Cellular Textile Composite: Configuration and Energy Absorption Mechanisms

P. Xue^a, X.M. Tao^b and T.X. Yu^a

^a *The Hong Kong University of Science and Technology*

^b *The Hong Kong Polytechnic University*

This chapter discusses the energy-absorption mechanisms of a class of cellular textile composites in macro and meso scales. An ideal cell configuration was proposed based on experimental observations and theoretical analyses. The effects of geometric parameters on the energy-absorbing capacity were investigated, leading to an optimal design of the cell geometry and cell distribution. Both elastic and rigid-plastic deformation models were formulated to describe the deformation process of a flat-topped conical cell, and to predict its load-displacement and energy dissipation characteristics. Comparisons showed that the theoretical predictions agree well with the experimental results.

3.1 Engineering Background

Energy-absorption capacity has become a major concern in selecting materials and designing structures for many engineering applications. It is of particular importance for materials and engineering structures subjected to collision or impact loads during service. Energy absorbers widely used in automobiles in order to arrest the vehicle and avoid subsequent impacts; the safety hardware used on roadway network, such as guardrails, various effective energy-absorption systems, and different auxiliary protective devices, like bicycle helmets, hard hats and bullet-proof jackets are all required to possess high energy-absorption capacity. Polymer foams and honeycombs used for packaging and cushion materials of electronic components or fragile goods are also designed to absorb impact energy during transportation.

Although the energy-absorbing components are designed and applied for different cases, the requirements for them are basically similar. As summarized

by Johnson & Reid [1] and Yu [2], the energy-absorbing components should satisfy the following requirements:

- The energy-absorbing components should utilize the dissipation processes such as plastic deformation, rather than elastic deformation as its major energy-absorption mechanism.
- While providing sufficient total energy-absorption capacity, the peak force (thus the deceleration) must be kept below the threshold that would cause damage or injury.
- The deformation stroke should be long, stable, repeatable and reliable under impact condition. It is desirable to have a constant reactive force.
- The energy-absorbing components should be light itself, possessing high specific energy-absorption capacity (i.e. energy-absorption capacity per unit weight).
- The manufacture and maintenance of such energy absorption devices should be easy and cost-effective.

Evidently, these requirements to the structural components are quite different from those aimed to sustaining high stress or high strain.

Cellular structures or cellular materials usually contain a large amount of space and display high specific energy absorption capacity, hence they may be used for energy absorption purpose, such as metal tube arrays [3-4], conical shells [5], honeycombs, foams and woods [6-7], etc.

On the other hand, textile structures consist of assemblies of fibers with certain orientations and low packing density. They can be deformed easily into required configurations. Therefore, with appropriate material system, fiber architecture, processing technique, and geometry of the cell's structure, combining the excellent characteristics of textile structures and cellular materials, cellular textile composites can be ideal candidates meeting the requirements for energy-absorption purpose.

Starting from early 1997, our research groups in HKUST and HKPolyU have formed an interdisciplinary research team to conduct a systematic investigation into the energy-absorption capacity of cellular textile composites. A new class of cellular textile composites with high specific energy-absorption capacity has been developed and studied thoroughly. In this paper, we merely report our research results on the optimization for the cell configuration of the cellular textile composite and their energy-absorbing mechanisms.

3.2 Initial Design and Improvement of the Grid-domed Textile Composites

Double jersey (1×1 rib) fabric made from multi-filament textured nylon yarn (DJ-N) were manufactured in a laboratory of Hong Kong Polytechnic University. The originally flat fabrics were formed into 3D cellular textile composites by a two-step method at HKUST. The fabric was shaped into a grid-domed sheet with cells comprising a truncated conical shell and a hemispherical dome (referred as

Configuration 1), then followed by a heat setting treatment at 200°C for 5 minutes.

Polyester resin was used with 1% methylethyl ketone peroxidie (MEKP) as the initiator and 0.5% cobalt naphthenate as the accelerator. The textile preforms were coated with this mixture, then cured at room ambient conditions. The cure cycle of resin was 7 days. A typical sample of DJ-N is shown in Fig. 3.1.

