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Energy Absorption and Deformation in Textile Composite Cellular Structures

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I. Introduction

COMPOSITE materials and cellular structures are extensively used in aerospace engineering. As a typical cellular structure, honeycomb cores are increasingly developed and implemented in aerospace industry, and successfully applied in aircraft, and examples can be seen in presentations by Miller [1] and Thévenin [2]. Composite materials can provide not only a multifunctional multilayered integrated structure, but also low-cost manufacturing. Textile composite material is one of the energy-absorption-efficient composites. There are different forms of textiles used for composite reinforcement, as reviewed by Bibo and Hogg [3].

Investigations into cellular structures and composite materials for energy absorption and crashworthiness have been conducted. Evans et al. [4] systematically reviewed the multifunctions of metallic cellular structures, examined their mechanical properties and thermal properties, and provided design analyses for prototypical systems that specify implementation opportunities relative to competing concepts. The mechanisms governing the in-plane crushing of hexagonal aluminum honeycombs have been investigated by Papka and Kyriakides [5,6] with finite size honeycomb specimens crushed quasi statically between parallel rigid surfaces. The force-displacement response is initially stiff and elastic, but this is terminated by a limited load instability. Through finite element (FE) simulations, Gibson and Andrews [7] modeled the steady state of the regular hexagonal honeycomb and found that the creep rates of the structure were lower than other cellular solids. Tan and Chen [8] and Tan et al. [9] investigated energy absorption and deformation in textile composite cellular structures (TCCSs) affected by various parameters. The energy-absorbing capacity of grid-domed textile composites was also studied by Yu et al. [10].

To develop TCCSs for various applications (in particular, for aerospace engineering), better understanding of the energy absorption of these cellular structures will promote knowledge in product design and manufacture, which is the purpose of this present work.

II. Cellular Geometry Creation

A textile composite cellular structure was assumed to be a rectangular and the applied load was assumed to be applied at the center of the structure. Figure 1 shows an example TCCS used for FE analysis in the present work. The outer surface is referred to as the exposed surface of the modeled structure being exerted against the applied load, and the opposite surface far from the applied load is called the inner surface. It is also assumed that the dimension and the applied force have double symmetry with respect to both the X and the Y axes. Therefore, only one-quarter of the structure is chosen for representation of the whole structure.

Figure 2 shows the profile of the in-house computer package used to create meshes for an example cellular structure. The code with friendly input interface was developed by using Microsoft Visual C + +. The necessary input parameters applied to create the geometry of a cellular structure include the following:

1) For designation of a cell, bonded-wall length, free-wall length, bonded-wall thickness, free-wall thickness, and opening angle are input.

2) For designation of the whole structure, the number of half-rows (in practice, a half-row is a layer material during fabrication), number of columns, and width of the structure are input.

Through the specification of these geometric parameters, a three-dimensional cellular structure was obtained. Moreover, an Initial Graphics Exchange Specification (IGES) file of the cellular structure geometry could be generated. The IGES neutral file is a common format used to exchange geometry between computer programs.

III. Finite Element Modeling

Processes of the quasi-static impact for the TCCSs were simulated with 3-D FE models using MSC.Marc Mentat [11]. The FE simulations were carried out as an isothermal, elastic–plastic, and double-symmetric problem in which only one-quarter of the structure was modeled. Boundary conditions were used to enforce symmetry in the X–Z plane and Y–Z plane. The dimensions for all cellular structures were the same ($20 \times 30 \times 50$ mm in thickness by width by length), and an example is shown in Fig. 2. For all impact cases, a foreign object was assumed to have a quasi-static impact at the center of cellular structure, and the impacted area was 12×20 mm.

