Design, Manufacture, and Experimental Analysis of 3D Honeycomb Textile Composites

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Abstract

In the current paper, it explains the basic concept of textile based 3D honeycomb composites, and the procedure of design and manufacture of 3D honeycomb fabrics and composites. Finite Element Analysis (FE) is carried out to examine the energy absorption behaviour of the textile honeycomb composite with different geometric parameters. And further experimental analysis of the 3D honeycomb composites for impact performance, based on the drop-weight impact tests carried out on 14 systematically designed honeycomb composites have been achieved. Energy absorption and the transmitted force measured through the tests were used as important indicators for the impact performance of the honeycomb composites. Influences of the structural parameters of the composites, including the cell opening angle, cell size, cell-wall ratio, and the cell density for the same cross-sectional area, were studied to systematically characterise the 3D honeycomb composites. It was found that changes in structural parameters affect impact energy absorption and impact force attenuation. Discussions were also carried out on the effect of the volume density of the honeycomb composites on impact characteristics, indicating that while the volume density has little effect on the energy absorption much, it has obvious influence on the transmitted force. The analytical results provide useful data for the engineering and application of 3D honeycomb composites.

1. INTRODUCTION

Various forms of textiles have been used as performs and reinforcements for composites, the advantages of textile composites have been widely recognised and utilised for appropriate applications. In the main, unidirectional and 2D woven textiles are the main forms used in creating composite material though new developments of composites are seen to have created from using different types of 3D textiles structures for improved properties. Such 3D composite reinforcements are advanced in that they possess structural integrity and fibre continuity, and they have attracted much attention in research and in applications. 3D honeycomb structures, which can be found in the great nature ranging from the spines of a porcupine to the stem of a plant of reed, have many features that are important for many of the composite application, as have been described by Gibson and Ashby [1]. Composites made from this type of 3D reinforcements can be super-light, energy absorbent, voluminous as well as being strong. This paper aims to introduce the technical process for designing and manufacturing the 3D honeycomb fabrics as reinforcements, and to characterise the behaviours and performance of the honeycomb composites. Theoretical analysis on the 3D honeycomb composites were carried out [3, 4] and it was suggested that the honeycomb composites have advantages over other types of cellular materials in energy absorption and force attenuation.

Much work has been carried out to study the characteristics of the cellular materials, natural and manufactured alike, with irregular shaped cells such as foams and regular shaped cells such as honeycombs. Reid and Peng [4] studied the general characteristics of the stress strain curves for wood materials including oak, redwood, pine and balsa along the axial and the radial directions. Ruan *et al* [5] worked on a typical CYMAT aluminium foam, a manufactured irregular cellular material, for its strain-stress relationship and the localised cell deformation. Theoretical and experimental studies by Papka and Kyriakides [6] were carried out on an aluminium honeycomb with regular cell shapes crushed in the X_2 direction, leading to a good agreement between the theoretical and experimental studies. However, no experimental studies on impact on textile honeycomb composites have been reported, which obviously is an important part of the comprehensive study on 3D honeycomb textile composites. This paper attempts to make a contribution in this field, by carrying out impact test on the 14 different honeycomb textile composites designed and manufactured in the research. It is aimed to evaluate the honeycomb composites for their energy absorption, force attenuation under the influence of structural parameters of the composites.

2. DESIGN AND MANUFACTURE HONEYCOMB TEXTILE COMPOSITES

2.1 Parameters of the 3D Honeycomb Structure

A general honeycomb structure is composed of an array of hexagonal cells. A cell structure is formed by 6 free and bonded walls. Free walls refer to the cell sides that are free from other sides, whereas the bonded walls are those having to be bonded together for the formation of the cellular cross-section. The parameters that are used to describe a cell are the open angle, thickness walls, and lengths of walls. Figure 1 illustrates the parameters of a hexagonal cell, where the height of cell $h = 2\, l_f \sin\theta$.

