

# The energy-absorbing properties of a novel cellular structure

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The energy-absorbing characteristics of a novel lightweight composite cellular structure have been evaluated. The cellular composite material is fabricated from resin-impregnated fabric sheets convoluted into a regular three-dimensional cellular structure. Specific energy absorption values,  $E_s$ , of greater than  $100 \text{ kJ kg}^{-1}$  have been achieved with a load uniformity approaching unity. The cell wall thickness, cell diameter and fabric orientation in the multilayer cell wall affect the energy absorption capability and determine the stability of the collapse mode. High energy-absorption values result from a controlled microscale progressive failure in compression which occurs in incremental steps equal to the inter-yarn spacing.

## 1. Introduction

This work concerns the energy-absorbing characteristics of a novel lightweight honeycomb structure termed "cellular composite" in a recent patent [1]. Cellular composite is a rigid multitubular structure which comprises a single sheet of constructional material convoluted to form a series of tubular cells without the need to bond together individual tube elements (Fig. 1a). The resulting flat panel can be produced in discrete thicknesses of double the diameter of the former rod used to fabricate the panel, and either cut down to short sections (resembling conventional honeycomb materials) (Fig. 1b) or used as a lightweight honeycomb panel in its own right (Fig. 1c). This makes the structure highly versatile since it can be used as a beam element or panel, or as a normal honeycomb core. The properties of cellular composite as a panel material are the subject of other publications [2, 3]. Here the unusually good energy-absorbing characteristics of the structure along the cell axis are examined.

Energy absorbers are found wherever there is a need to cushion out unnecessary jolts and bumps and where protection against impact damage is needed. There are two basic types of energy absorbers, re-usable devices such as pistons and gas bags [4] and "one-shot" devices such as frangible tubes [5] and crushable honeycombs [6]. The ability of the latter to absorb energy relies on their destruction and as a consequence a successful one-shot absorber will be one in which not only the specific energy absorption is high but also one in which the failure mechanisms and rates and hence force-deflection characteristics can be accurately predicted.

Foremost among "one-shot" devices at the current time are composite tubes [6, 7] which absorb energy by crushing along the longitudinal axis. Values in excess

of  $100 \text{ kJ kg}^{-1}$  are achieved in comparison to a maximum of  $90 \text{ kJ}$  for common metallic devices. Equally desirable are the constant load-deflection characteristics, which show little fluctuation about a mean level of crush load and nearly approach the characteristics of an ideal energy absorber (Fig. 2a). Metallic devices, despite high specific energies absorbed, typically show large and unpredictable fluctuations (Fig. 2b) about a "mean" crush load level. Current research suggests that when composite tubes are crushed much energy is absorbed because although the process is essentially brittle, fine-scale progressive fracture results in the destruction of the material to a finely powdered form.

## 2. Fabrication and test methods

Cellular composite is prepared by convoluting a single sheet of constructional material around PTFE-coated former rods which are held in place in a rigid alignment jig. The structure can be prepared by wet lay-up or more efficiently by the use of pre-impregnated woven fabric (prepreg) which allows close tolerances on cell diameter and wall thickness. The structure is prepared in discrete sizes of double the former rod diameter plus the respective thicknesses of the cell walls, which can be varied from just one layer of prepreg to as many layers as is possible to convolute around the former rods. In this study the former rods were of diameters 4.2, 6.2 and 11.2 mm and the wall material was a pre-impregnated eight-harness satin woven glass-epoxy composite (Ciba-Geigy 916). The ply thickness was 0.3 mm. Composite structures were therefore fabricated with inner cell diameters of 4.2, 6.2 and 11.2 mm with wall thicknesses which varied between 0.3 and 1.5 mm in increments of 0.3 mm.

Compression test specimens were cut from cellular composite samples to give a ratio of tube length to outer tube diameter of 3. The energy-absorbing

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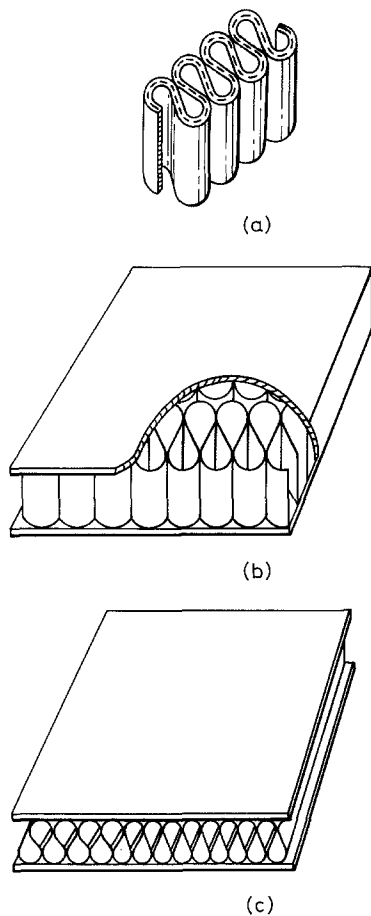