The material of the modeled TCCSs was chosen from the previous work by Zic et al. [12], the fibers were R136/2-tex EC9 glass, and the fabrics were converted into composite cellular structures by impregnating by mixture of resins Araldite LY 1927 GB with HY

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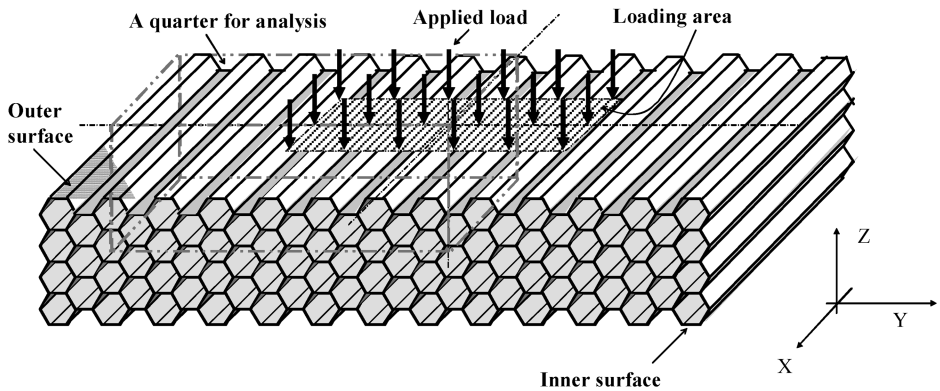

Fig. 1 An example of TCCSs used for the finite element modeling.

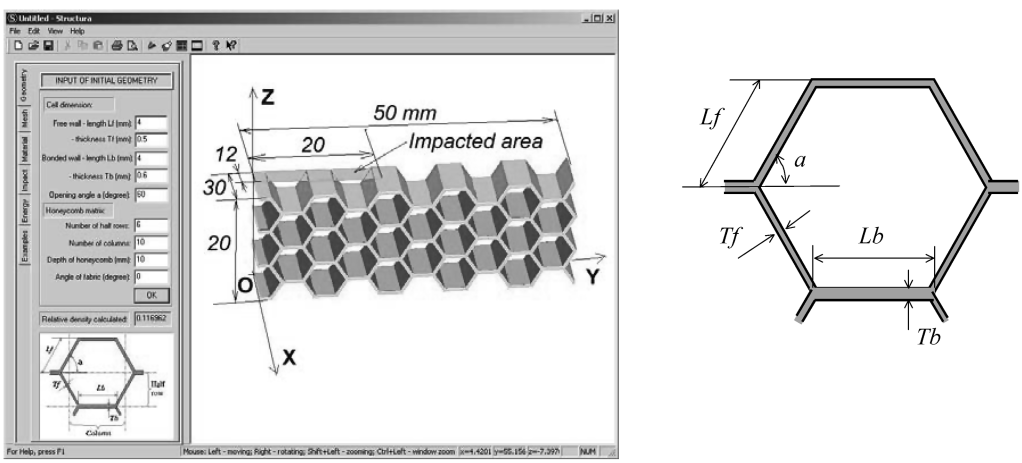

Fig. 2 TCCS geometry generated by an in-house computer package.

1927 GB. The experimentally measured Young's modulus for the textile composite material was 13.2 GPa in the longitudinal direction and 5.3 GPa in the transverse direction, the value of the shear moduli was 2.038 GPa, and the Poisson ratio was given as 0.3.

Two sets of models were chosen for the present FE simulations: 1) different original cell-wall lengths and 2) different opening angles. Each cell wall had 48 elements. To increase the accuracy of numerical calculation, smaller elements were generated in the applied load areas. The strain energy density was calculated as the strain energy absorbed per unit volume of impacted structure. The predicted local result data (such as the strain energy density and the deformation) were collected from the nodes of the outer or inner horizontal outer surfaces of the applied structures. The strain–stress relationship for the chosen material was considered as orthotropic laminates during application.

A. Model Set I: Different Original Cell-Wall Lengths

Four different original cell-wall lengths were chosen: 2, 3, 4, and 6 mm. Correspondingly, different numbers of both half-rows and columns were designed to keep the cellular structures in the identical dimension: $20 \times 30 \times 50$ mm in thickness by width by length. The shorter the original cell-wall length, the more the numbers of both half-rows and columns. The original free-wall length and the original bonded-wall length were always kept the same for each set. The original free-cell-wall thickness and the original bonded-cell-wall thickness were 0.5 and 0.6 mm, respectively. The 3-D FE original meshes for TCCSs with different cell-wall lengths are shown in the "Before impact" column of Fig. 3. The final deflection of the center point on the top surface of a structure after impact was given a magnitude of 5 mm.