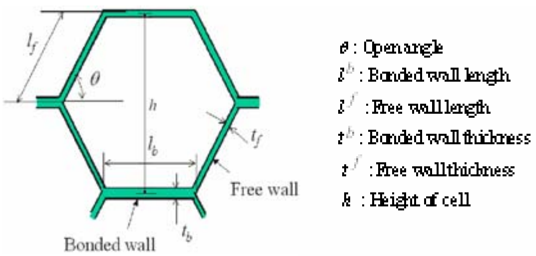


Figure 1. Parameters of a honeycomb cell

2.2 Design of 3D Honeycomb Weaves

In this research work, it is assumed that the tunnels run in the weft direction, though they can be arranged to go in the warp direction too. One repeat of the honeycomb structure can be divided into 4 regions, i.e. region I, II, III and IV, as shown in Figure 2. Region I corresponds the section of the 3D honeycomb structure where the fabric layers are separated from each other; region II is where the adjacent layers join together; region III is the same as region I; and region IV is again the joining section but the joining layers are different from that in region II. Because of the nature of weaving, the honeycomb fabric is woven with all cells flattened as indicated in Figure 2 (a), and the honeycomb structure is achieved when the fabric is opened up and consolidated as shown in Figure 2 (b). According to the definition of a cell, regions II and IV correspond to the bonded walls with length l_b and regions I and III the free walls with length l_f. It needs pointing out that Figure 2 (b) shows only part of the honeycomb structure that would open up to from Figure 2 (a).

(a) Honeycomb fabric woven before opening (b) Honeycomb fabric after opening

Figure 2 Region division of a honeycomb structure

2.3 Representation of woven honeycomb structures

As can be understood, a woven honeycomb structure can be defined by specifying the structural parameters. The following general coding format is used to denote a particular honeycomb structure: $xL(y+z)P\theta$ where

- x is the number of fabric layers used to form the honeycomb structure;
- y is the length of bonded wall measured in the number of picks;
- z is the length of free wall measured in the number of picks;
- θ is the open angle of the hexagonal cells;
- L is used to denote "layer"; and
- P is used to denote "pick".

There are situations when the lengths of free and bonded walls are the same, i.e. $y=z$. In such case, the coding format can be reduced to $xLyP\theta$

Further, when the open angle of the cell is 60˚, the coding format becomes $xLyP$

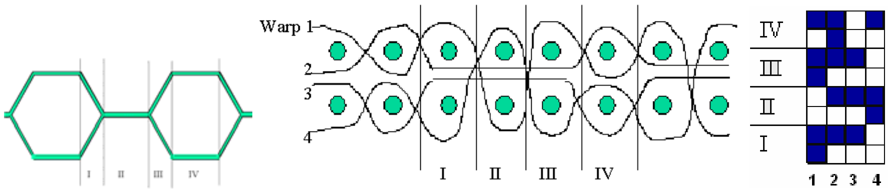
In all the above code expressions, x, y, z are integers and $x \geq 2$, $y \geq 1$, $z \geq 1$.

2.4 Weave creation

A procedure for creating weaves for the honeycomb structure has been created and it has been implemented into software Hollow CAD© [7]. In this section, three examples are used to explain the principals of the weave generation for honeycomb fabrics. In all examples, the plain weave is used for single layer fabric sections.

<u>The 2L1P structure</u>

This is the simplest honeycomb structure where there are 2 fabric layers with 1-pick being the length for both free and bonded walls. Figure 3 (a) shows the honeycomb structure when opened, and (b) is the illustration of the interlacement between warp and weft yarns for this honeycomb structure. It can be seen that there are altogether 4 warp ends, ends 1 and 2 being responsible for weaving the top layer and 3 and 4 for the bottom layer. The 4 regions are a complete repeat along the warp direction. Let us take warp end 1 for example to explain the weave creation. In region I, warp end 1 goes above the two picks and therefore in the weave diagram shown in Figure 3(c) the first warp end received two warp-up marks. When this warp end travels into region II, it goes under both picks and therefore in the weave diagram the first warp end receives two warp-down marks, which are indicated as blank grids. In region III, the warp ends travels above the 2 picks again, and correspondingly in the weave diagram there are two warp-up marks. In the final region, this warp end is underneath the pick for the top layer but above the one for the bottom layer. Accordingly, in region IV in the weave diagram, there is firstly and a blank then followed by a mark. In the same way, following the movement of warp ends 2, 3, and 4 will complete the columns 2, 3 and 4 in the weave diagram respectively.



(a) 2L1P honeycomb structure (b) Cross-sectional view of 2L1P (c) Weave diagram

Figure 3 Honeycomb structure 2L1P

2.5 Manufacture of 3D Honeycomb Composites

In order to investigate systematically the 3D honeycomb composites, 10 honeycomb fabrics are designed and manufactured, which are 4L6P, 6L4P, 8L3P, 8L4P, 8L5P, 8L6P, 8L(4+6)P, 8L(4+3)P, 8L(3+6)P, and 8L(6+3)P.