Fig. 3.1 A grid-domed DJ-N sample of Configuration 1

As observed in quasi-static and impact tests, the large deformation process for a cell with Configuration 1 consisted of three stages, *i.e.* the local inversion of the hemispherical dome, the global plastic collapse of the truncated spherical cap and the large plastic deformation of the truncated conical shell. It is also proved [8] that most of the energy-absorption capacity of the grid-domed composite come from the membrane-force-dominated large plastic deformation of the truncated conical shells. Therefore, a new cell configuration, Configuration 2 as shown in Fig. 3.2, was proposed, in which each cell contains a flat-topped truncated conical shell only.

Fig. 3.2 A grid-domed textile composite sample of Configuration 2

Fig. 3.3 Load-displacement curves for samples of Configurations 1 and 2 under quasi-static compression

Both types of samples with Configurations 1 and 2 were tested under identical quasi-static and impact conditions. The material system, resin add-on and the fabrication conditions of the samples were identical, too, for samples of two configurations. Samples containing 4 cells were used for quasi-static compression tests and samples containing 20 cells were used for impact tests. For impact tests,

the samples was 100mm×100mm in size, 10.5g in weight, 13.8mm in height and 155-162% in its resin add-on percentage.

Quasi-static compression tests were carried out on Instron Universal Material Tester with loading speed of 5mm/min. Impact tests were conducted on GRC 8250 Dynatup Drop Weight Impact Tester. The mass of drop weight, including a plate striker of 120×120×12mm, was 3.85kg. The impact velocity, normal to the plane of the samples, was 3.5m/s. Samples were put on the supporting base of the Tester and were compressed or impacted, respectively, by a flat steel plate.

Figure 3.3 depicts the load-displacement curves under quasi-static compression. Figures 3.4(a) and 3.4(b) show the load-displacement curves and energy-displacement curves under impact loading for the samples of two configurations. Comparing the two kinds of samples under quasi-static and impact conditions, the cells of Configuration 2 behaved elastically at early stage, which was much shorter than that of the samples of Configuration 1. As deformation progressed, the increasing rate of load diminished and the plastic deformation became dominant. The force required for its deformation remained almost constant, and the deformation stroke was long and in a stable mode.

It is obvious from these results that compared with those of Configuration 1, the grid-domed textile composites of Configuration 2 demonstrate higher energy-absorption capacity, more stable deformation mode, lower peak force and almost constant force magnitude during its large deformation process, so it provides an ideal candidate for energy absorption purpose.

Fig. 3.4 (a) Load-displacement and (b) Energy-displacement curves for samples of Configurations 1 and 2 under impact loading

3.3 Effects of Cell Geometry and Cell Distribution upon Energy-Absorption Capacity

3.3.1 Cell geometry

Based on our investigation on geometrical variables [9] it was found that the diameter of the cell top or the semi-apical angle is an effective parameter to control the energy absorption performance when the diameter of cell bottom remains constant.

Figures 3.5(a) and 3.5(b) present the curves of load vs. vertical displacement and the energy per unit weight vs. vertical displacement under the impact velocity of 3.5 m/s and impact energy of 26.0 joules for the samples with the same percentage of resin add-on 170% and the same cell height 13.8mm, but different diameter ratio, d_t/d_b , which changed from 0.22 to 0.72, whilst the corresponding semi-apical angles of the truncated conical shell varied from 26.6° to 10.1° .

From the test results, it is clear that the energy-absorption capacity varies with the diameter ratio, d_t/d_b . A smaller top diameter or a larger semi-apical angle of the truncated conical shell would not be beneficial to the energy-absorption capacity of the composite. The optimal top diameter within the examined parameter range is 10 mm and the corresponding semi-apical angle is about 16° .

Fig.3.5 Effect of diameter ratio on (a) load vs. displacement (b) energy vs. displacement

3.3.2 Cell distribution

As observed in the tests, the cell top and the flat base of the grid-domed composites did not deform notably when the conical wall underwent a large deformation. Therefore, the area of conical wall can be regarded as the effective area in absorbing energy under compression and impact loading. To verify this observation, two sets of samples were produced with the same level of resin add-on. Both sets of samples possessed the same total area of cell walls (the cell wall area of sample No. 1 was 0.98 time of that of sample No. 2), but different cell

number and cell size. The detailed information about the two sets of samples are summarised in Table 3.1.