B. Model Set II: Different Opening Angles

Four different original opening angles were chosen: 30, 45, 60, and 90 deg. The free-cell-wall thickness was 0.5 mm, the bonded-wall thickness was 0.6 mm, and both the free-wall length and the bonded-wall length were the same: 4.0 mm. For each of the cases in this model set, a given resultant load of 6 kN was applied to the modeled structure during the quasi-static impact. To keep the cellular structures in the identical dimension ($20 \times 30 \times 50$ mm in thickness by width by length), different half-rows and columns were chosen for different opening angles. The 3-D FE original meshes for TCCSs with different cell-wall lengths are shown in the "Before impact" column of Fig. 4.

IV. Results and Discussions

A. Deformation

1. Different Original Cell-Wall Lengths Under a Certain Deflection

Figure 3 shows three-dimensional TCCS patterns for model set I before and after impact, obtained by FE simulations. From the "After impact" column, it is seen that the maximum deformation always occurs in the center of the loading area for each structure. The farther the distance from the center of the loading area, the less deformation of the structure. In a certain column, deformations of the inclined cell walls are quite similar in the height direction. All of the cells within the loading area deform together against the applied load.

Expanding deformation is seen transferring from the loading area to nonloading areas. The magnitudes of the expanding deformation in the width direction are generally more significant than those in the length direction. In the width direction, a cell wall is a whole continuous sheet on which deformation transits readily and continuously. In the length direction, a number of different cell walls have to be deformed, and so deformation has to transmit from one cell wall to another, from an inclined cell wall to a horizontal cell wall, to another inclined cell wall, and then to another horizontal cell wall. Moreover, the characteristics of deformation for the inclined cell wall differ very much from those of the horizontal cell wall.