Before making the fabrics, the weft density of the overall fabric must be worked out based on the number of picks specified for each of the cell walls in the fabric specification and the actual length expected. Suppose that z is the number of picks specified for a wall of single layer fabric session (picks), l is the required length of the fabric session (cm), d_i is the weft density for this single layer (picks/cm), then

$$d_i = \frac{z}{l} \qquad (1)$$

If the honeycomb fabric is composed of m fabric layers, then the weft density of the honeycomb fabric, d, will have to be set to

$$d = \sum_{i=1}^{m} d_i \qquad (2)$$

In the case that all layers have the same weft density, the weft density of the honeycomb fabric becomes

$$d = md_i \qquad (3)$$

The honeycomb fabrics are designed to have 4, 6, and 8 layers. In all cases, it was decided that each layer of fabric will have a warp and weft density of 20 yarns/inch. The warp and weft density of the overall honeycomb fabric can be found by multiplying the number of layers to the warp and weft density per layer, as described by equation (3). Therefore, the warp and weft densities of these three honeycomb fabrics are 80, 120, and 160 yarns/inch respectively. In all these designs, the tunnels run in the weft direction, and the length of the cell walls can be found using the equation (1). With the wall length being 3, 4, 5, and 6 picks, the actual length of the walls will be 3.81mm, 5.08mm, 6.35mm, and 7.62mm respectively.

This research does not intend to examine the influence of fibre type on composite properties. For convenience, a cotton of 14.8/3 tex was used for making the 3D honeycomb fabrics.

2.6 3D Honeycomb Composites

As aforementioned, the honeycomb fabrics are in flat form when manufactured and need opening before impregnation. In preparation, all fabric samples were cut into the size of 20cm × 20cm. To open up the fabric, two sets of metal wires coated with PTFE were inserted to the top and bottom rows of tunnels respectively, which are pushed open to the required extent by an opening device shown in Figure 4. The fabric consolidation solution was made as a mixture of resin and hardener. According to the fibres type used for making the honeycomb fabrics, resin LY5152 and hardener HY5052 was used for fabric impregnation, with a mixing ratio of 100:38. After the resin has been applied on the fabric, the samples are placed in the fume cupboard for quicker hardening.


Figure 4 A photograph of the opening device

2.7 Sample groups

14 3D honeycomb composites with different parameters were manufactured from the 10 honeycomb fabrics, and they are organised into 4 groups. The first group is for the investigation of opening angles, and they are all made from the 8L6P honeycomb fabric. The opening angles used in this group are 30º, 45º, 60º, 75º, and 90º. The honeycomb composites in second group are all based on 8-layer fabrics, each cell-wall length being 3, 4, 5, and 6 picks respectively. The opening angle for this group of composites is 60º for all. The third group of composites is made from 8-layer fabrics, but with different length ratios of free wall to bonded wall. The cell opening angle is 60º for all samples. The last group of composites is made from fabrics with different number of fabric layers and cell wall length, but opened to very similar composite thickness, with the opening angle being 60º in all cases. Table 1 lists the 4 groups of honeycomb composites. Figure 5 illustrates the cross-sectional view of the 4 groups of honeycomb composites. Figure 6 shows photographs of honeycomb composites in group 4.

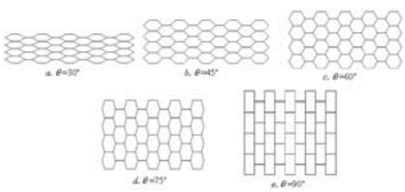
Group	Composites
Group 1: Opening angle	8L6P30, 8L6P45, 8L6P60, 8L6P75, 8L6P90
Group 2: Cell size	8L3P60, 8L4P60, 8L5P60, 8L6P60
Group 3: Length ratio	8L(3+6)P60, 8L(4+6)P60, 8L6P60, 8L3P60, 8L(4+3)P60, 8L(6+3)P60
Group 4: Similar thickness	4L6P60, 6L4P60, 8L3P60