Sample No.	Top-diameter d_t (mm)	Bottom-diameter d_b (mm)	Cell-height H (mm)	Center distance D (mm)	Cell number
1	10	18	12.4	23	20
2	15	23	12.8	23	14

Table 3.1 Cell size and cell number on a sample

Figures 3.6(a) and 3.6(b) depict the curves of load vs. vertical displacement and the energy per unit weight vs. vertical displacement under the impact velocity of 3.5 m/s and impact energy of 26.0 joules. As seen from these results, changing the size of cells did not affect the energy-absorption capacity of the samples and the magnitude of the load, provided the total effective area of the samples remained unchanged. It is thus concluded that the effective cell wall area of cells dominates the energy-absorption capacity of the grid-domed textile composites when other conditions remain the same. Therefore, we should aim at increasing the effective area within the specified total area so as to enhance the energy-absorption capacity of the samples. Cell density (i.e. the cell number per unit area) is one of the parameters that are related to the effective area. Increasing cell density will result in the increase of the effective area for energy absorption within the same specified projected area, thus raising the energy-absorption capacity of the material. However, further increasing cell density is restricted by the formability of the fabrics.

(a)

(b)

Fig. 3.6 Effect of conical wall area on (a) load vs. displacement curves; and (b) energy vs. displacement curves

3.4 Experimental Observations on Flat-Topped Conical Shell under Axial Compression

3.4.1 Macroscopic Deformation Modes

The macroscopic deformation modes of thin-walled structural components subjected to axial loading greatly affect their energy-absorption capacity. In order to observe the deformation mode of flat-topped conical shell under axial compression, a particularly designed compression test was carried out on Instron Universal Material Tester. Flat-topped samples, with 20 cells and area $100 \times 100 \text{ mm}^2$, were put on the supporting base of the Tester and vertically compressed by a transparent rigid flat plate moving down at a speed of 1 mm/min . The experimental setup is shown in Fig. 3.7. A mirror and the transparent plate used made it possible to observe the deformation process of cells from the top direction.

During compression, a series of photographs were taken from the front-view, side-view and top-view of the samples to record the deformation process of a flat-topped conical shell under axial compression and the geometric details of the collapse mode. Some of the photographs are shown in Fig. 3.8. It is evident that a two-lobe diamond-pattern mechanism was formed. The front-view and side-view of a typical deformed cell are as shown in Fig. 3.9. During the deformation process, the following deformation characteristics were observed:

- 1) The circumferences on the top and bottom circles remained almost unchanged, whilst the cell top simply descended vertically in the large deformation process of the shell.
- 2) During its large deformation under axial compression, the flat-topped conical shell plastically collapsed into a two-lobe diamond-pattern.
- 3) Plastic hinge lines were formed along the top and bottom circles of a cell, as well as along a horizontal circumferential loop at about two third of the height, resulting in two rhombuses on the front and back surfaces of the cell.

Fig. 3.7 Experimental setup of a compression test on grid-domed samples

Fig. 3.8 The front-view (X), the side-view (Y) and the top-view (Z) of deformation process of a flat-topped conical shell under axial compression

(a)

(b)

Fig. 3.9 A deformed cell from (a) front-view, and (b) side-view

3.4.2 Mesoscopic Failure Mechanisms Observed by SEM

For composite materials, internal material failure generally is initiated before any change in its macroscopic appearance or behavior is observed. In this Section, attention is focused on the major features of mesoscopic failure mechanisms in

typical zones. An attempt is also made to correlate the levels of energy absorption with the meso-structural failure process.

Fig. 3.10 Experimental setup of an axial compression test with in-situ SEM observation

For the flat-topped conical shell made of nylon/polyester material system subjected to axial compression, mesoscopic failure mechanisms were in-situ examined by SEM. The experimental setup is shown in Fig. 3.10. The sample coated with gold was put between two parallel steel plates and compressed at a crosshead speed of 0.3mm/min. The images were taken with an interval of every 1mm increase in the crosshead displacement; therefore the mesoscopic failure process in the observed zones was recorded.