Figure 1 (a) The cellular composite structure; (b and c) sandwich beams with cellular composite core.

characteristics of the structure were studied as a function of the number of tube elements in the specimen, the test speed, the ratio of cell wall thickness  $t$  to cell diameter  $D$ , and the fibre orientation  $\theta$ . The effects of triggering mechanisms for controlled failure initiation were also studied in thick-walled samples.

Static compression tests were performed on an Instron 1195 screw-driven testing machine with a maximum load capacity of 100 kN and test rates between 1 and 500 mm min<sup>-1</sup>. Dynamic crushing tests were carried out on an ESH testing machine with a load capacity (dependent on test speed) of around 150 kN and test rates of up to 4 m sec<sup>-1</sup>.

The energy absorbed by each specimen was calcu-

lated as the area beneath the load–deflection (crush distance) trace. The specific energy absorption  $E_s$  is calculated as the energy absorbed per unit mass of collapsed tube. The load uniformity is the ratio of maximum load reached to the mean crush load. For specimens with irregular crush characteristics in their “stable” region the mean crush load was calculated from the total energy absorbed in that region divided by the crush distance.

### 3. Results and discussion

#### 3.1. Collapse characteristics

Axial compression of the structure resulted in two main modes of collapse, stable and unstable and an intermediate form. Stable collapse was observed to be a steady progressive crushing of the composite material in which small fragments (< 1 mm<sup>2</sup>) were formed but retained some coherency with the structure. Fig. 3a shows that most of the crushed material collects within the centre of the individual tube elements. As crushing progressed this debris formed a hard compact core, increasing the resistance of the structure to further crushing. It can also be seen that some of the failed material has “peeled” from the specimen structure in a “banana peel” fashion. The specimen has an inner cell diameter of 6.2 mm and a cell wall thickness of 0.6 mm. The original length of 35 mm has been crushed by 12 mm at a rate of 1 m sec<sup>-1</sup>. The corresponding load–deflection trace Fig. 3b shows the load rising rapidly to a maximum at which the failure process is initiated, and the subsequent progressive crushing of the material is characterized by a near-constant load–deflection trace.

Unstable collapse was observed particularly in specimens of large cell diameter and low wall thickness or in samples where a critical flaw led to a catastrophic failure at an early stage in the deformation. The onset and timing of unstable collapse was unpredictable. Fig. 4a shows a specimen of cell wall thickness 0.3 mm and cell diameter 6.2 mm. Its original length of 35 mm has been compressed through 12 mm at a rate of 1 m sec<sup>-1</sup>. A catastrophic failure has been caused by a crack spreading quickly across the width of the specimen, allowing the top half to collapse in on the bottom half in a telescopic manner. This is a low-energy process, involving the propagation of a single