Table 1 List of the honeycomb composite groups

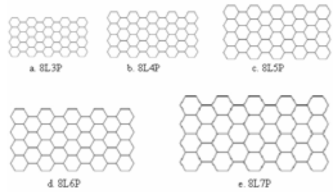
3. SIMULATION ANALYSIS AND IMPACT EXPERIMENT

3.1 Finite Element Analysis (FE) for honeycomb textile composites

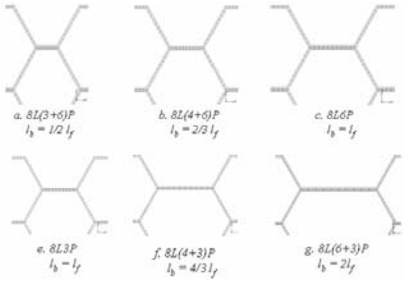
Finite Element Analysis (FE) is conducted to examine the energy absorption behavior of cellular structure woven composites according to the given structural parameters optimized in the research work. The work investigates is conducted by using MSC Marc Mentat V2005r2. Three set of models are designed for the FE analysis: (a) different original cell wall length (4.07mm, 5.08mm, 6.35mm, 7.62mm), (b) different opening angle (30°,45°,60°,75°,90°) and (c) Different length ration of cell boned walls and free walls (1:2, 2:3, 4:3, 2:1). Figure 6(a)(b) shows a typical theoretical results from FE analysis and its comparison to the experimental results. And Figure 6(c) shows the transmitted forces from bottom nodes of the cellular structure composite are collected to evaluate its force attenuation behavior.



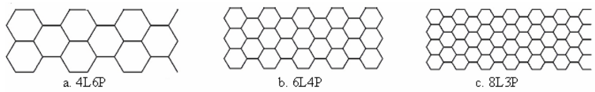
(a) Group 1



(b) Group 2



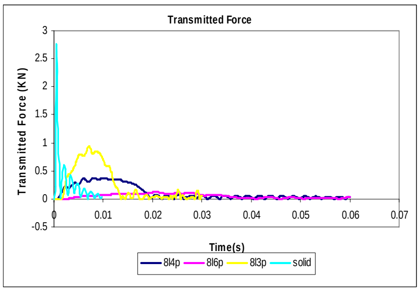
(c) Group 3



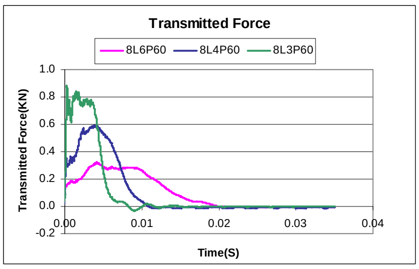
(d) Group 4

Figure 5 Cross-sectional views of the 4 groups of honeycomb composites

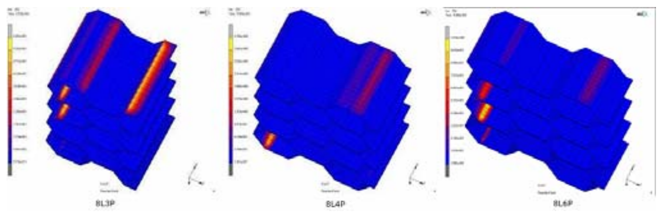
Figure 6 Photos of honeycomb composites in group 4



(a) Transmitted force collected by finite element (FE) analysis



(b) Transmitted force collected by experiment



(c) Transmitted force illustrated in the simulated sample

Figure 6 Transmitted force collected by finite element (FE) analysis

	8L3P	8L4P	Solid
Kinetic Energy(J)	8.3954	8.30704	8.09379
Strain Energy(J)	8.10308	4.36588	1.34834
Energy Absorption	96.5%	52.6%	16.7%

Table 2. Energy absorption of various cellular structure composites

Table 2 shows that the results from FE analysis and for a given cellular structure (for example 8L3P60),it result in 96.5% energy absorption while the same volume solid structure only absorb 16.7% which indicates cellular structure holding a very good capacity of energy absorption.