Two distinct regions, with different microscopic characteristics, were focused: the region near top of the shell marked by Zone 1, shown in Fig. 3.11, where the material was mainly subjected to a compression, and the region near the plastic hinge line BC marked by Zone 2 where the material mainly underwent a bending deformation. The mesoscopic deformation mechanisms governing these two zones are quite different.

Fig. 3.11 Zone 1 and Zone 2 on a flat-topped conical shell

Fig. 3.12 SEM images showing the evolution of microscopic failure Mechanisms at Zone 1 (70X)

Taking Zone 1 as an example. The SEM images are shown in Fig. 3.12. Within Zone 1, the material was mainly compressed. When the local strain approached 12%, which is the breakage elongation of matrix material (polyester), some cracks were initiated.

As deformation proceeded, these cracks propagated. The cracks propagated preferably through the weakest regions of the composite structure, i.e. through resin-rich regions or interfaces between fibers and matrix. In this process, interface between the fiber and the matrix material failed, resulting in debonding. When a crack had to propagate in the direction normal to a fiber, the fiber breakage eventually occurred. Thus, the main microscopic features of energy dissipation in Zone 1 during the compression process, can be characterised as

- development and propagation of cracks in matrix;
- fiber/matrix interface debonding;
- fiber fracture.

The local out-of-plane buckling and the change of the fabric architecture were observed in Zone 2, i.e. the middle part of the shell wall.

The cracks initiated at the near-top region propagated towards the middle part of the conical shell without causing shell separation. By comparing the images in Zones 1 and 2, it is apparent that the strain in Zone 1 increased more quickly than that in Zone 2; consequently, cracking in Zone 1 occurred earlier than in Zone 2.

For the grid-domed 3D textile composites, the cells collapsed plastically into a diamond pattern, which dominated the total energy absorption. The energy-absorption capacity of the material can be obtained by integrating the area under the load vs. displacement curve in Fig. 3.3. It is observed that the load-displacement curve does not fluctuate notably or drop sharply. This implies that the contribution to the energy-absorption capacity from meso-scopic damages,

i.e. matrix cracking, fiber fracturing and the fiber/matrix debonding, is not very significant. The effect of the meso-scopic damages on macroscopic material response can be observed only when they have been accumulated to a certain level.

3.5 Theoretical Models of Flat-topped Conical Shell under Axial Compression

As described above, the flat-topped conical shell collapses into a two-lobe diamond pattern under axial compression. Because of the complexity of the elastic-plastic transition coupled with the geometric change of the shell, it is difficult to formulate a single analytical model to simulate the entire large elastic-plastic deformation process of the flat-topped conical shell under axial compression. However, it is evident that the shell displays an elastic behavior in the early stage of its deformation, and when the shell experiences large deformation, the elastic deformation becomes negligible. Therefore, it is possible to propose two separate models suitable for different stages and capable of predicting the major characteristics of the shell under axial compression.

3.5.1 Basic Assumptions of Theoretical Models

The deformed configuration of a flat-topped conical shell is schematically depicted in Fig. 3.13(a), with the cross-section of the cell sketched in Fig. 3.13(b).

Fig. 3.13 (a) The configuration of a flat-topped conical cell; (b) Sketch of a vertical cross-section of the cell

The radius of the top and the bottom circles is denoted by a and c , respectively. The height of the cell is H and the semi-apical angle is β , whilst these parameters should meet the relation

$$c = a + H \tan \beta \quad (3-1)$$

Based on the experimental observations (Section 3.4.1), the following assumptions are made in the theoretical modeling:

- 1) The top circle of the cell remains unchanged and simply descends vertically during the deformation process; while the bottom circle of the cell is unchanged and fixed on the base.
- 2) On the position of a horizontal plastic hinge line being formed, the circle deforms into an elongated circle, whilst the perimeter of the horizontal plastic hinge line along the circumferential direction remains constant (so as to reduce the membrane deformation).
- 3) At least one generator of the conical shell remains unchanged in its length and that generator will be specified in the elastic model and the rigid-plastic model, respectively; while all the other generators are under compression.
- 4) The energy dissipated by the shear deformation is neglected.
- 5) In elastic model, the material is assumed to be linearly elastic, and in rigid-plastic model it is rigid plastic.