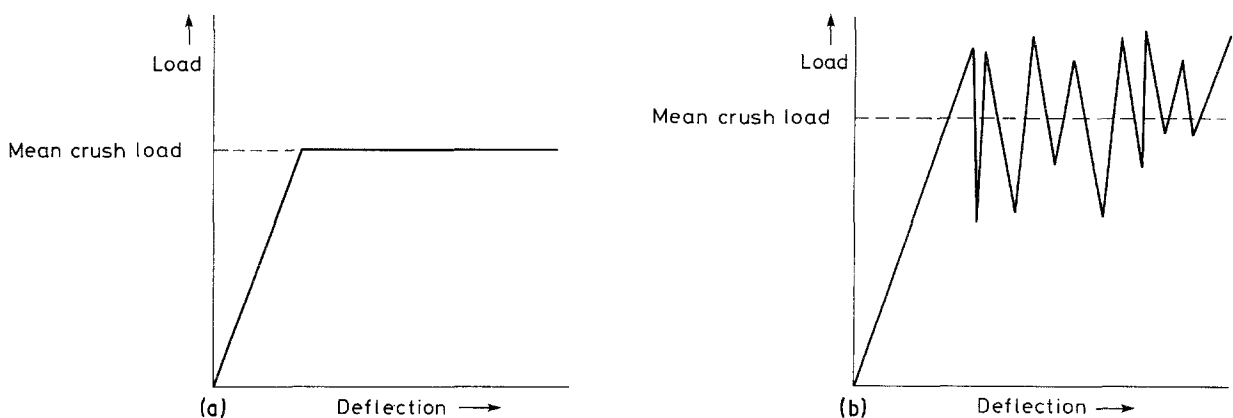


Figure 2 (a) The load deflection characteristic of an ideal energy absorber; (b) the load deflection characteristic of a typical metal tube loaded axially.

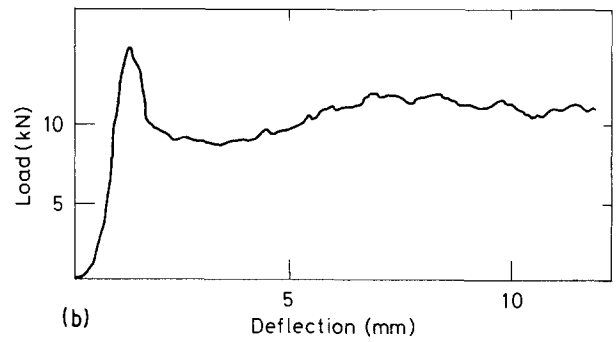
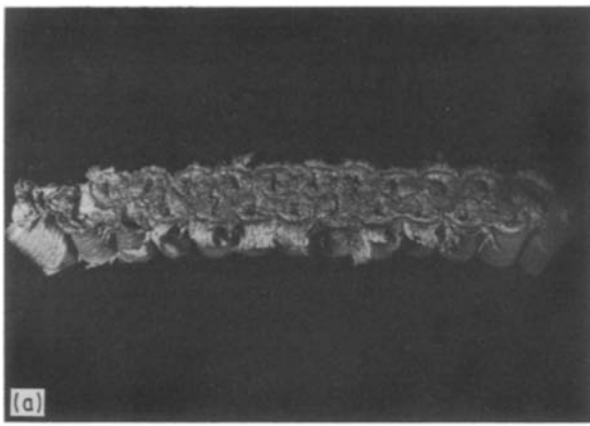


Figure 3 (a) Cellular composite crushed under stable conditions; (b) the load deflection trace for Fig. 3a.

crack and weak interpenetration of the two halves. The load–deflection trace for this sample (Fig. 4b) shows a rapid rise in load level to that required to propagate the crack, followed by an equally rapid decline and then a constant and very low mean crush load associated with the interpenetration of the two sets of tube elements.

Intermediate forms of structural collapse involve some material crushing and some interpenetration of the tube elements. Fragments are of a larger size than those encountered in the stable crush mode. This infers that less energy is needed to create them. The associated load–deflection trace shows a rise to the failure initiation load, followed by a load–deflection trace which fluctuates about a mean load intermediate between that found in stable and unstable collapse.

### 3.2. The effect of inner cell diameter and cell wall thickness on energy absorption

In general for constant wall thickness the specific energy absorption decreases as the cell diameter increases. Similarly, for constant cell diameter the specific energy absorption increases as the wall thickness increases. The combined effects of the variables are made clear in Fig. 5, which is a plot of specific energy absorption against the ratio of cell wall thickness to cell diameter. As this ratio increases so does the specific energy absorbed. The increasing trend tails off at high ratios, indicating a limiting value of energy absorbed which might be difficult to achieve practically

because of fabrication difficulties. It was also apparent that the type of failure encountered (stable or unstable) was highly dependent on the wall thickness to cell diameter ratio. All specimens of cell diameter 11.2 mm failed in an unstable fashion while all specimens of diameter 4.2 mm exhibited stable collapse characteristics. This indicates that for this structure (as has been found by other workers [6]) there is a wall thickness to diameter ratio at which a boundary exists between stable and unstable collapse. The position of this boundary must necessarily depend on material type and fabric structure, but 6.2 mm diameter samples with 0.3 mm thickness often failed in a mixed mode. The plot of load uniformity against the ratio of cell wall thickness to cell diameter (Fig. 6) shows a significant improvement in load consistency at high ratios. A load uniformity of unity is exhibited by an ideal absorber. It should be noted that the load uniformity of the cellular composite specimens with  $t/D$  ratios of more than 0.05 are approaching that value.