3.2 Drop-weight Impact Experiment

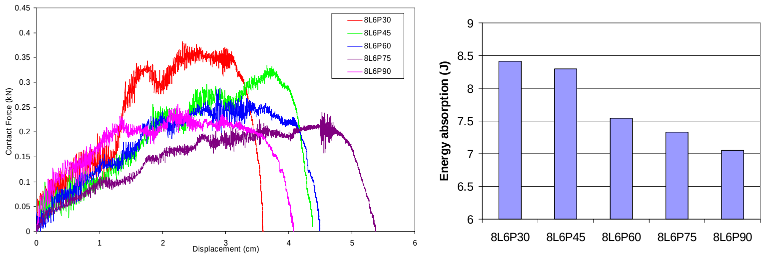
Based FE analysis, experimental studies on impact on textile honeycomb composites have been conducted, and experimental study of 14 systematically designed and manufactured 3D honeycomb textile composites was carried out with an emphasis on the impact behaviour. The drop-weight principle was used in the set-up of the impact tester. Based on the intended application, a low energy, low speed impact tester was established, which is capable of measuring the change in acceleration of the impact head and the transmitted force from beneath the specimen.

Test Results

As has been explained in previous of this paper, the 14 honeycomb composites are designed in 4 groups, i.e. the opening angle group, the cell size group, the length ratio group, and the similar thickness group. It is of interest to investigate the influence of these parameters on the impact performance of the honeycomb composites.

3.2 1 Influence of cell opening angle

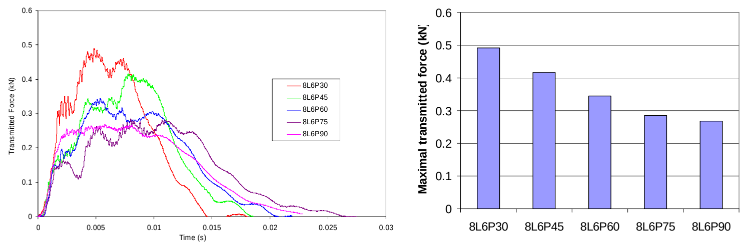
This group involves composites 8L6P30, 8L6P45, 8L6P60, 8L6P75, and 8L6P90. These composites are made from the same fabric as reinforcement but opened up to different angles, as indicated by the last two digits in the codes. Figure 7(a) shows the relationship between the impact force and the displacement of the honeycomb composites during the impact. No obvious trend can be followed in the curves and in the shape of the area covered by the curves to indicate the opening angle as a major mechanism by which the impact energy was absorbed. Other structural parameters such as the overall thickness of the honeycomb composites must have played important roles too. Figure 7(b) depicts the influence of opening angle on the energy absorption of this group of honeycomb composites. The message is clear that an increase in the opening angle leads the decrease of energy absorption. This is believed to be because the honeycomb composites with smaller opening angles present lower resistance to the bending of its angled cell walls and therefore create larger deformation. All the composites made from 8L6P reinforcement contain 4 rows of cells which in this case seem to be sufficiently thick not to be totally crushed by the application of the impact energy. , In contrast, when the 4L6P60 composite, which has only two rows of cells, was subjected to the same impact energy, it was crushed completely leading to lower energy absorption. The relevant curves can be found in Figures 12 and 13.



(a) Impact force –displacement curves (b) Energy absorption

Figure 7 Opening angle influence on energy absorption

Figure 8(a) shows the time dependency of the transmitted force associated with the 5 composites in the group. Whilst the peak transmitted force is reduced along with the increase in composite opening angle, it is clear that the peak forces tend to be smoothed when the composites get thicker due to the increase in opening angle. Figure 8(b) displays the maximal transmitted force for the 5 honeycomb composites in the group. It shows a clear tendency that when the opening angle increases the maximal transmitted force gets reduced. The thickness of the composites is believed to have an important role to play in this together with the cell geometry in the cross-section of the composites. Both the energy absorption and transmitted force showed good agreements to the theoretical results [8].



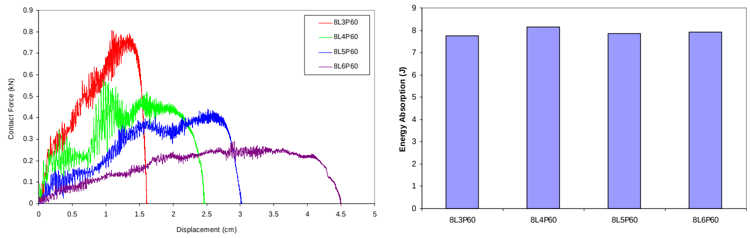
(a) Time dependency of transmitted force (b) Maximal transmitted force

Figure 8 Transmitted force with different opening angles

3.2.2 Influence of cell size

All honeycomb composites in this group are made from 8 layers of fabrics involving 4 regular hexagonal cells, where the 6 walls of each cell have the same length. The opening angle of the cells in these composites is 60°. With the same weft density for all reinforcing fabric sections, the cell wall length changes from 3, 4, 5, to 6 picks, resulting in cells with increasing sizes. These composites are 8L3P60, 8L4P60, 8L5P60, and 8L6P60, with 8L3P60 with the thinnest and 8L6P60 the thickest.