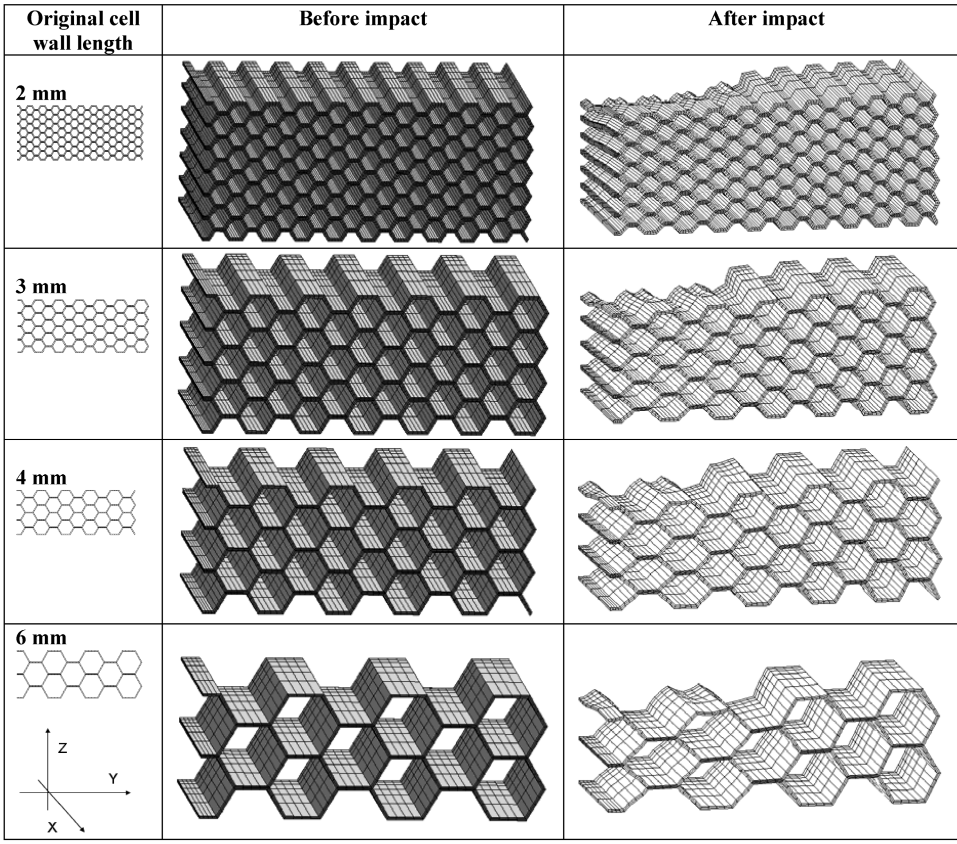

Fig. 3 Modeling patterns of TCCSs with different original cell-wall lengths.

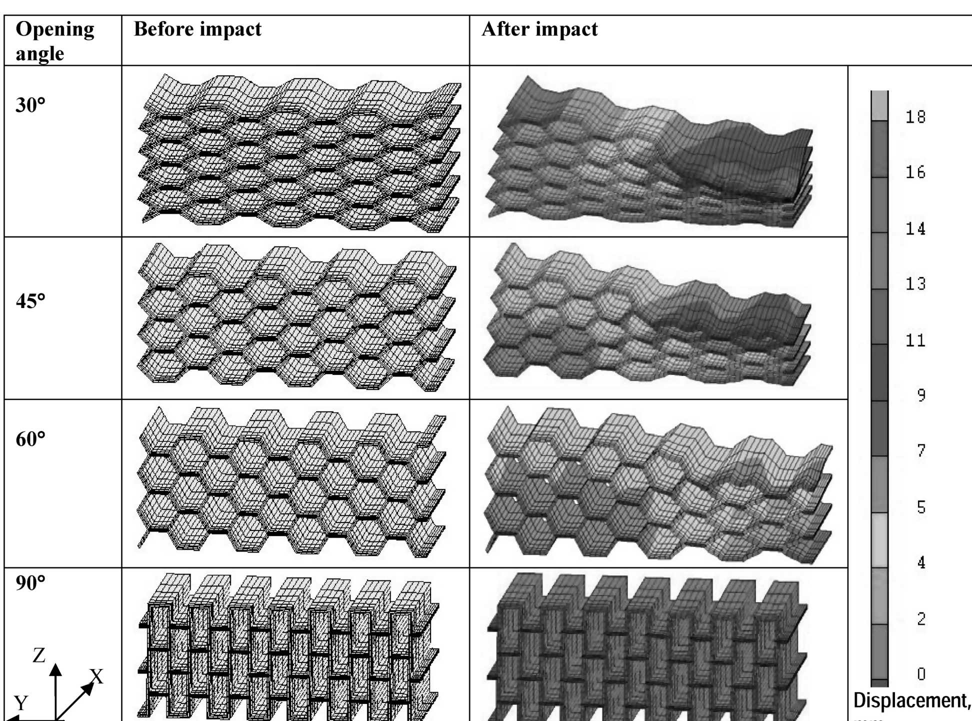

Fig. 4 Modeling patterns of TCCSs with different opening angles.

2. *Different Opening Angles Under a Certain Resultant Load*

Figure 4 shows 3-D TCCS patterns of model set II before and after a quasi-static impact. From the “After impact” column, it is seen that the maximum deformation appears in the center of the loading area. The farther the distance from the center of the loading area, the less deformation of the structure. For a certain column of cells, the bending deformation for the series of the inclined cell walls occurs very similarly. For the nonloading areas, the deformation also takes place. There, the expanding deformation magnitude in the width direction X is more significant than that in the length direction Y.

