Cantwell2

1 School of Engineering, University of Liverpool, Liverpool, L69 3GH, U.K.

2 Department of Aerospace Engineering, Khalifa University of Science, Technology and Research (KUSTAR), 127788, Abu Dhabi, UAE.

3State Key Laboratory of Manufacturing Systems Engineering, Xi’an Jiaotong University, Xi’an, 710054, China.

\*Corresponding email: jinzhou@liv.ac.uk

**Abstract**

This paper investigates the energy-absorbing characteristics of composite tube reinforced PVC foam cores for use in lightweight impact-resistant sandwich structures. Compression tests have been conducted on crosslinked PVC foam cores with densities ranging from 40 to 130 kg/m3, reinforced with both glass fibre and carbon/glass fibre composite tubes. The energy-absorbing capability of these reinforced foams was evaluated by determining the specific energy absorption of each configuration. The mechanical response of the tube-reinforced foams was also modeled using the finite element method. The validated models shown good agreement with the experimental data, with the model accurately predicting the compressive responses and failure characteristics in the samples. Drop-weight impact tests have also been undertaken in order to investigate their dynamic performance and ability to absorb energy under crash conditions.

It has been shown that embedding the tubes in a foam panel serves to modify the failure process occurring within the composite tubes, greatly enhancing their ability to absorb energy. However, when normalized by the mass of the test sample, the SEA values of the hybrid tube reinforced foams were found to be largely insensitive to variations in foam density, suggesting that reinforced low density foams, where the associated crushing forces are low, are best suited to energy-absorbing applications. In contrast, the SEA data for the unidirectional glass tube reinforced systems steadily increase with increasing foam density. The dynamic values of SEA for the tube-reinforced systems were lower than those measured at quasi-static rates, suggesting a rate-sensitivity in the fracture processes within the composite. Finally, it is shown that the energy-absorbing capability of tube-based foams is higher than many comparable core systems, where their potential for use under conditions of extreme crushing are highlighted.

Keywords: Composite tube, Reinforced PVC foam, Energy absorption, Finite element method

Nomenclature

, damage initiation conditions in the warp fibre directions,

, damage initiation conditions in the weft fibre directions,

, damage under compression in the warp, weft and through-the-thickness direction

,,,,,,, damage initiation stresses

, coefficient controls the contribution of the shear component.

, strain-rate functions in the strength

, strain-rate constant,

, reference strain-rate,

, strength values of  at the reference strain-rate.

, yield surface for a closed-cell foam material

, uniaxial yield strength of the foam

 , Von Mises stress

, mean stress.

 , the term defines the shape of the yield surface

, ratios of the initial uniaxial yield stress

, hydrostatic tensile yield stress

1. **Introduction**

Carbon and glass fibre reinforced tubes are currently finding increasing use in many high-performance engineering structures, where energy-absorption is a key design parameter. An attractive characteristic of composites, when appropriately designed, is their ability to crush in a controlled manner under well-controlled testing conditions. Previous studies have shown that composites, particularly when manufactured in a tubular form, absorb energy through a number of failure mechanisms, such as fibre fracture, fibre-matrix debonding, matrix cracking, and delamination [1]. This energy-absorbing ability has resulted in composites being used in the automotive, marine and aerospace industry. Jacob *et al*. showed that less than one kilogram of composite material is capable of absorbing the energy of a vehicle travelling at 35 mph [2]. Eshkoor *et al.* [3] investigated energy absorption and load carrying capability of woven natural silk epoxy–triggered composite tubes to evaluate crashworthiness and failure morphology. Xu *et al.* [4] evaluated dynamic failure and durability properties of marine composites structures for naval ships using a developed composite seawater tank approach. Jover *et al.* [5] investigated ballistic impact response of balsa core and carbon fiber skins based sandwich structures. The specific energy absorption (SEA) parameter is widely used to characterise the energy-absorbing capacity of tubular structures. SEA values can vary greatly, for example, from 20 kJ/kg for a pultruded glass fibre/epoxy [2] to values well in excess of 100 kJ/kg for carbon fibre-based systems [6]. The precise value depends on a number of parameters, such as the geometry of the composite, its fibre architecture, as well as the properties of the polymeric phase. Esnaola *et al*. [7] studied the influence of fibre volume fractions on energy absorption capabilities of semi-hexagonal glass/polyester composite structures for automotive crash applications. The specific energy absorption value of the material was enhanced to 56 kJ/kg by increasing the fibre percentage up to 47%. Three fracture mechanisms, including axial splitting, axial crack propagation and fibre breakage, have been observed. Dorival *et al.* [8] performed dynamic crushing tests on the designed reinforced composite structures to evaluate their energy absorption. The failure mechanisms and performance of six types of structure designed were evaluated for potential applications in aeronautical structures.

A number of researchers have studied the influence of specimen geometry on the energy-absorbing capability of composite tubes [9]. Thornton and Edwards [10] investigated the energy-absorbing response of tubes with circular, square and rectangular cross-sections and showed that the former out-performed both their square and rectangular tubular counterparts. Farley *et al*. [11] conducted tests on Kevlar and carbon fibre reinforced tubes, with ply orientations typical of those used in sub-floor beam structures and showed that the tube diameter to thickness ratio played a significant role in determining its subsequent strain energy-absorbing capacity. Similar trends were observed by Alia *et al*. [12] following tests on circular composite tubes, with values increasing by over fifty percent as the D/t ratio was reduced from approximately 42 to 6. This evidence suggests that the use of very low values of D/t can lead to a great enhancement in energy absorption in tubular structures. Following these initial tests on small diameter reinforcements, individual tubes were embedded in a polymer foam and crushed at quasi-static rates of strain. Eshkoor *et al.* [13] carried out axial quasi-static crushing tests on woven natural silk/epoxy-triggered composite rectangular tubes to study energy absorption and load carrying capability. The study also reported that the geometry of the specimens had a significant effect on both crashworthiness characteristics and failure mode. However, the triggering mechanism had no influence on average sustained load and energy absorption.

Several studies have been undertaken to investigate the influence of strain-rate on the energy-absorbing capacity of composite reinforced foams [14,15]. Although carbon tubes exhibit attractive SEA values under quasi-static compressive loading, the SEA values were lower at dynamic rates of loading. Schmuesser and Wickliffe [14] studied the energy absorption response and failure characteristics of composite tubes manufactured from carbon fibre/epoxy, glass/epoxy and Kevlar/epoxy composites. Quasi-static compression and impact tests were conducted and the SEA values of composite tubes were found to be greater than those of metal tubes. In addition, the SEA values of individual angle-ply composites tube were significantly greater than those for individual unidirectional composites. The latter exhibited reductions in energy absorption of up to 30%. The dynamic properties of rod-reinforced foams were investigated by Zhou *et al.* [15] where a dynamic enhancement factor (DEF) was employed to characterize the change in properties in passing from quasi-static to dynamic rates of loading. Here, dynamic enhancements of 76% were noted in terms of energy absorption and more than 100% in compression strength, over the range of strain rates considered.