### 3.3. The effect of test rate on energy absorption

The specific energy absorption of the structure changes little with test rate (Fig. 7) above a certain critical aspect ratio. The values plotted were measured for cellular composite of inner cell diameter 6.2 mm and cell wall thickness 0.4 mm which from the original “static” tests was found to be well within the range of aspect ratios leading to stable collapse. Test speeds

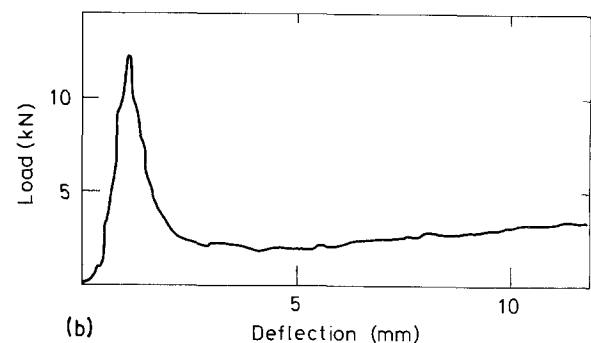
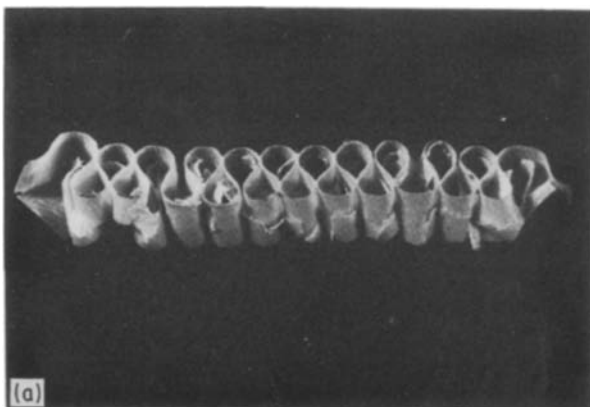


Figure 4 (a) Cellular composite crushed in an unstable fashion; (b) the load deflection trace for Fig. 4a.

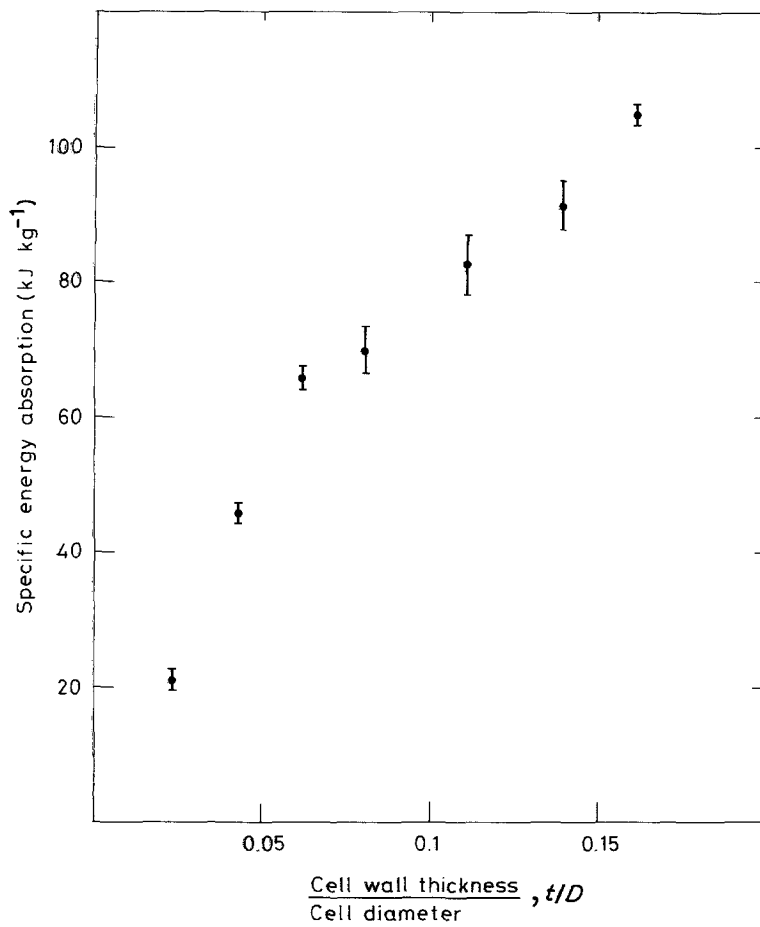


Figure 5 Specific energy absorption as a function of cell wall thickness to cell diameter ratio. Bars indicate standard errors of means.

from  $3 \text{ mm sec}^{-1}$  to  $1 \text{ m sec}^{-1}$  caused little or no variation in the energy absorbed where stable collapse occurred. High test rates increased the incidence of unstable collapse, and where this occurred the specific

energy absorption was correspondingly reduced. Where the cell wall thickness was large enough to allow a  $45^\circ$  bevel to be machined at one end of the specimen (i.e. those specimens of cell wall thickness, above 0.9 mm) it was found that unstable collapse even at high test rates, was eliminated and the load uniformity was reduced to almost unity.