It is seen from the force-displacement relations in Figure 9(a) that composites with smaller cell sizes have higher impact modulus and those with larger have low impact modulus, leading to harder and softer composite materials, respectively, with similar level of energy absorption as indicated in Figure 9(b). This experimental result suggests that for honeycomb composites having the same number of cells in a column, cell sizes can be used as the key parameter for altering the softness of the composite material. Also, from the energy absorption perspective, the use of smaller cells in honeycomb composites results in less bulky materials for similar energy absorption capability.



(a) Impact force - displacement curves (b) Energy absorption

Figure 9 Influence of cell size on energy absorption

Impact force attenuation is much affected by the cell size for honeycomb composites as demonstrated in Figure 10. It is clear that honeycomb composites with larger cells performs better in that the altitude of the peak transmitted force is much reduced and that the peak transmitted force gets smoothened out. It is also evident that the maximal transmitted force occurs later in general as the cell size becomes larger. This is certainly a favourable feature for materials to be used for body and limb protection against trauma impact, with composites with larger cells allowing more preparation time for the human body to react to the impact hence reducing the chances for more serious injuries.

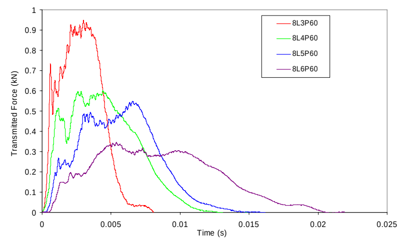
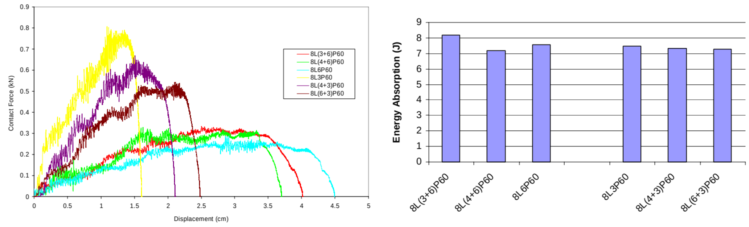


Figure 10 Influence of cell size on transmitted force

3.2.3 Influence of length ratio cell walls

Two subgroups of honeycomb composites, based on the 8-layer construction, have been created for the study of influence of cell wall ratio on the impact performance. The first group involves 8L3P60, 8L(4+3)P60, and 8L(6+3)P where the free wall length is kept to be 3 picks and the bonded wall length takes the values of 3, 4, and 6 picks. In the second subgroup, the free length remains to be 6 picks while the length of the bonded walls change from 3, 6, to 6 picks. The cell opening angle for all the composites is 60º.

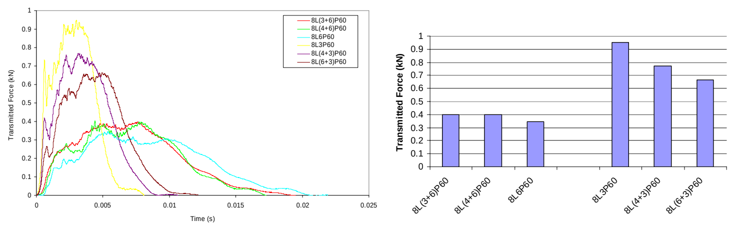
Figure 11(a) plots the impact force – displacement curve for these composites. It is clear that the two subgroups perform distinctively differently. The composites whose length ratio of free wall to bonded wall $\frac{l_f}{l_b} \leq 1$ demonstrated higher impact modulus than the other group. With the $\frac{l_f}{l_b} \leq 1$ subgroup, it is clear that 8L3P60 whose cell wall length ratio is 1 showed the highest impact modulus and 8L(6+3)P60, with a length ratio of 0.5, displayed the lowest impact modulus in the subgroup. For the subgroup with $\frac{l_f}{l_b} \geq 1$, a ductile behaviour was demonstrated for all three samples involved, with the 8L6P60 being the most ductile. Obviously, these two subgroups absorb impact energy in a distinctively different way. The cell wall ratio, therefore, can be used as an important parameter to influence the format the honey composites absorb impact energy. Figure 11(b) shows however the total amount impact energy absorbed by the composites of each subgroup is about the same. The subtle differences in the absorption of impact energy among the composites, especially in the $\frac{l_f}{l_b} \geq 1$ subgroup, require further investigation.