A number of workers have investigated the effect of embedding tubes in foam and filling tubes with foams [16-19]. Tarlochan *et al.* [16] undertook an experimental investigation on energy-absorbing characteristics of tubes based on a glass fibre/epoxy polystyrene foam sandwich design, with SEA values ranging from 17.7 to 32.6 kJ/kg. The failure mechanisms included splaying and fragmentation, bending of the fronds, both internally and externally as well as transverse shearing of the outer wall. Tarlochan and Ramesh [17] developed a nested design and grouped up to six quadrilateral glass or carbon/epoxy composite tubes with foam centres. The measured values of SEA for the optimised design were as high as 47.1 kJ/kg and the primary failure mode in these structures was progressive crushing. Ochelski and co-workers [18] investigated the influence of filling tubes with different materials on their impact energy absorption capability. Here, the carbon and glass/epoxy tube-shaped specimens were filled with foamed PVC and foamed aluminium and offered SEA values ranging from 16.7 to 48.3 kJ/kg. Recently, Othman *et al*. [19] conducted experimental work on performance of E-glass/polyester resin pultruded composite square tubes filled with polyurethane (PU) foam subjected to axial and oblique loading. The influence factors on the specific energy absorption, including the wall-thickness, the density of the filled foam and the loading condition, were investigated. The SEA value of the composite tube filled with 90 kg/m3 foam was improved significantly.

A number of FE models [20-26] have been developed to simulate the impact response of sandwich structure. A few numerical techniques using the finite element code LS-DYNA [20-23]. Styles *et al*. [20] investigated the flexural behaviour of a composite sandwich structure with an aluminium foam core using LS-DYNA. The aluminium foam was modeled using an existing foam material model based on the Deshpande– Fleck yield surface. Kalhor *et al.* [21] investigated the energy-absorbing characteristics of square hybrid metal-composite tubes composed of glass/epoxy composites and 304 stainless steel. Numerical models were developed to study the effects of thickness and stacking sequence on energy absorption using LS-DYNA. However, the model was not able to model delamination and the dissipated energy due to the friction between delaminated layers. Boria *et al.* [22] presented a study on lightweight design and the crashworthiness analysis of a carbon/epoxy based square composite impact attenuator for a Formula racing car. Numerical models were developed to simulate car crash using finite element explicit code LS-DYNA and the FE predictions were compared between shell and solid element models. Wu *et al.* [23] investigated dynamic crash responses and crashworthiness characteristics of carbon fiber reinforced plastic (CFRP) panels and aluminum honeycomb based sandwiches numerically. They reported that the peak load, absorbed energy and SEA increased under a high velocity impact. Raimondo *et al.* [24] developed three-dimensional composite damage model based on a mesh-regularisation strategy to predict the low velocity impact response of unidirectional PMC laminates. The model is implemented into the finite element code ABAQUS/Explicit for one-integration point solid elements. It is applicable to predict mesh size-independent impact results for any target discretization. Esnaola *et al.* [25] developed a constitutive model to predict the crushing behaviour of semi-hexagonal E-glass/polyester composite structures using ABAQUS/Explicit. The influence of the wall angle and the overall size of the semi-hexagonal section were investigated. The load carrying capability of the structure decreased due to high stress concentration with increasing the wall angles and lengths. Luo *et al.* [26] proposed a stiffness degraded model which involves the modified Hashin failure criterion and damage evolution law to simulate the crashworthiness and energy-absorbing characteristics of carbon/epoxy composite tubes.

This paper presents the findings of a study into the energy-absorbing response of PVC foam cores reinforced with composite tubes. Quasi-static and dynamic compression tests on carbon and glass fibre/epoxy tubes in a PVC foam have been undertaken to investigate their energy-absorbing behaviour. In the final part of this study, the energy-absorbing properties of these lightweight materials are compared to previously-published data on a range of lightweight core materials, including rod-reinforced foams.

# Experimental Procedure

## 2.1 Constituent Materials

Crosslinked PVC foams, with nominal densities of 40, 80 and 130 kg/m3, have been reinforced with carbon and glass fibre reinforced epoxy tubes to increase their energy-absorbing capability. The mechanical properties of the three foam materials, supplied by Airex A.G, Switzerland, were determined at quasi-static rates of loading in an earlier investigation [27]. Initial tests were undertaken on square foam samples, with an edge length of 33 mm and a thickness of 20 mm. Here, a single hole was drilled in the centre of each sample, into which a composite tube was inserted, as shown in Figure 1a. In all cases, the diameter of the hole was equal to outer diameter of the tube that was inserted into it. In the second part of this investigation, testing was conducted on 100 mm square, 20 mm thick foam blocks containing nine holes, into which an equal number of tubes were inserted, as shown in Figure 1b. The energy-absorbing capacity of the plain foams was also investigated through a series of tests on samples with dimensions of 100 x 100 x 20 mm.

Two types of composite tube were investigated in this study. The majority of tests were undertaken on roll-wrapped carbon/glass fibre reinforced composite tubes, supplied by Easy Composites U.K. The carbon/glass tubes were manufactured from high-modulus Toray T700 unidirectional carbon fibre prepreg oriented along the length of the tube and unidirectional E-Glass fibres oriented at 90° to give a [0o,90o,0o,90o,0o] stacking sequence. The inner diameter, D, of these tubes varied from 8 to 12.5 mm, with the D/t (t = thickness) ratio varying between 8.0 and 9.26. These cylindrical structures are henceforth referred to as hybrid tubes, using the code ‘C’, since the higher strength carbon fibres are aligned in the loading direction. An additional series of tests was undertaken on samples reinforced with unidirectional glass fibre reinforced epoxy tubes, with an inner diameter of 8.5 mm, a wall thickness of 2.1 mm and a value of D/t of 4.1. These tubes were manufactured via a pultrusion process. Table 1 summarises the geometrical details of all of the tubes investigated in this study. Prior to use, a small chamfer was introduced at each end of the tube to facilitate triggering of the failure process. A total of fifteen material configurations were prepared (including the three plain foams), details of which are given in Table 2. Here, C130C8 corresponds to a 130 kg/m3 crosslinked PVC foam reinforced with 8 mm (internal diameter) hybrid (C) tubes. Similarly C130G8 refers to a 130 kg/m3 crosslinked PVC foam reinforced with glass fibre (G) tubes. Figure 1 (b) shows a hybrid tube reinforced foam sample. Tests were also undertaken on tube-reinforced foams with glass fibre reinforced epoxy skins. Here, four plies of woven glass fibre/epoxy prepreg (MTM56FR from ACG Ltd.) were cured on the core materials to yield a sandwich panel with 0.4 mm thick composite face sheets.

## 2.2 Quasi-static Mechanical Tests

Quasi-static compression tests on the plain and reinforced foams were carried out on a Dartec universal testing machine (500 kN capacity). The specimens were placed between stainless steel circular platens and loaded at a crosshead displacement rate of 1 mm/min. The load-displacement curves were recorded and subsequently used to determine the specific energy absorption of the material. Compression tests were also undertaken on the individual tubes in order to characterize their energy-absorbing capability. These tests were conducted at a crosshead displacement rate of 1 mm/minute. Three repeat tests were conducted on each type of test sample.

**2.3 Dynamic Tests**

The dynamic behaviour of the tube reinforced sandwich panels was investigated via a series of falling-weight impact tests. These tests were conducted on the square samples described above, using an instrumented drop-weight impact tower. The specimens were placed on a rigid square platen fixed on top of a 100 kN load cell. The reinforced specimens were crushed by a rigid steel platen attached to the falling carriage. The mass of the carriage was increased to 40 kg in order to ensure successful crushing of the test samples. The release height of the impact carriage was increased up to a maximum of 1.5 meters. The displacement and impact force were recorded using a high-speed video camera and a piezoelectric load-cell, respectively.

### Numerical modelling

Numerical models were prepared using the finite element software Abaqus/Explicit to predict the behaviour of the tube reinforced foam cores subjected to compressive loading. Individual constitutive models and failure criteria were described for the different constituent materials for composite tube and PVC foam core material.