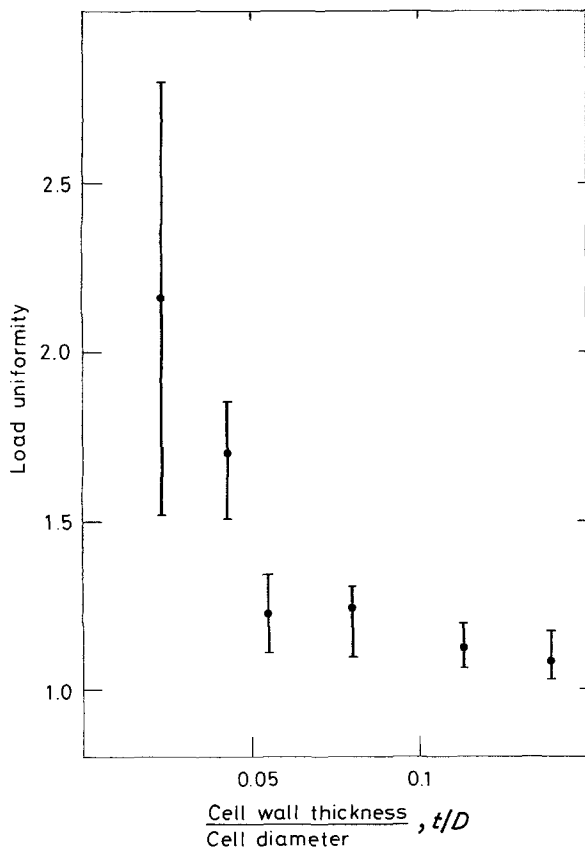


Figure 6 Load uniformity as a function of cell wall thickness to cell diameter ratio. Bars indicate the maximum scatter.

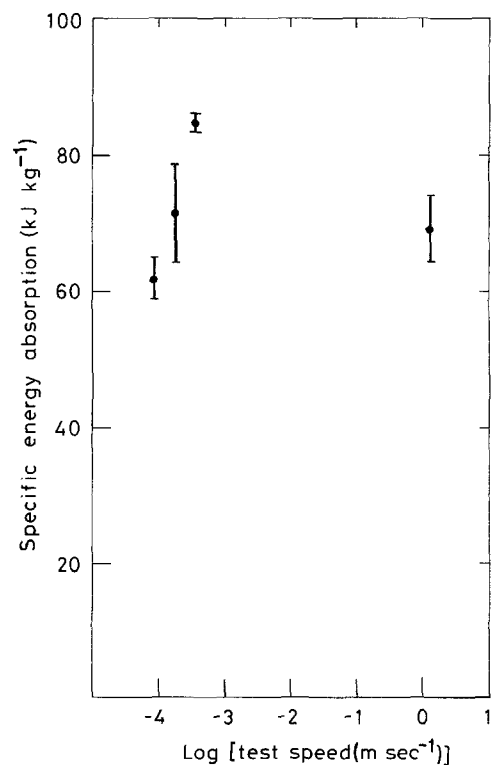


Figure 7 Specific energy absorption as a function of test speed. Bars indicate standard errors of means.

TABLE I The effect of fabric construction on the energy-absorbing characteristics of selected cellular composites

Inner tube diameter (mm)	Tube wall thickness (mm)	Orientation	Test speed (m sec <sup>-1</sup> )	Specific energy (kJ kg <sup>-1</sup> )	Load uniformity
6.2	0.9	3 × (0°/90°)	1.6 × 10 <sup>-4</sup>	80.7	1.30
6.2	0.9	0°/90°/45°/45°/90°/0°	1.6 × 10 <sup>-4</sup>	97.9	1.11
6.2	1.5	5 × (0°/90°)	3.3 × 10 <sup>-5</sup>	103.0	1.01
6.2	1.5	0°/90°/45°/45°/90°/0°/45°/45°/90°/0°	8.3 × 10 <sup>-4</sup>	104.4	1.02