(a) Impact force – displacement curves (b) Energy absorption

Figure 11. Influence of cell wall ratio on energy absorption

Clear influence of the cell wall ratio on transmitted force has been demonstrated through the experiment. Figure 12 (a) depicts the relationship between the transmitted force and impact time, where distinctive differences are observed between the two subgroups. The subgroup with $\frac{l_f}{l_b} \geq 1$ clearly demonstrated better capability for impact force attenuation than the subgroup with $\frac{l_f}{l_b} \leq 1$. The maximum transmitted force of all honeycomb composites in this group are shown in Figure 12 (b). It is true for both the $\frac{l_f}{l_b} \geq 1$ and $\frac{l_f}{l_b} \leq 1$ subgroups that increase in the ratio leads to a higher transmitted force, and decrease in the ratio results in a lower transmitted force. It is also evident that $\frac{l_f}{l_b} \leq 1$ subgroup permits higher transmitted force than the other subgroup.



(a) Time dependency of transmitted force (b) Maximal transmitted force

Figure 12. Influence of cell wall length ratio on transmitted force

3.2.4 Influence of density of honeycomb composites with similar thickness

This group of honeycomb composites includes 4L6P60, 6L4P60, and 8L3P60, whose thickness is 29.2mm, 30.4mm and 31.6mm respectively, which are similar in practical terms. It is of interest to investigate the influence of the density of the honeycomb composites with the similar thickness dimension.

The three honeycomb composites were subject to the same impact condition as was described earlier. The composite specimens of 4L6P60 were crushed in the 8.3J impact test as indicated in Figure 13 by the sharp increase in contact force. The other two composites performed normally with composite 8L3P60 showing a higher impact modulus than 6L4P60. In creating engineering materials, low density is one of the features sought for the materials. Figure 11 would suggest that a lightweight honeycomb composite must be combined with strong cell walls in order for the composite to be of engineering significance. For honeycomb with particularly low volume densities, it is more important for the cell walls to have high strength.

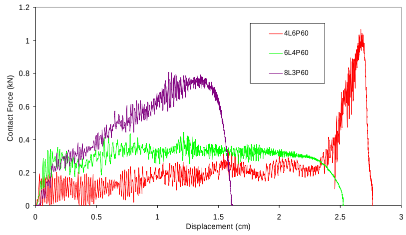


Figure 13 Influence of composite density on energy absorption

Figure 14 displays the transmitted force against impact time. It is again evident that composite 4L6P60 is crushed by the impact leading to large transmitted force. Composite 8L3P60 is associated to a higher transmitted force than 6L4P60 because the former has a higher impact modulus than the latter, which relates to the volume density of the composites.

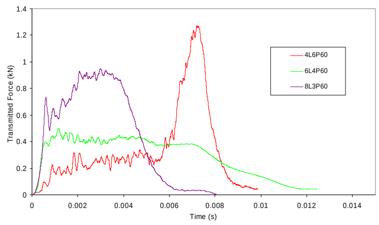


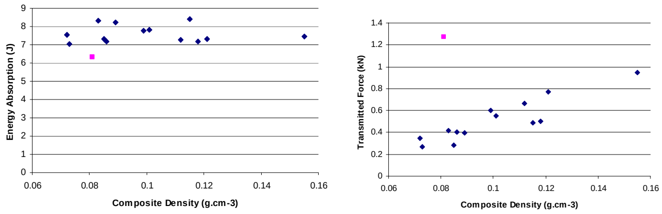
Figure 14. Influence of composite density on transmitted force

3.2.5 Discussions on Composite Density and Composite Thickness

So far, analysis has been carried out for the influence of the structural parameters, including cell opening angle, cell size, cell wall ratio, and cell density in the composite cress-section, on the impact characteristics of the honeycomb composites. It is important to be able to engineer the composites with required properties by manipulating the structural parameters. However, changes in structural parameters will have to lead to alteration of the volume density and thickness of the honeycomb composites. Therefore, it is necessary to see how the volume density and the thickness of all composites would affect the impact performance, particularly the impact energy absorption by the honeycomb composites and the transmitted force through the honeycomb composites.