### 3.1 Modelling of GFRP composite tube using a modified 3D Hashin’s failure criteria

Here, the composite tubes were modelled using the modified Hashin’s 3D failure criteria for anisotropic composite materials. The material properties of the composite are given in earlier studies [27]. The failure criteria [28] were used to simulate the onset damage and damage evolution of the composite in a Cylinder coordinate system. The tensile-shear failure criteria and the associated constitutive model, were introduced into the ABAQUS/Explicit using a user-defined subroutine [29]. It was used to describe the damage initiation conditions in the warp and weft fibre directions, which is similar to the fibre failure criteria as follows:

 (Eq. 1)

 (Eq. 2)

where the coefficient controls the contribution of the shear component. Under shear loading, the material exhibits a plastic-like response, which becomes non-linear at low values of stress, while ultimate failure occurs at high values of strain. Since shear nonlinearity is not incorporated in the present model, to prevent premature predictions of failure, due to the contribution of shear component, its value was scaled down. The remaining three damage modes define damage under compression in the warp, weft and through-the-thickness direction. These are described by the maximum stress criteria as:

 (Eq. 3)

The properties,,,,,,, in Equations (1-3) are the damage initiation stresses.

**3.2 Strain-rate effects in strength**

The effect of strain-rate on the strength of a composite material is frequently studied using strain-rate dependent functions. In order to represent the dynamic material response, the strain-rate dependency was assigned [30, 31]. Yen proposed the following logarithmic functions to account for strain-rate effects in the strength and modulus of composite materials [32]:

 (Eq. 4)

Here,  is the strain-rate constant, is a reference strain-rate,  are strength values of  at the reference strain-rate. The user-defined VUMAT subroutine employed for the material model and the above failure criteria in the ABAQUS/Explicit software package. During every computational time step, the subroutine is compiled giving ABAQUS/ Explicit the required information about the state of the material as well as its response at integration points within each element in the model. The stresses are calculated in VUMAT using the strains and material stiffness coefficients.

3.3 Modelling of the PVC foam

The polymer foam core was modelled as a crushable foam under uniform loading. It was assumed that the PVC foam exhibited a rate-dependent strain hardening response in which shear and ductile failure were used to model the damage. The yield surface for a closed-cell foam material can be defined by [33]:

 (Eq. 5)

where  is the uniaxial yield strength of the foam, in this case in compression,  is the Von Mises stress, and  is the mean stress. The term  defines the shape of the yield surface [26], which is related to the ratios of the initial uniaxial yield stressand the hydrostatic tensile yield stress  respectively. The rate-dependent hardening behaviour was considered by relating the stress ratio to the equivalent plastic strain-rate. Details on compressive properties and fracture energy of the foam, together with the approach to consider the strain-rate effect, are given in Ref. [34]. Damage development in the foams was modelled using a ductile damage criterion combined with a shear damage criterion.

The mesh generation geometric, loading and boundary conditions for the tube-reinforced foam subjected to compressive loading are shown in Figure. 2. Here, the composite tubes and foams were modelled using eight-noded solid elements with a reduced integration capability (C3D8R). The density of the mesh was varied in order to undertake a mesh sensitivity analysis was studied by varying the mesh. Several interfaces were considered in the finite element model, these being those between the specimen and the loading platen, as well the interfaces between the composite tubes and foam core.

1. **Results and Discussion**

## 4.1 Quasi-static tests on individual composite tubes

Prior to testing the reinforced foams, a series of tests were undertaken to characterise the energy-absorbing properties of the individual composite tubes. Figure 3a shows a comparison of typical compressive load-displacement traces following tests on individual hybrid tubes with inner diameters of 8, 10, and 12.5 mm (D/t values between 7.41 and 9.26). An examination of the trace for the 12.5 mm hybrid tube indicates that the force rises up to approximately 10.6 kN, before dropping slightly and subsequently stabilizing at approximately 10.3 kN. In contrast, the trace for the 8 mm diameter tube increases in a linear fashion with a relatively low stiffness up to the peak at 7 kN, followed by a lower plateau value of approximately 4.6 kN. Based on the energy under the load-displacement trace, the 12.5 mm hybrid tubes offer an energy-absorbing capability that is more than double that of the 8 mm tubes. All three traces exhibit similar characteristics, involving crushing in a stable mode at an approximately constant force, before dropping during the final stages of the test. The resulting specific energy absorption values for the three tubes were found to lie between 67.7 and 89.8 kJ/kg, values that are relatively high for this type of material [2]. It is interesting to note that the SEA increases with increasing D/t, an observation that contrasts with earlier findings [11,12]. It should be noted, however, that the spread in the D/t values investigated in this study is small and unlikely to be statistically significant. Reasonably good correlation has been obtained in terms of the initial stiffness, the first peak load, plateau load and damage evolution. It clearly shows that the predicted load from FE modeling, similar to the testing, is in a reducing trend after the first peak load during the compression process.

Figure 3b compares typical load-displacement traces for the glass fibre tube with that of a hybrid tube. The trace for the glass fibre trace indicates that the force rises in a linear fashion up to approximately 17.5 kN before dropping sharply to a much lower plateau value of 3.7 kN, this latter value being less than 25% of the initial peak load. This is in contrast to the plateau values for the hybrid tubes, which correspond to a significant fraction (over 75%) of the initial force. Clearly, the hybrid tube exhibits a stable crushing mode throughout the whole test, whereas the unidirectional glass fibre tube initially failed in an unstable mode, probably as a result of the lack of constraint in the hoop direction. The average SEA value for the glass-based system was 31 kJ/kg, significantly lower than the aforementioned values associated with the hybrid tubes.

Figure 4a presents the failure processes in the hybrid and plain glass fibre tubes during compression testing. An examination of the failed tubes indicates that the crushing process leads to the upper part of the cylinder splaying outwards against the moving platen, generating a large amount of fine composite fragments during the test. The presence of such debris and dust suggests that a significant amount of energy has been absorbed during the failure process. In contrast, the glass fibre tube failed as a result of extensive longitudinal splitting, with delamination and localised splitting occurring during the initial stages of crushing. Given that the fracture energies associated with these matrix-dominated failure modes are significantly lower than that associated with fibre fracture, these observations support the observation that the unidirectional glass tubes are less effective energy absorbers than their hybrid counterparts. Figure 4b shows a comparison of the progressive deformation and failure modes in the 10 mm CFRP tube following experimental testing and FE modelling. The basic failure modes observed experimentally, extensive splaying, fibre fracture and matrix cracking for the crushed tube have been captured in the FE model. Both the model and the test sample exhibit progressive collapse of the tube. However, the finite element analysis shows less extensive splaying of the fibres, which may be caused by the automatic removal of the failed elements

## 4.2 Compression tests on single tube-reinforced foams

Figure 5 compares the load-displacement traces following quasi-static tests on the 12.5 mm plain hybrid tube, a similar tube embedded in the 130 kg/m3 foam and an equivalent unreinforced plain foam specimen. The dashed line corresponds to the FE predictions whilst the solid line to the experimental results. The load-displacement traces indicate that the stabilised crushing load for the reinforced foam is approximately 23.9 kN. This value contrasts with the average crushing load for the individual tube, which is 10.3 kN and that for the plain 130 kg/m3 foam, which is approximately 2.7 kN. The evidence indicates that the reinforced foam structure provides a crushing resistance that is significantly greater than the sum of individual components. Clearly, the composite tube makes the greatest overall contribution to energy absorption, however, the PVC foam serves to constrain the splaying process, resulting in greater levels of fragmentation and friction in the embedded tube, as it crushes and subsequently disintegrates. Indeed, a post-failure analysis of the test sample indicated that embedding the composite tubes in the foam resulted in much greater levels of debris than observed in the plain unsupported tubes. The enhancement in the average plateau crushing forces for this tube in the 130 kg/m3 foam is approximately 10.9 kN. From the load-displacement curves of the tube embedded it is evident that the tube contributes over 80% of the load-bearing capacity load and the energy absorption of the foam panel and the performance of the embedded tube is more than double that of an individual tube without foam support for the case of the 12.5 mm tube embedded in C130 foam. This evidence clearly supports the suggestion embedding the tube in a foam panel can modify the failure process and greatly enhance the crush performance of the tubes. Agreement between the model and the experimental data is good, suggesting that the finite element analysis is capable of predicting the response of tube-reinforced foams.