### 3.4. The effect of fabric orientation on energy absorption

On their own, 45°/45° plies in the cellular structure have inferior energy absorption characteristics to 0°/90° plies. This is not a surprising result since in the latter specimens the load is applied along the fibre axes rather than at 45° to them, and therefore it meets more resistance. However, when combined with 0°/90° plies, 45°/45° plies produce a marked improvement in specific energy absorption as shown in Table I. Thornton and Edwards [6] suggested that delamination between adjacent plies of composite material could have an advantageous effect on energy absorption when it encourages crushing and disintegration. In the cellular structure with a compressive force applied to alternate 0°/90°, 45°/45° plies, the force possibly causes individual plies to rotate with respect to each other such that shear displacements or interlaminar splitting must occur (Fig. 8). Interlaminar splitting is a relatively energy-intensive process and should contribute significantly to the overall energy-absorbing capacity of the structure. The major mechanism contributing to high energy absorption is the progressive propagation of cracks between fibre and matrix as the crack damage passes along the specimen. As each microcrack progresses, individual fibres are left unsupported and subsequently buckle and fail.

This process can be an unsteady one with low energy absorption if the crack is localized, leaving relatively long sections of fibres unsupported and easily buckled. The bond between fibre and matrix should be sufficiently strong to prevent uncontrolled propagation of the crack, but not so strong as to prevent the separation of the two phases which is itself the energy-absorbing mechanism. High *t/D* ratios promote the

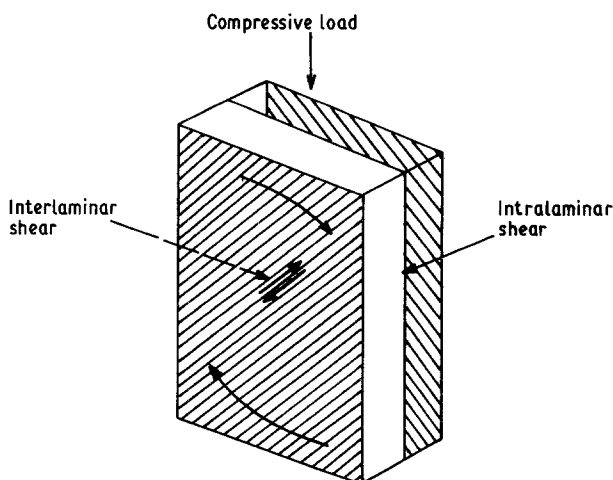


Figure 8 Shear displacements under compression in a composite laminate.

preferred failure mode. In addition 90° fibres slow down the failure process by diverting the progress of potentially long cracks. The cellular composite structure was fabricated from a satin weave fabric with a high number of interlacing points between warp and weft yarns. As cracks spread down the warp yarns they meet the weft yarns running perpendicular to them. These effectively halt the progress of the crack until enough stress builds up to break through these barriers and repeat the process again. Hence it is suggested that the crack spreads in discrete units of length equivalent to the distance between the weft yarns. One way of ensuring good crack blocking would be to select a fabric with the maximum number of warp–weft crossover points, such as a plain weave. The yarns should also be relatively thin to ensure that the crack only propagates in small increments. If load–deflection traces are examined it can be seen that the load rises by an increment and then stays constant over an increment of length of about 0.3 mm (the yarn thickness). It then builds up another increment before again staying constant over another increment of displacement, thus confirming this mechanism.

### 4. Conclusions

The cellular composite structure absorbs energy efficiently, attaining specific energy absorption values in excess of those found in single composite cylinders with comparable aspect ratios. The superior performance of cellular composite lies in the extra stability imparted to each tube element by its nearest neighbours, and in the containment of crushed debris within the centre of individual tube elements, creating a more stable and crush-resistant structure. The energy absorption characteristics of the structure with a trigger bevel at one end closely approach those of an ideal absorber, allowing confidence in performance prediction.

Furthermore, the geometry of the structure and its mode of manufacture give it distinct advantages over single composite cylinders. The cell wall thickness and diameter can be varied to suit a particular application, and the structure can then be formed into specific shapes and sections to allow its incorporation into existing components, such as motor vehicle bodies. The simple manufacturing route, employing commercially available prepregged fabrics, allows flexibility in the design of energy-absorbing surfaces to suit the geometrical requirements of the substrate structure.

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