3.5.2 Theoretical Models

Initially, the shell behaves elastically. According to an equilibrium analysis of the thin-walled conical shell [10] and comprehensive geometric considerations [11], the load-displacement relationship can be expressed as

$$\begin{aligned}
 P &= -2\pi(a + \frac{1}{2}H \tan \alpha)E\bar{\varepsilon} \cos \alpha \\
 &= \frac{\pi(a + \frac{1}{2}H \tan \alpha)E\Delta \cos^3 \alpha}{H} \left(\frac{2}{3} \sin \alpha \sqrt{\frac{6\Delta}{H}} + 1 \right) \quad (3-2)
 \end{aligned}$$

Fig. 3.14 Elongated circle as a horizontal circumferential hinge line.

where E is the Young's modulus of the material, t the wall thickness of the shell, Δ the vertical displacement at the top, and P the vertical load applied.

With the increase of the vertical displacement, the flat-topped conical shell is deformed plastically. The large deformation mode is sketched in Fig. 3.11. Plastics hinge lines are formed along the top and bottom circles, along a horizontal circumferential loop at height $(1-\lambda)H$, as well as along the sides of rhombus ADBF. The geometry of the horizontal circumferential hinge line is shown in Fig. 3.14, where the length of straight line AB is supposed to be equal to that of arc A'B' based on Assumption 2, so the magnitude of b satisfies the following equation

$$b = b_0(1 + \phi - \sin \phi) \quad (3-3)$$

where angle ϕ serves as a process parameter. Because of the orthotropic property of the material, the outward portions of the horizontal hinge line, i.e. arcs AA₁ and BC, take place where the wale direction of the fabric is perpendicular or nearly perpendicular to the generator of the conical shell. The inward portions of the horizontal hinge line, i.e. lines AB and A₁C take place where the wale direction of the fabric is parallel or almost parallel to the generator of the conical shell. Obviously, the shape of the horizontal hinge line, as an elongated circle, evolves with increasing ϕ .

The deformed shapes of cross-sections I-I and II-II during large plastic deformation are sketched in Fig. 3.15(a) and 3.15(b), respectively. The dash line and solid line depict the profile before and after large plastic deformation, respectively. As stated in Assumption 3, the length of the generator on cross-section II-II is assumed to remain constant during large plastic deformation, so that

$$f_1 = \frac{\lambda H}{\cos \alpha}, \quad f_2 = \frac{(1-\lambda)H}{\cos \alpha} \quad (3-4)$$

(a) at cross-section I-I

(b) at cross-section II-II

Fig. 3.15 Sketches of the cell in its plastic deformation stage

Similarly, all other geometric quantities can be expressed in terms of ϕ and λ (refer to [11] for details). Calculations confirm that the generator on I-I is under compression.

In this large deformation model, the material is assumed to be rigid-plastic. The energy is plastically dissipated by bending along the plastic hinge lines as well as by stretching of the wall segments between hinge lines. The first part of energy dissipation can be written as

$$W_b = (W_b)_{top} + (W_b)_{bottom} + 2(W_b)_{AB} + 2(W_b)_{BC} + 4(W_b)_{DA} + 4(W_b)_{AF} \quad (3-5)$$

which is proportional to the plastic bending moment per unit width of the shell wall, M_o .

The second part of the energy dissipation is due to the stretching of the shell segments between the plastic hinge lines, while the change in the wall thickness is assumed to be negligible during stretching. The initial side surface area of the flat-topped conical shell before compression is

$$S_0 = \frac{\pi H}{\cos \alpha} (2a + H \tan \alpha) \quad (3-6)$$

During large deformation, the side surface area is changing. The area of segments ABD, AFB, BCDE and BCFG can be approximately expressed in terms of their side lengths and angles, so eventually depend on ϕ and λ (refer to [11] for details). By considering all those areas, we find

$$W_m = \sigma_y t \sum |S_i - S_{i0}| \quad (3-7)$$

where t is the wall thickness of the shell, S_i is the areas of the segments after deformation and S_{i0} is the initial areas corresponding to S_i . σ_y denotes the flow stress of the material, which may vary with the equivalent strain.