Figure 6a presents load-displacement traces following tests on a 130 kg/m3 foam containing hybrid tubes with inner diameters of 8, 10 and 12.5 mm (C8, C10 and C12). The figure also includes a trace following a test on a plain foam specimen (i.e without a CFRP tube). Clearly, the force increases significantly as the diameter of the reinforcing tube is increased, reaching average plateau values of 11.3, 18.5 and 23.9 kN for the 8, 10 and 12.5 mm tube reinforced foam panels, respectively. The approximate enhancement in force as a result of embedding the tubes in the PVC foam was 5.3, 7.7 and 10.9 kN for the 8, 10 and 12.5 mm tubes, respectively. This will be discussed further below. Again, agreement between the experimental results and the finite element simulations is very good, with features such as the initial stiffness, the peak load, damage evolution and the densification process being captured. Clearly, the force increased significantly to an average plateau load that varied from 11.3 to 22.7 kN for the 8, 10 and 12.5 mm tube reinforced foam panels, respectively. It is worth noting that the plateau load of 12.5 mm tube reinforced foam panel is eight times of the plain foam panel without embedded tube.

Figure 6b compares the experimental and numerical cross-sections of deformation and failure modes in a C80 foam core panel with embedded hybrid tubes. The core structure was deformed by 75% from its original configuration. The basic features of crushing failure in the foam and the tube failure are captured. Again, the failure modes in the FE exhibit less crushing debris, due to the failed elements being removed automatic by the element control. The failed tubes are displayed in the crushing states, which highlight a progressive collapse of tube embedded in the PVC foam. The failure processes also indicate the high level of constraint applied by the foam constrains the CFRP tube to crush along its longitudinal axis, which explains the enhancing effect of the foam in terms of the overall energy absorption.

Compression tests on single unidirectional glass tubes (inner diameter = 8.5 mm) embedded in PVC foams with densities ranging from 40 to 130 kg/m3 were conducted to investigate the effect of varying the properties of the embedding medium. The resulting curves, Figure 7, exhibit similar features to the hybrid-reinforced foams, where a linear elastic region, a zone of progressive crushing, a subsequent sharp drop in load, followed by a final region associated with core densification are apparent. The plateau values increase from 9 to 18 kN as the foam density passes from 40 to 130 kg/m3. It is interesting note that these values are between two and four times the corresponding value for the individual glass fibre tube shown in Figure 2b. This evidence suggest that the presence of the PVC foam greatly enhances the crush resistance of these unidirectional glass fibre/epoxy tubes. Indeed, the previously-discussed enhancement effect was found to be significantly greater in the unidirectional glass fibre tubes than in the hybrid tubes, indicating that the failure processes in the unidirectional glass fibre tubes are significantly modified by the constraint applied by the surrounding PVC foam.

Figure 8 shows the variation of the enhancement in the average value of the plateau force associated with embedding the glass and three hybrid tubes in the various crosslinked PVC foams. As discussed previously, these values correspond to the difference between the plateau value for reinforced sample and the sum of the plateau forces for the unsupported tube and the plain foam. It is interesting to note that there appears to be a linear relationship between this increment in force and foam density for all types of tube. This evidence supports the conclusion that the foam substrate enhances the level of support applied to the tube as it fails. Concerning the hybrid tubes, the enhancement clearly increases as the tube diameter increases, with the greatest change occurring for the C12 tubes. However, the greatest enhancement is associated with the glass fibre tubes, where a three hundred percent increase in this force value is observed as the foam density is increased from the 40 to 130 kg/m3. It is also worth noting that all four trendlines appear to extend back to the origin, a point that effectively corresponds to tests on an individual tube, i.e. without the foam support. This evidence suggests that it should be possible to crudely predict the plateau force using the information in Figure 8.

## 4.3 Foams Containing Multiple Reinforcements

The next stage of this investigation focused on studying the influence of increasing the foam density on the energy-absorbing response of the foams reinforced by an array of nine hybrid tubes, this being considered as a representative section of a larger panel. Figure 9 shows typical load-displacement traces for the reinforced 80 and 130 kg/m3 foams. All of the traces exhibit similar trends to the previously-observed responses of the individual tube-reinforced foams. The plateau value of force increases from 89 to 160 kN for the 80 kg/m3 foam samples and from 119 to 188 kN for the 130 kg/m3 foams, as the tube diameter increases.

An examination of cross-sections of the failed tubes in the 130 kg/m3 foam, Figure 10, indicates that the triggered end of the cylinder splay both inwards and outwards during the crushing process. It is clear that a great number of fragments and fine particles have been generated, due to the level of constraint and the degree of interaction between the PVC foam and the composite skins during the test. This interaction resulted in a higher plateau force during the crushing process, which in turn increased the energy absorption.

Figure 11 shows the variation of the enhancement factor (as previously defined as being the difference between the plateau stress for the tube reinforced foam and the sum of the corresponding force for the plain foam and the sum of nine individual tubes) with foam density. As observed previously for the single tube foams, the data for a given tube diameter appear to fall on a straight line, with the gradient of the line increasing with tube diameter. Once again, the glass fibre tubes benefit the most from being embedded in the cellular solid. Once again, all of the trendlines appear to extend backwards to the origin, the point that corresponds to a compression test on nine unsupported tubes. The increased area under the load-displacement trace associated with embedding the tubes results in additional energy absorption, whose values clearly increases with foam density. The energy required to crush the various reinforced foam structures is shown in Figure 12. Clearly the energy increases with tube diameter for a given foam density. The absorbed energy also increases with foam density in a linear fashion for a given tube diameter. It is interesting to note that the slopes of the trendlines for the different diameter hybrid tubes are similar. In contrast, the slope of the trace for the glass tube is significantly greater than those of its hybrid counterparts. The energy absorbed by this glass-based system increases from 720 to 2900 J in passing from the equivalent of nine plain tubes to a similar array in a 130 kg/m3 foam. This suggests that the failure processes in the unidirectional glass tubes are greatly modified by the local constraint applied by the PVC foam. The presence of the foam clearly constrains the lateral movement of the tubes following the onset of longitudinal splits, leading to greater overall stability and increased energy absorption.

The variation of SEA as a function of core density is shown in Figure 13. Over the range of core densities considered, the specific energy absorption values for the hybrid tube reinforced systems vary from 61.1 to 87.7 kJ/kg and that of the glass tube systems from 41.3 to 62.9 kJ/kg. The resulting values of the compression strength, energy-absorption and SEA are summarised in Table 3. It is clear that the SEA values for the hybrid tube reinforced foams are largely insensitive to variations in foam density. As before, the SEA values of these reinforced systems are higher for the larger diameter samples, with the values for the C12 system being up to fifty percent higher than the corresponding C8 structures. The information in Figure 13, combined with the data in Figure 11, suggests that the foam density should be a low as possible, since this will ensure that the average crushing force will be low whilst offering a high value of SEA. In contrast to the hybrid materials, the values for the glass tube reinforced system show an uptrend with increasing foam density. The evidence suggests that the SEA value for a glass fibre tube embedded in a 200 kg/m3 foam could potentially out-perform an equivalent hybrid tube reinforced foam. However, as reported in Figure 10, the plateau force will be significantly higher in the cores based on higher density foams and this will need to be considered, if this is a limiting design parameter.