It is obvious that the opening angle does significantly influence the deformation. Under the same process conditions (the same material, the same structure direction, the same applied load magnitude, and the same loading area), except for the opening angle (in the range of not larger than 90 deg) for a cell, the larger the opening angle, the less the deformation of the cellular structure will be after impact. For the TCCS with the opening angle of 30 deg, the deformed cells appear to be completely crushed in the loading region, although the cells far from the loading area have only very little deformation. For the TCCS with the opening angle of 45 deg, the bending of the cells within the loading region in the height direction is quite serious, whereas for the TCCS with the opening angle of 60 deg, the bending of the cells within the loading region in the height direction is significant. For the TCCS with the opening angle of 90 deg, little cell deformation is seen, including those within the loading region. It indicates that a cellular structure with the maximum opening angle of 90 deg has the maximum capability of energy absorption. In such a cellular structure with an opening angle of 90 deg, there are some vertical, long, and continuous cell walls from the outer surface to the inner surface. These long continuous walls of the in-plane structure are very similar to the cell walls of an out-of-plane cellular pattern (as discussed by Gibson and Ashby [13]), which has a relatively higher capability of energy absorption than an in-plane structure.

B. Strain-Energy-Density Distribution

1. *Different Original Cell-Wall Lengths Under a Certain Deflection*

Corresponding to the deformation shown in Fig. 3, strain-energy-density distributions on both outer and inner surfaces for TCCS structures after impact are shown in Fig. 5. It can be seen that visual indent values in the length direction clearly indicate the inclined and horizontal cell walls for each cell. In general, the values of the local energy absorption are most significant for the cell corners of the outer/inner surface, significant for the inclined walls, and less significant for the sublayer horizontal walls. The values of the strain energy density within the impacted area are much higher than those outside the impacted area. The farther the distance from the central of the loading area, the smaller the strain energy density. In total, the magnitudes of the strain energy density along the width direction X are larger than those along the length direction Y. Corresponding to the indent shapes of both outer and inner surfaces, the distributions of