Thus, the total energy dissipation during large plastic deformation of the flat-topped conical shell is

$$W = W_b + W_m \quad (3-8)$$

which should be equal to the external work done by the axial compressive force P during the deformation process. That is,

$$W(\phi, \lambda) = W_b + W_m = \int_0^\Delta P d\Delta \quad (3-9)$$

which results in

$$P = \frac{\partial W(\phi, \lambda)}{\partial \Delta} = \frac{\partial W(\phi, \lambda)}{\partial \phi} \cdot \frac{\partial \phi}{\partial \Delta} = \left(\frac{\partial W_b(\phi, \lambda)}{\partial \phi} + \frac{\partial W_m(\phi, \lambda)}{\partial \phi} \right) \cdot \frac{\partial \phi}{\partial \Delta} \quad (3-10)$$

where the relationship between ϕ and Δ can be obtained as

$$\frac{\partial \Delta}{\partial \phi} = b_0 \sin \phi \left[\frac{(a - b_0 \cos \phi)}{h_1} + \frac{(c - b_0 \cos \phi)}{h_2} \right]$$

whilst $\frac{\partial W_b(\phi, \lambda)}{\partial \phi}$ and $\frac{\partial W_m(\phi, \lambda)}{\partial \phi}$ can be determined from the Eqs. (3-5) and (3-7). Thus, the load-displacement curve of a flat-topped conical shell under axial compression as well as its energy-displacement relationship can be obtained.

By taking the same cell parameters as those of the tested samples, *i.e.* $a=5\text{mm}$, $c=9\text{mm}$, $H=13.8\text{mm}$, $t=1\text{mm}$, $\alpha=16.16^\circ$, and the material properties as described in [11], a numerical example is computed. The load-displacement curves predicted by the two theoretical models and that obtained from the experiment are compared in Fig. 3.16, where “Linear elastic” pertains to the numerical prediction from the elastic model, whilst “Rigid-plastic” pertains to that predicted by the rigid-plastic model.

Based on the experimental results, it is evident that the shell displays an elastic behavior in the early stage of its deformation; therefore, the load-displacement curve can be predicted by the elastic model in this stage. When the shell experiences large deformation, the elastic deformation becomes negligible, so its behavior can be reasonably approximated by the rigid-plastic model, which has incorporated the large geometric changes. During the transition from elastic deformation to large plastic deformation, the load-displacement curve should undergo a smooth path between the two theoretical curves depicted in Fig. 3.16. This implies that the discrepancy between the theoretical predictions and the experimental result in the transition stage would be much smaller than that exhibited in Fig. 3.16.

Fig. 3.16 Comparison of the load-displacement curve by the theoretical models with the experimental result

Fig. 3.17 Partitioning of the energy dissipation

Because the deformation modes proposed are merely kinematically admissible for a flat-topped conical cell, they do not satisfy the equilibrium equation. Therefore, these theoretical models only provide upper bounds for the load-displacement characteristics, as evidently exhibited in Fig. 3.16. Good agreement between the theoretical prediction and the experiment is obtained.

Figure 3.17 shows the proportion of the energy dissipated by bending deformation, W_b , within the total energy dissipation, W . Clearly, W_b/W gradually reduces with increasing vertical displacement, implying that the membrane deformation of the cell will be dominant when the deformation of the cell is large. For the cell geometry given here, the membrane deformation dissipates about 85% of the total energy when the vertical displacement reaches a half of the cell height.

3.5.3 Strain distributions

Caused by membrane deformation, the distribution of strains in the shell wall is depicted in Fig. 3.18, where ε_m denotes the average strain in a wall segment resulted from the membrane deformation. ABD marked in Fig. 3.18 pertains to segment ABD shown in Fig. 3.11, and so on. From Fig. 3.18, it is found that the strains in segments DEBC and BCFG are much larger than those in segments ABD and AFB. The magnitude of the compressive strain in segment BCFG increases with the increase of the vertical displacement. In segment DEBC, the material is compressed when vertical displacement Δ is less than $0.2H$, then extended as the cell experienced even larger deformation.