## 4.4 Dynamic compression tests on the tube reinforced foam sandwiches

The final part of this investigation focused on studying the dynamic response of the single fibre reinforced foams. The load-displacement traces for the hybrid tube reinforced 130 kg/m3 foams are shown in Figure 14. The corresponding curve for the plain foam is also included in the figure. All of the traces for reinforced foam exhibit similar trends, with the force rising rapidly to a maximum value, before a significant drop followed by a highly oscillatory response. A comparison of the traces for quasi-static loading (Figure 6) and the dynamic loading (Figure 14) indicates that the plateau values for the tube-reinforced 130 kg/m3 form at dynamic rates is approximately 20-30% lower than its quasi-static value. This strain-rate effect is likely to be linked to the rate-sensitivity of the predominant failure mechanisms occurring in the tubes, most particularly matrix-dominated failure modes including delamination and splitting.

Figure 15 shows the variation of SEA with the volume fraction of composite tube in the foam core. The figure includes data from a previously-published study on rod-reinforced foams (based on the same three PVC systems considered here) subjected to quasi-static and dynamic loading [27]. The symbols in the figure highlight different diameters of rod or tube embedded in a particular foam. It is interesting to note that the SEA of the rod-reinforced foams increases as the strain-rate is increased whereas the converse is true for the tube-reinforced foams. The figure suggests that rod-reinforced foams based on a higher volume fraction of composite material could potentially out-perform their tube-based counterparts under dynamic loading conditions. The previous investigation showed that the rod-reinforced foams absorbed significant energy absorption through frictional effects between the splaying ends of the composite rod and the steel platen during the crush process. It is possible that rate-effects in the coefficient of friction between the composite and the platen may, in part, be responsible for the enhanced dynamic response.

Finally, Figure 16 compares the quasi-static energy absorption capacity of the tube-reinforced foams with previously published data from tests on a wide range of core systems, including corrugated-cores, aluminium foam, honeycombs, foldcore designs as well as truss and lattices structures [36-43]. An examination of the figure indicates that the reinforced foams compare very favourably to the other core materials, suggesting that they offer potential for use in the design of lightweight energy-absorbing structures. It is possible that the maximum values could be further increased by using fibre-reinforced thermoplastic tubes, such as carbon fibre reinforced PEEK.

# Conclusions

The energy-absorbing behaviour of composite tube reinforced PVC foam panels for use in lightweight energy-absorbing structures have been studied both experimentally and numerically. Here, a series quasi-static and dynamic compression tests have been conducted on a number of foam panels, reinforced by either hybrid carbon/glass and glass fibre reinforced epoxy tubes.

Tests on the tube-reinforced PVC foam panels have shown that increasing the density of the foam results in an increase in SEA and that increasing the tube diameter serves to increase the measured values of SEA. Embedding the hybrid tubes in the foam serves to greatly increase the load-carrying capability of the tube, with the level of enhancement increasing with foam density. However, the increased ability to absorb energy in the higher density foams is offset by their greater mass. As a result, the specific energy absorption of the samples and panel reinforced with carbon/glass hybrid tubes did not vary significantly with foam density. In contrast, the SEA of the foams reinforced with glass fibres increased steadily with increasing foam density. The numerical model accurately predicted the compressive properties of the tube-reinforced foams, successfully capturing the observed failure modes.

The tube reinforced foams have been shown to exhibit an impressive energy-absorbing capability relative to other core materials, with SEA values of up to 87.7 kJ/kg being recorded under quasi-static testing conditions. However, increasing the strain-rate results in a decrease in the energy-absorbing capability of the reinforced foams, possibly due to the rate-sensitivity of the failure processes occurring in the composite materials. In spite to this reduction, the dynamic values for the SEA of these lightweight cores remain very high.

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Table1. Summary of geometries and measured properties of the glass and hybrid tubes investigated in this study.

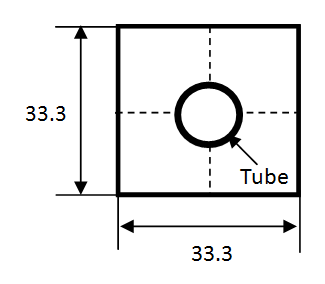
|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Fibre type  Code | Glass  G8 | Hybrid  C8 | Hybrid  C10 | Hybrid  C12 |
| Length (mm) | 20 | 20 | 20 | 20 |
| Inner dia. (mm) | 8.5 | 8 | 10 | 12.5 |
| Outer dia. (mm) | 12.7 | 10 | 12.7 | 15.2 |
| Thickness (mm) | 2.1 | 1 | 1.35 | 1.35 |
| D/t | 4.05 | 8.0 | 7.41 | 9.26 |
| Mass (g) | 2.58 | 0.97 | 1.5 | 1.8 |
| Energy (J) | 79.9 | 65.7 | 111.3 | 161.7 |
| SEA (kJ/kg) | 31.0 | 67.7 | 74.2 | 89.8 |

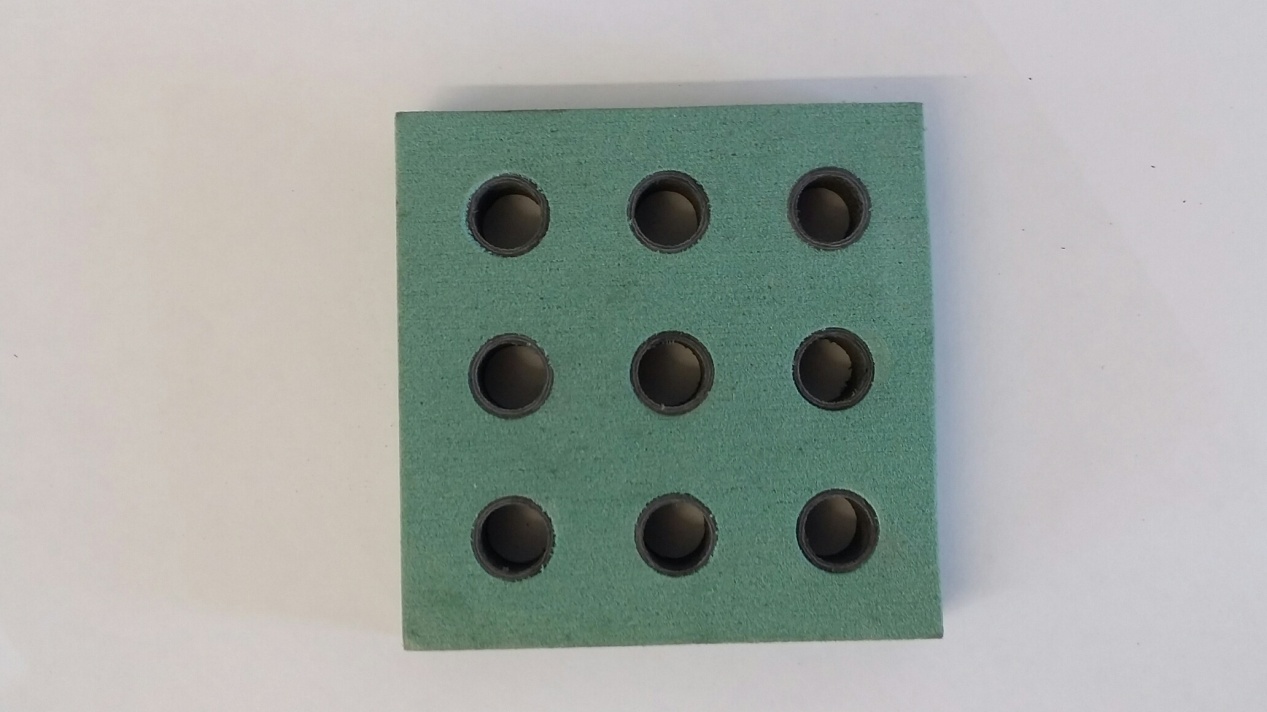
Table 2.Summary of the panel convention for the tube reinforced sandwich panels.