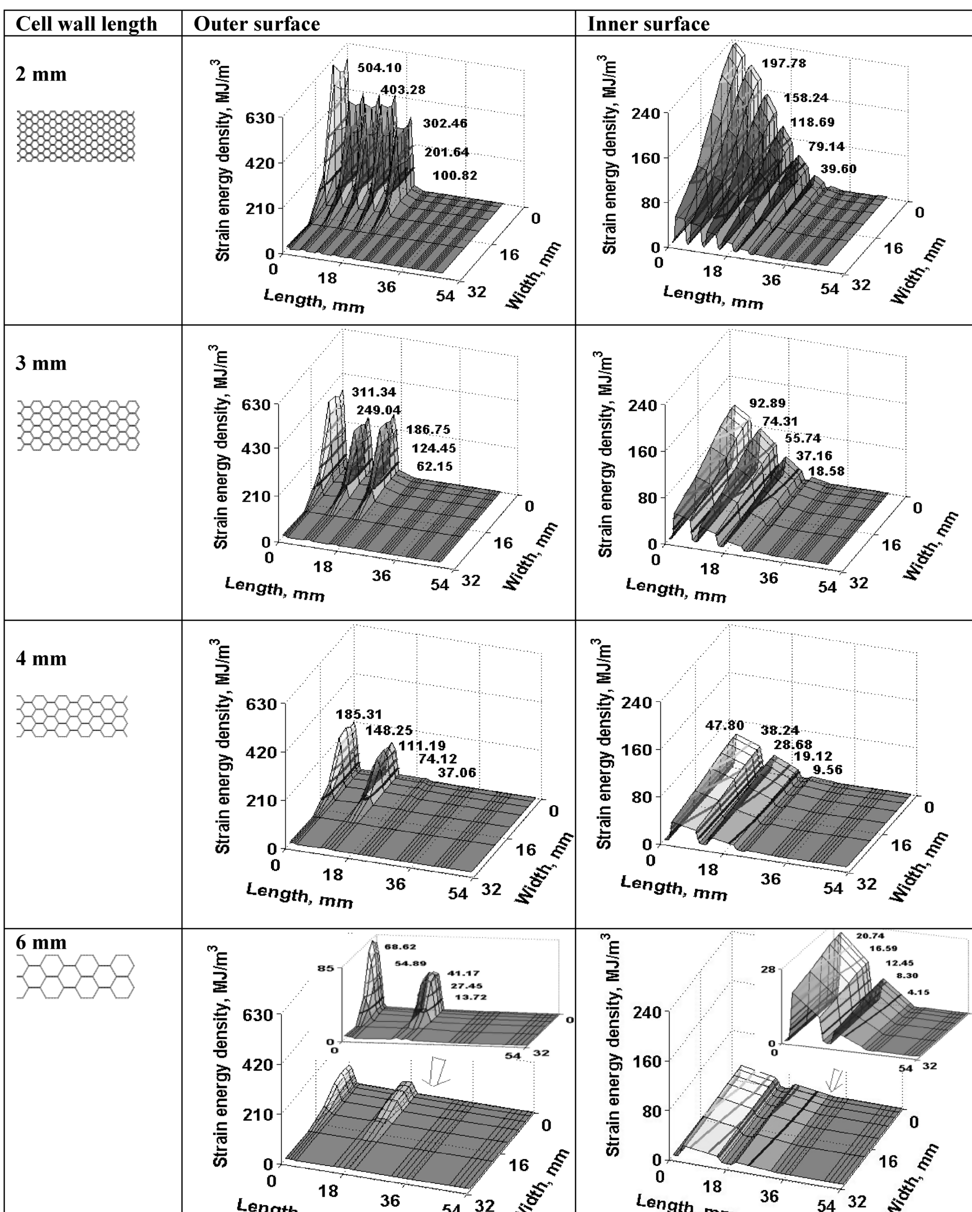

Fig. 5 Predicted strain-energy-density distributions of TCCSs with various original cell-wall lengths.