Fig. 3.18 Distribution of strains in the shell segments resulted from membrane deformation

The distribution of strains resulted from the bending deformation along the plastic hinge lines is depicted in Fig. 3.19, in which the effective length of the plastic hinge is taken as three times of the wall thickness. ε_b denotes the maximum strain along a plastic hinge line resulted from bending deformation. AB marked in Fig. 3.19 pertains to plastic hinge line AB shown in Fig. 3.11, and so on. Strain ε_b is defined positive when the outer surface of the shell is extended. It is seen that the magnitude of the maximum strain along plastic hinge line AB is

the largest among all the strains caused by bending. It also increases with increasing vertical displacement.

Fig. 3.19 Distribution of strains along the plastic hinge lines resulted from bending deformation

3.6 Potential Applications of the Cellular Textile Composites

It has been demonstrated that the cellular textile composites developed and studied in this paper can be ideal candidates for energy absorption purpose. These materials possess higher specific energy-absorption capacity and better impact performance compared with polymer foams. They are light in weight and have good ventilation properties. These materials can be adopted in many engineering applications, e.g. the energy-absorbing layers of safety helmets, the packaging material for valuable goods, etc. In particular applications, several layers of the cellular textile composites may be stacked together to achieve the required energy-absorption capacity. In this case, the joining configuration may play a dominant role on the total energy-absorption capacity as indicated by the impact testing results of two-layer stacked samples.

Three configurations in joining the two pieces of grid-domed samples, as shown in Fig. 3.20, were studied. The stacked grid-domed samples were tested under impact condition to examine how the energy-absorption capacity of the samples depends upon the joining configuration of the grid-domed samples and which one possesses the greatest potential in energy absorption.

Fig. 3.20 Three configurations in joining two grid-domed samples

The nylon/polyester samples were produced, in which the reinforcement was double jersey knitted fabric made from multi-filament textured nylon yarn, then sandwiched by PP films. The ratio of the fiber to matrix was 1.5:1. Two pieces of identical grid-domed samples were stacked together by one of three different joining configurations. The total mass of the drop weight was 6.94 kg, including a tup and an aluminum loading plate of 120×120×12 mm. The impact velocity, normal to the plane of the samples, was set as 2.33 m/s, which was the same for all impact tests on the samples with different joining configurations.

The typical load vs. time curves, the load vs. displacement curves and the specific energy vs. displacement curves for the samples under identical impact condition are shown in Fig. 3.21. As indicated by the figures, the maximum displacement of the samples with joining configurations 1 and 2 were approximately double that of the sample with joining configuration 3, and the peak load of the formers was only about a half of the latter. The original height of the sample would be a dominant factor in this issue. As shown in the schematic drawing of the joining configurations of two pieces of grid-domed samples (in Fig. 3.20), the height of the samples with joining configurations 1 and 2 was twice that of the sample with joining configuration 3. The experimental results indicate that the samples with joining configurations 1 and 2 behave similarly under impact condition. The sample with configuration 3 responded by a much higher peak load and a shorter displacement than the samples with configurations 1 and 2. Based on these results, it is not difficult to select the joining configuration for particular applications. For example, for bicycle helmets, the total thickness of the energy absorption layer is an important factor in concern. Hence, as long as the peak load is below the threshold, the joining configuration 3 may be a better choice. On the other hand, if the space is not very critical for some other applications, *e.g.* used as a packaging material, the joining configurations 1 and 2 could satisfy the requirements for energy absorption while keep the peak load very low so as to protect the packaged goods from damage during transportation.

In most bicycle helmets presently available in market, the inner layers (*i.e.*, the liners) of the helmets are made of polymer foams. An ITF project entitled “Light Weight Safety Helmets with Super Impact Protection” has been funded by the SAR Innovation & Technology Commission (ITC), so that HKUST and HKPolyU are now closely collaborating with an industrial partner in Hong Kong to investigate and produce a new generation of bicycle helmets by utilizing the cellular textile composites.