|  |  |  |  |
| --- | --- | --- | --- |
| Foam | C40 | C80 | C130 |
| 8 mm I/D hybrid fibre tube | C40C8 | C80C8 | C130C8 |
| 10 mm I/D hybrid fibre tube | C40C10 | C80C10 | C130C10 |
| 12.5 mm I/D hybrid fibre tube | C40C12 | C80C12 | C130C12 |
| 8 mm I/D glass fibre tube | C40G8 | C80G8 | C130G8 |

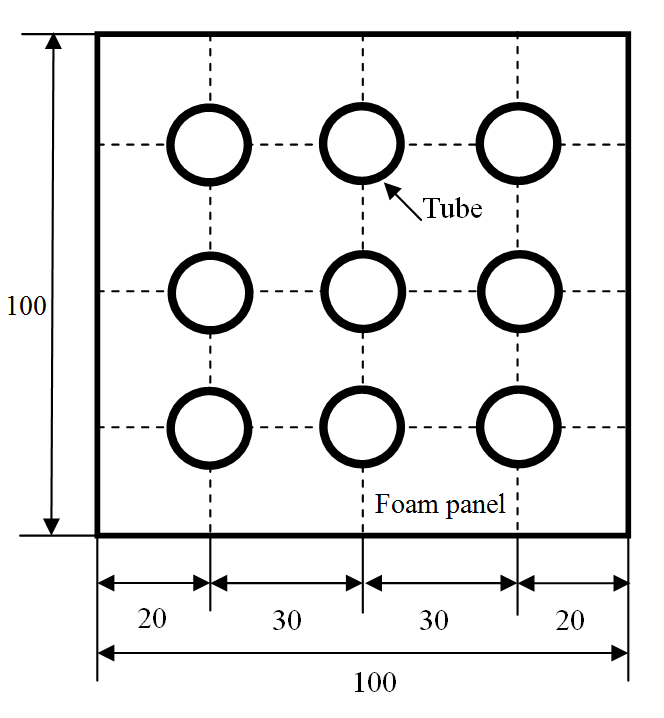
Table 3. Summary of the compression strengths and energy absorption properties of the tube reinforced foams

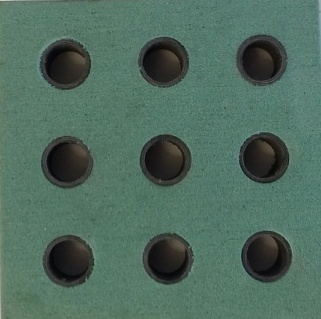
|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Spe**c**imen details | | | Quasi-static | | | Dynamic | | |
| Specimen ID | Volume (%) | Mass (g) | Strength (MPa) | Energy (J) | SEA (kJ/kg) | Strength (MPa) | Energy (J) | SEA (kJ/kg) |
| C40 plain | - | 0.9 | 0.6 | 7.8 | 9.0 | 0.7 | 10.4 | 7.9 |
| C40C8 | 7.1 | 1.8 | 10.8 | 109.7 | 61.1 | 24.3 | 103.4 | 57.6 |
| C40C10 | 11.4 | 2.3 | 16.1 | 162.2 | 70.9 | 37.1 | 148.1 | 64.7 |
| C40C12 | 16.3 | 2.5 | 19.6 | 214.7 | 84.4 | 46.8 | 185.0 | 72.7 |
| C40G8 | 11.4 | 3.4 | 22.7 | 139.0 | 41.3 | 54.4 | 165.9 | 51.9 |
| C80 plain | - | 1.7 | 1.8 | 23.6 | 13.5 | 2.3 | 34.4 | 9.3 |
| C80C8 | 7.1 | 2.6 | 11.7 | 164.0 | 62.6 | 21.5 | 117.8 | 44.9 |
| C80C10 | 11.4 | 3.1 | 19.0 | 229.2 | 74.5 | 37.5 | 172.6 | 56.1 |
| C80C12 | 16.3 | 3.3 | 23.8 | 288.4 | 87.7 | 47.4 | 224.6 | 68.3 |
| C80G8 | 11.4 | 4.2 | 33.4 | 211.5 | 50.9 | 57.4 | 220.3 | 53.0 |
| C130 plain | - | 2.8 | 4.4 | 44.8 | 15.8 | 5.3 | 69.4 | 10.1 |
| C130C8 | 7.1 | 3.7 | 12.8 | 219.2 | 60.0 | 25.9 | 137.8 | 37.7 |
| C130C10 | 11.4 | 4.1 | 22.8 | 278.4 | 68.6 | 46.6 | 199.9 | 49.2 |
| C130C12 | 16.3 | 4.2 | 26.0 | 342.4 | 81.2 | 54.9 | 259.6 | 61.6 |
| C130G8 | 11.4 | 5.1 | 44.3 | 323.0 | 62.9 | 63.8 | 230.6 | 44.9 |





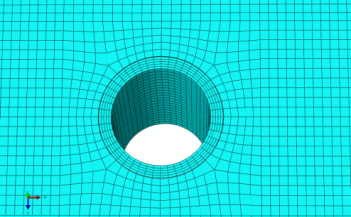
1. Example of a C130 foam reinforced with a single hybrid tube.

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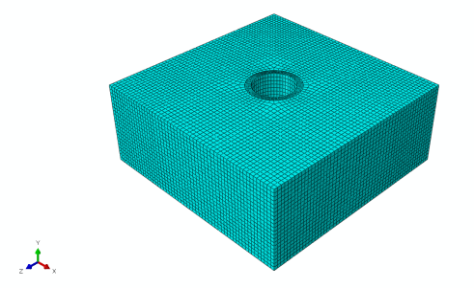
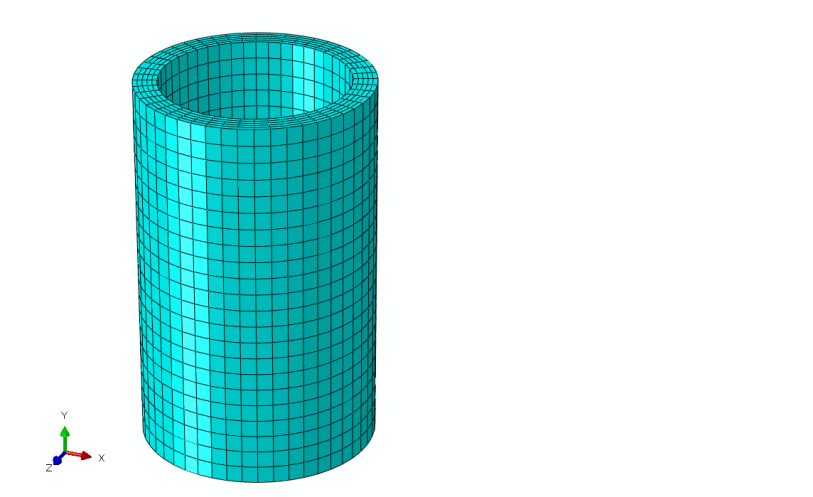
(b) Example of a C130C10 sample reinforced with multiple hybrid tubes.