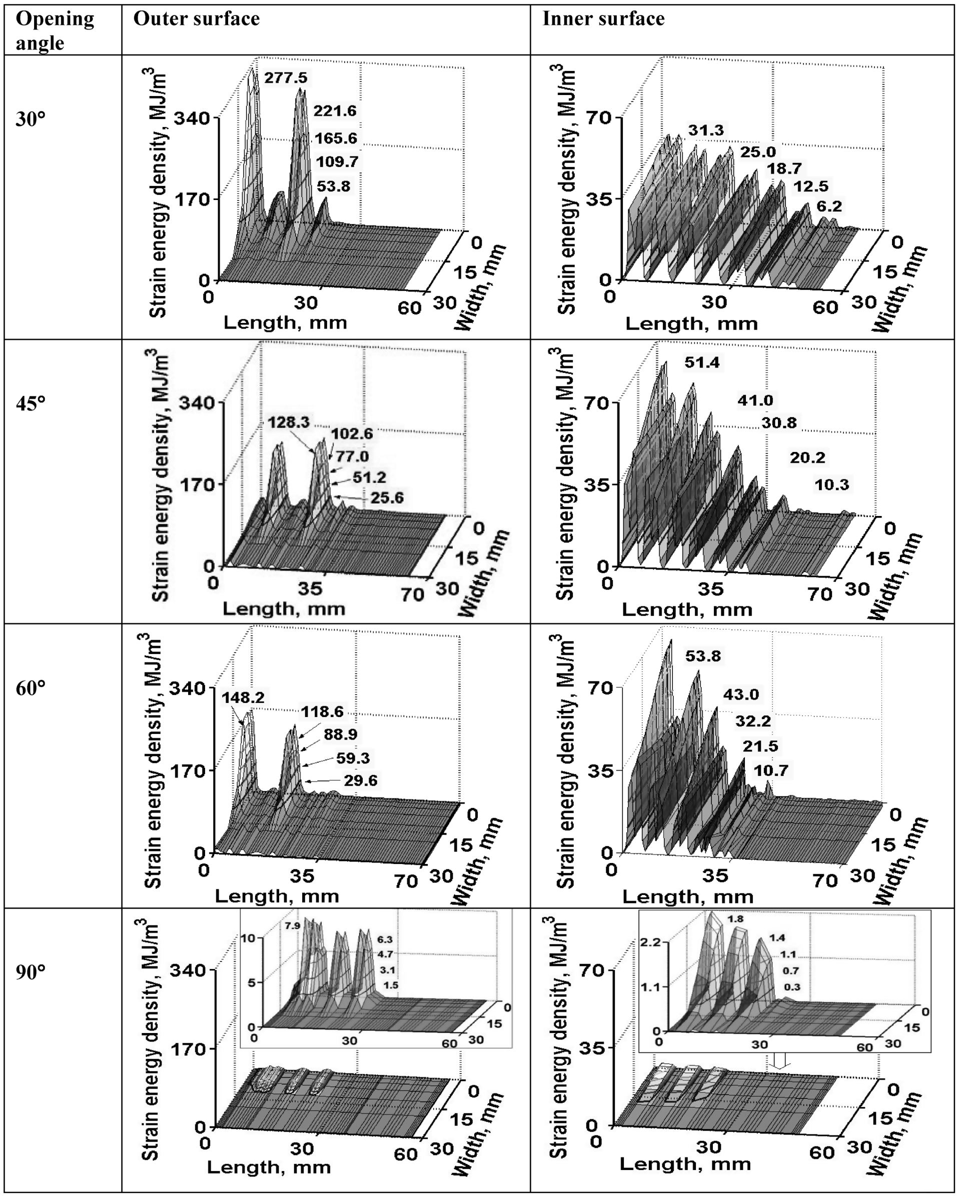

Fig. 6 Predicted strain-energy-density distributions of TCCSs with different opening angles.

the strain energy density have indent-shape magnitudes for which higher-layer data are for the joint edges between the outer horizontal cell walls and the inclined cell walls. For a cellular structure with a certain dimension under an impact with a certain deflection, the shorter the original cell-wall length, the higher the strain energy density, or the higher the capability of energy absorption for the structure.

Note that the energy absorption for the outer surface is always higher than that for the inner surface. For example, the maximum values of the strain energy density for the outer surface are about 3 times that for the inner surface. This can explain why the cellular structures can protect the structure/body from impact, because the energy absorption for the outer surface is much higher than that for the inner surface, which does normally contact with a body to be protected.

2. *Different Opening Angles Under a Certain Resultant Load*

Corresponding to the deformation shown in Fig. 4, distributions of the strain energy density on both the outer and inner surfaces of the TCCSs with different opening angles under a quasi-static impact are shown in Fig. 6. It is seen that the peaks of the strain energy density always appear in the loading area for both outer and inner surfaces. The regions against the inclined cell walls have higher magnitudes of the strain energy density than those against the horizontal cell walls for outmost surfaces (both outer surface and inner surface). By comparison of the distributions of the strain energy density on both the outer and inner surfaces, it can be seen that the magnitudes of the strain energy density on the inner surface are generally much lower than those on the outer surface.

Under the given impact, for the cells of a TCCS with a higher opening angle, the magnitude of the strain energy density appears to be lower. This implies that a TCCS with a higher opening angle has stronger strength and thus experiences less strain energy.

V. Conclusions

An investigation into energy absorption and deformation in TCCSs under a quasi-static impact has been conducted with various cell dimensions through 3-D FE modeling.

1) For a given TCCS under impact, the energy absorption on the outer surface is always higher than that on the inner surface. It provides good theoretical evidence to explain why the cellular structure can be effectively applied to absorb external impact energy and to minimize or release the impact.

2) For a given cellular structure, the magnitudes of the original cell-wall length significantly influence its energy-absorption capability. A cellular structure with a shorter original cell-wall

length will have higher strain-energy-density values, although the structural relative density will be relatively high.

3) The effect of the opening angle on both deformation and energy absorption is marked. For a given dimension of the cellular structure with the same original cell-wall length, the structure with a smaller opening angle will deform more easily and will absorb higher energy under the same loading condition.

4) Inhomogeneous energy absorption resulting from inhomogeneous deformation and inhomogeneous stresses is very significant during quasi-static impact of a cellular structure. The maximum deformation and the peak of the strain energy density usually take place at the center of the loading area.

5) The data in this work were measured theoretically from finite element simulations and they may be used as references for the engineering design of applied structures using TCCSs. These data have to be verified by experiments before their practical applications to real solutions. Thus, further experiments are needed based on these predictions.

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