Fig. 3.21 (a) Load vs. displacement curves; (b) Specific energy vs. displacement curves for grid-domed samples with various joining configurations under impact

3.7 Concluding Remarks

(1) A new class of cellular textile composites with high specific energy-absorption capacity has been developed and studied. An ideal configuration of the cell was proposed, in which each cell merely consists of a flat-topped conical shell (Configuration 2). Comparing with the grid-domed textile composite of Configuration 1, the grid-domed textile composite of Configuration 2 displays a considerably higher energy-absorption capacity, more stable deformation mode, lower peak force and almost constant magnitude of force during its large deformation process.

(2) The energy-absorption capacity of the grid-domed textile composites varies with the geometric parameters of the samples, such as cell height, diameter ratio of cell-top to cell-bottom and semi-apical angle of the truncated conical shell. When the diameter of cell-bottom remains constant, the diameter of cell-top or the semi-apical angle of the flat-topped conical shell is an effective parameter to control the energy-absorption performance of this kind of cellular textile composites.

(3) The effective area of the cells, that is, the sidewall areas, dominates the energy-absorption capacity of the grid-domed textile composites. With different cell size, the energy-absorption capacity of the material almost remains the same as long as the effective area remains unchanged. With the same cell size, increasing the cell density results in an enhancement of the energy-absorption capacity, but also in an increase of the maximum pre-extension of the fabric, so that an upper limit exists.

(4) Under axial compression, the conical shell collapses into a two-lobe diamond pattern. On the meso-scale, matrix cracking, fiber/matrix debonding and fiber fracturing were observed in the region close to the top of the conical shell. The local out-of-plane buckling and the change of the fabric architecture were observed in the middle part of the shell wall.

(5) Based on the experimental observations on the deformation mechanisms of a flat-topped conical cell under axial compression, elastic and rigid-plastic deformation models are formulated to describe the deformation process of a cell, and to predict the load-displacement and energy dissipation characteristics. The load-displacement curves predicted by the theoretical models are in good agreement with our experimental results.

(6) The numerical results also show that the most of the energy dissipation is resulted from the membrane deformation and its proportion increases as the deformation proceeds. The theoretical models not only lead to a good upper bound estimate for the energy-absorption capacity of the grid-domed textile composite, but also serve as a powerful tool in optimizing the geometric parameters of the cells and predicting the strain distribution and possible failures of the composite during its large deformation.

Acknowledgements

The authors would like to thank the Hong Kong Research Grant Council for its support to this research under RGC grant HKUST 6017/98E.

References

1. Johnson W, Reid SR and Reddy TY. The compression of crossed layers of thin-tubes, *Int. J. Mech. Sci.* 1977;**19**:423.
2. Yu TX. Energy-absorbing devices utilizing plastic deformation of metals, *Advances in Mechanics*, 1986;**16**(1):28-39.
3. Reddy TY and Reid SR. Phenomena associated with the crushing of metal tubes between rigid plates. *Int. J. Solids Struct.* 1980;**16**:545.
4. Reid SR and Bell WW. Influence of strain hardening on the deformation of thin rings subjected to opposed concentrated loads. *Int. J. Solids Struct.* 1982;**18**:643.
5. Gupta NK, Prasad G LE and Gupta SK. Plastic collapse of metallic conical frusta of large semi-apical angles, *IJCrash*, 1997;**2**(4):349-366.
6. Gibson LJ and Ashby MF. *Cellular Solids: Structure and Properties*, 2nd edition, Cambridge University Press, Cambridge. UK, 1997.
7. Hua YL and Yu TX. Mechanical behavior of cellular solids. *Advance in Mechanics*, 1991;**21**(4):457-469.
8. Yu TX, Tao XM and Xue P. Energy-absorbing capacity of grid-domed textile composites. *Composite Science and Technology*, 2000;**60**(5):785-800.
9. Xue P, Yu TX and Tao XM, Effect of cell geometry on the energy-absorbing capacity of grid-domed textile composites, *Composites Part A – Applied Science and Manufacturing*, 2000, **31**, 861-868.
10. Gould PL. *Analysis of Shell and Plates*. Prentice Hall, New Jersey, 1999.
11. Xue P, Yu TX and Tao XM, Flat-topped conical shell under axial compression, to appear in *Int. J. Mech. Sci.* **43**, 2001