3.2.6 Composite volume density

The impact energy absorption for all the composites against the composite density is illustrated in Figure 15(a), where the pink square mark is for 4L6P60 which was crushed during the impact test. No clear trend can be found in the relationship between the composite density and the energy absorption. As long as the honeycomb composites are not completely crushed, they demonstrated similar capability for impact energy absorption. This suggests that for a given level of impact energy, it is possible to create low density honeycomb composites for impact energy absorption. Work in this direction will lead to materials of high energy absorption to density ratio, which is attractive to many engineering applications. Figure 15(b) shows the relationship between the transmitted force and the composite volume density. Apart from the composite that was crushed during the test, a trend is clearly shown that for the honeycomb composites the transmitted force increases as the volume density goes up. As long as the composites are strong enough not to be crushed, lower density composites will be more capable to attenuate the impact force. This prompts more work in engineering design of honeycomb composites which are lightweight and mechanically protective.

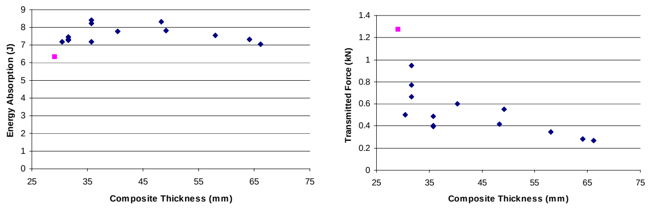


(a) Energy absorption (b) Transmitted force

Figure 15 Influence of volume density on honeycomb composites

3.2.8 Composite thickness

Again the pink square mark in Figure 16 represents composite 4L6P60 which was crushed in the test. It is observed from Figure 16(a) that the thickness of the composites did not demonstrate obvious influence on the energy absorption. Similar to the case of composite density, it seems that all honeycomb composites were capable to absorb similar amount of impact energy so long as the composite is not completely crushed. On the other hand, the thickness of composites seems to have a seemingly obvious effect on the transmitted force, i.e., the thicker is the composite, the smaller is the transmitter force, as demonstrated in Figure 16(b). These findings are in line with those found from Figure 15.



(a) Energy absorption (b) Transmitted force

Figure 14 Influence of thickness on honeycomb composites

4. CONCLUSIONS

Experimental study of 14 systematically designed and manufactured 3D honeycomb textile composites was carried out with an emphasis on the impact behaviour. In contrast to the honeycomb materials which are made from metal and paper for instance in the main and by connecting cells together to form the honeycomb structure, the 3D honeycomb textile composites are created from integral 3D textile reinforcements with the required material continuity in the composites. As described in Part I of this paper, the 3D honeycomb fabrics as composite reinforcements can be manufactured using the conventional textile technology which will lead to honeycomb composites with high performance but low cost. The experimental study described in this part of the paper leads to the conclusions which provide useful information for engineering honeycomb textile composites against impact.

1. The opening angle of the cells in the honeycomb composites plays an important role in determining the properties of the honeycomb composites. For the same fabric, increase in the opening angle results in the honeycomb composites being less energy absorbent and less force attenuating, and vice versa.
2. Increase in the cell size in the honeycomb composites makes the composites more efficient in impact force attenuation. It also makes the peak force disappear and the maximum transmitted force delayed in time. Also, reducing the cell size can lead to the least bulky engineering material for similar impact energy absorption.
3. Manipulation of the length ratio of cell walls leads to the creation of two damping materials with different impact behaviour in absorbing impact energy. $\frac{l_f}{l_b} \geq 1$ is associated to honeycomb composites with high modulus and high strength, whereas the inverse design lead to composites that has low modulus and low strength when encountered with the same level of impact. However, it was found that the total energy absorption was not affected by the length ratio of cell walls.
4. For the same volume, low density of the honeycomb composite leads to low contact force and low transmitted force. But, composites with too low density can be easily crushed as in the case of composite 4L6P60 in this study. So long as the composite is not destroyed by crushing, they are able to absorb similar amount of impact energy.

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