Figure. 1. Configurations of the reinforced foams.



o d

i d

(F)

h=20 mm

Figure 2 The geometry, mesh, boundary and loading conditions of the tube reinforced foam model.

C8 (D/t = 8)

C12 (D/t = 9.3)

C10 (D/t = 7.4)

Fig. 3a Typical load-displacement traces following crush tests on individual tubes with different diameters. The solid lines correspond to test data and the dashed lines to the predictions of the FE model.

G8 (D/t = 4.1)

C12 (D/t = 9.3)

Fig. 3b Comparison of the load-displacement response of a glass fibre and hybrid tube. The solid lines correspond to hybrid tube and the dashed lines to the glass fbre tube.

|  |  |  |
| --- | --- | --- |
| Disp. | Hybrid fibre tube | Glass fibre tube |
| 1 mm | E:\104_FUJI-specimen\201306Tube reinforced foam\DSCF7332.JPG | E:\104_FUJI-specimen\201306Tube reinforced foam\DSCF7349.JPG |
| 5 mm | E:\104_FUJI-specimen\201306Tube reinforced foam\DSCF7336.JPG | E:\104_FUJI-specimen\201306Tube reinforced foam\DSCF7352.JPG |
| 10 mm | E:\104_FUJI-specimen\201306Tube reinforced foam\DSCF7340.JPG | E:\104_FUJI-specimen\201306Tube reinforced foam\DSCF7353.JPG |
| 15 mm | E:\104_FUJI-specimen\201306Tube reinforced foam\DSCF7341.JPG | E:\104_FUJI-specimen\201306Tube reinforced foam\DSCF7359 ok4.JPG |
| 18 mm | E:\104_FUJI-specimen\201306Tube reinforced foam\DSCF7344.JPG | E:\104_FUJI-specimen\201306Tube reinforced foam\DSCF7364.JPG |
| Top view | E:\104_FUJI-specimen\201306Tube reinforced foam\DSCF7261.JPG | E:\104_FUJI-specimen\201306Tube reinforced foam\DSCF7374.JPG |

Fig. 4a. The failure processes in the hybrid and glass fibre tubes following quasi-static compressive testing.

|  |  |
| --- | --- |
| TEST | FE |
| E:\104_FUJI-specimen\201306Tube reinforced foam\DSCF7336.JPG | Tube-FE-2Layer-v9-3 |
| E:\104_FUJI-specimen\201306Tube reinforced foam\DSCF7340.JPG | Tube-FE-2Layer-v9-4 |
| E:\104_FUJI-specimen\201306Tube reinforced foam\DSCF7341.JPG | Tube-FE-2Layer-v9-5 |
| E:\104_FUJI-specimen\201306Tube reinforced foam\DSCF7261.JPG |  |
| DSCF8021 | Tube10-FE-V3-ZHGEN-V7-11 |

Fig. 4b Comparison of experimental and predicted deformation and failure modes for the 10 mm CFRP tubes.

Embedded tube

Individual tube

Foam

Foam+ tube

Fig. 5 Comparison of the compression load-displacement traces for the C130 plain foam, an individual hybrid tube with an inner diameter of 12.5 mm (D/t=9.26) and a similar tube embedded in the 130 kg/m3 foam. The solid lines correspond to test data and the dashed lines to the predictions of the FE model.（The green dash line is FE extracted load-displacement traces for a foam supported tube and blue solid line is load-displacement traces for an individual tube without foam support.）

12.5 mm

10 mm

8 mm

Foam

Fig. 6a Compression tests on 130 kg/m3 foam samples containing a single hybrid tube. The inner diameter of the tube is indicated. The sample have GFRP skins. The solid lines correspond to test data and the dashed lines to the predictions of the FE model.

|  |  |
| --- | --- |
| Test | FE |
| D:\我的资料库\Documents\Jin LIVPC\201311 Tube foam Fmls pic\DSCF9682.JPG | TubeFoam-mesh2-NoClamp-v1-18 |
| C130T8 | |
| D:\我的资料库\Documents\Jin LIVPC\201311 Tube foam Fmls pic\DSCF9673.JPG | TubeFoam-mesh2-NoClamp-v1-20 |
| C130T10 | |
| D:\我的资料库\Documents\Jin LIVPC\201311 Tube foam Fmls pic\DSCF9656.JPG | TubeFoam-mesh2-NoClamp-v1-22 |
| C130T12 | |
| a. comparison of the cross-sections | |
| Tube-foam-2layers-V2-23 | TubeFoam-mesh2-NoClamp-v2-18 |
| b. FE simulation | |

Fig. 6b Comparison of the cross-sections and deformation/failure modes in the crushed tube-reinforced foam panels.

C130

C80

C40

Fig. 7. Compression tests on three grade of PVC foam containing a single G8 glass fibre tube. The samples have GFRP skins.

Fig. 8. The influence of tube diameter and foam density on the enhancement in force associated with embedding the tubes in the foam.

12.5 mm

8 mm

10 mm

1. C80

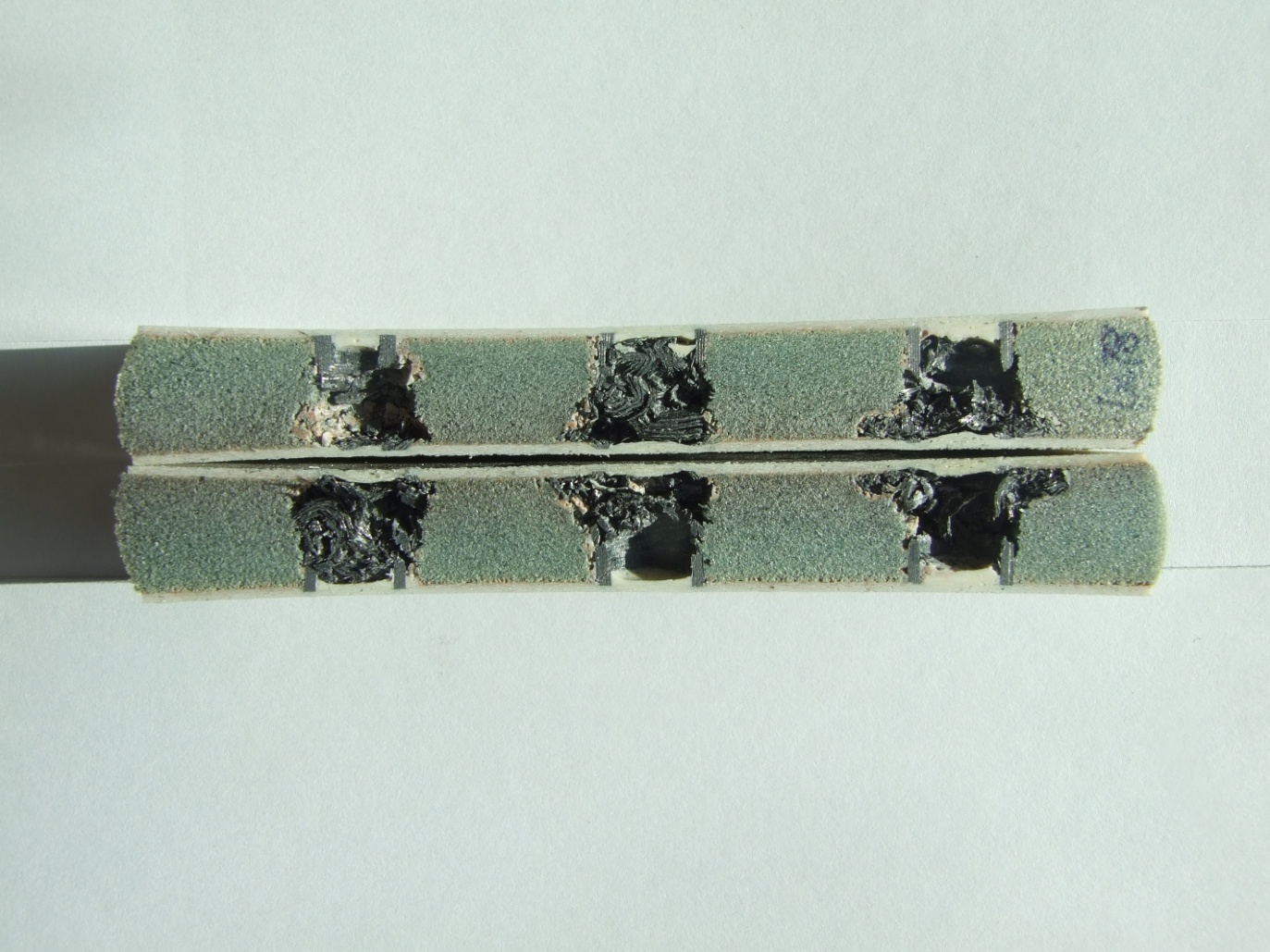
12.5 mm

10 mm

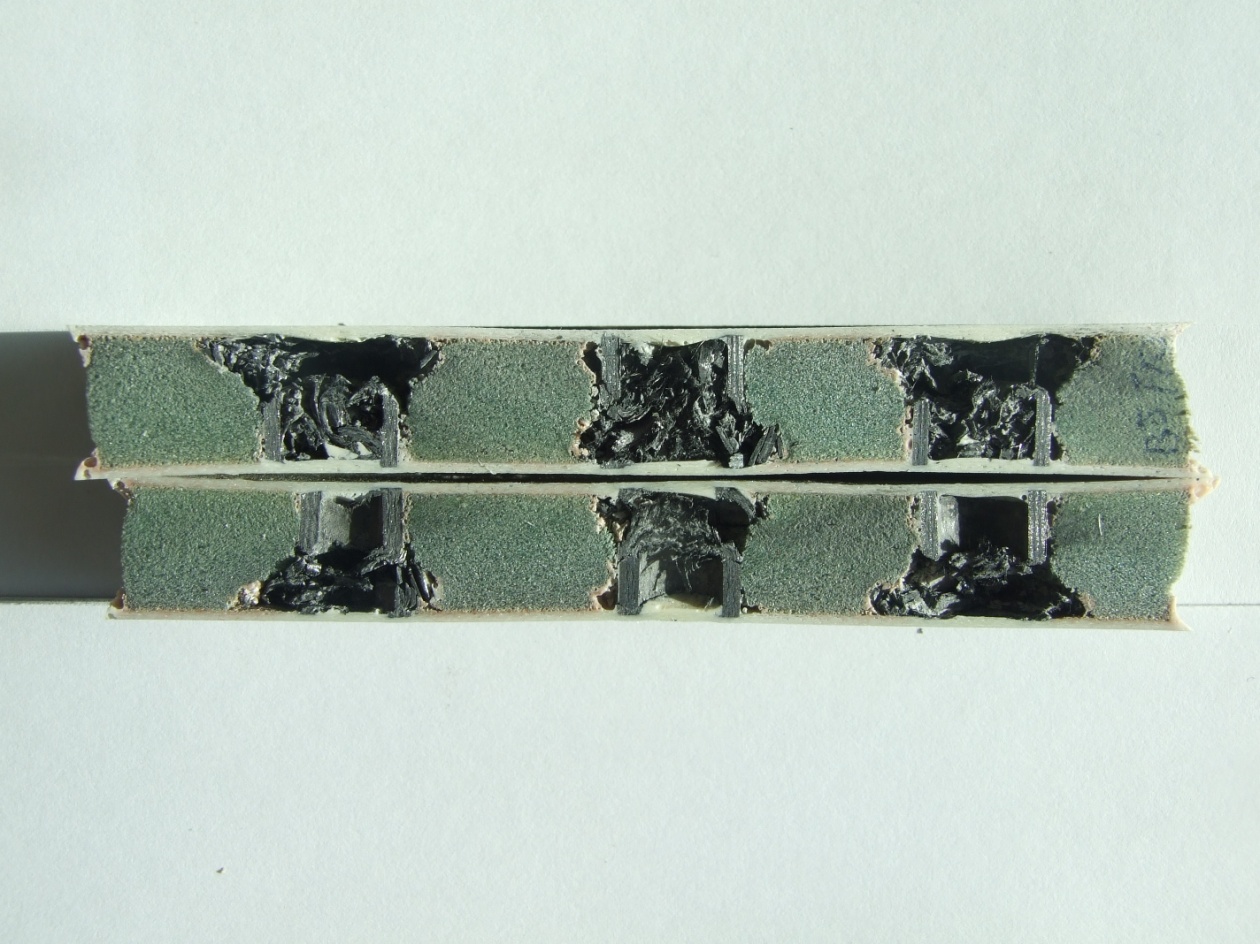
8 mm

1. C130

Fig. 9. Load-displacement traces following compression tests on sandwich structures containing nine hybrid tubes (a) C80 foam (b) C130 foam.



C130T8



C130T10



C130T12

20 mm

Fig. 10. Cross-sections of samples following quasi-static compressive testing on the nine hybrid tube reinforced 130 kg/m3 foams.

Fig. 11. The influence of tube diameter and foam density on the enhancement in the plateau force for the tube reinforced foams.

Fig. 12. The influence of tube diameter and foam density on the energy-absorbing characteristics of the composite tube reinforced foams.

C12

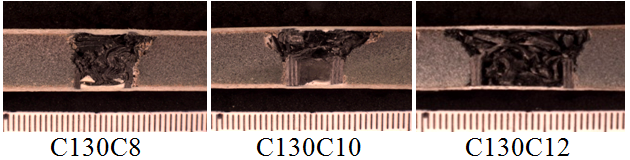
C10

C8

G8

Plain foam

Fig. 13. The influence of tube diameter and foam density on the specific energy absorbing of the composite tube reinforced foams.



Plain foam

12.5 mm

8 mm

10 mm

Fig. 14 Load-displacement traces of the 130 kg/m3 foam reinforced by either a simple 8, 10 or a 12.5 mm hybrid tube subjected to dynamic loading. The samples have 0.8 mm thick GFRP skins.

Rod

Dynamic

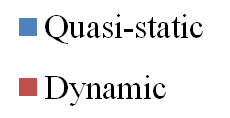
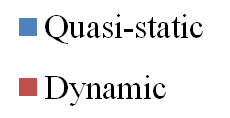
Tube

Quasi-static

Dynamic

Quasi-static

Fig. 15. The influence of the composite volume fraction on the specific energy absorbing characteristic of the tube-reinforced and rod-reinforced composites. Rod-reinforced data is taken from Ref. 13.

Fig. 16. The comparison on the specific energy absorbing characteristics between various core structures. Data taken from references [35-42].