A numerical investigation on factors affecting in-plane deformation modes of honeycomb

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Abstract. The main factors affecting honeycomb in-plane deformation modes are researched using Patran/LS-DYNA in this paper. All changes in deformation modes can be summarized as changes in constraints. The main factors affecting the deformation modes include the material constitutive models, the boundary constraints, the cell wall thickness-to-length ratio \( h/l \) and the aspect ratio of honeycomb. Inner cells’ constraints and shape of crush bands are affected by the material constitutive models. The sliding difficulty of boundary cells and the initiation of crush bands are influenced by the boundary constraints especially the horizontal frictions and the cell wall thickness-to-length ratio \( h/l \). The number and region of crush bands are affected by the aspect ratio.

1. Introduction

Aluminium honeycomb is a kind of widely used cushion structures which absorbs energy with the elastic and plastic deformations. The in-plane energy absorption ability of honeycomb is closely related to the deformation modes. Therefore, the research on honeycomb deformation is an important part of the investigations of honeycomb. Deformation modes of honeycomb are characterized by distribution and shape of crush bands and are different in varied mechanical environments in pioneering works.

The in-plane mechanical properties of honeycomb and its single “Y” shape cell were well studied by Gibson and Ashby \(^1\) in both analytical and experimental methods. Papka \(^2, 3\) investigated the differences of honeycomb deformation modes under in-plane compression by simulation method. He found out that different deformation modes had different mechanical properties and if the key geometric, material and processing parameters were known the compress processes could be reproduced both qualitatively and quantitatively. Guo \(^4\) researched the intact and damaged honeycombs under in-plane compression with finite element method. The deformation modes of damaged honeycombs are different from those of the intact honeycombs and the crush bands are centered on the damaged cells for the lack of surrounding conditions.

Honig \(^5, 6\) studied the effect of elastic wave propagation on the crush bands’ initiation. When the impact velocity is larger than a critical velocity, the crush bands will be reinforced or delayed and the crush bands will initiate at the impact surface. For smaller impact speed, the initiation of crush bands is related to the distribution and extent of initial imperfections. Ruan \(^7\) divided the Aluminium honeycomb...
deformation modes under vertical compression into three types according to impact velocity and wall thickness-to-length ratio $h/l$. Zheng [8] repeated the simulations of honeycomb compression in vertical direction using finite element method. The deformation modes of honeycombs under vertical compression are different from Ruan’s results. He summarized that both results were the Quasi-static compressive modes and the crush bands initialized at the fragile parts in the whole stress field. The differences were caused by the different boundary conditions with same wall thickness-to-length ratio $h/l$ and same material parameters. In his simulation, the honeycombs could slide in horizontal direction. However, in Ruan’s work the honeycombs were fixed in horizontal direction.

Li [9] investigated the honeycomb with irregular shape and non-uniform cell wall thickness. The non-uniform cell wall thickness could be regarded as the artificial initial imperfections. In the compression of honeycomb with random cell wall thickness, the crush bands initialized at cells with thinner wall thickness. Moreover, the “X” shape crush bands and the boundary of a single crush band were not obvious for the random distribution of cell wall thickness. Zhang[10] studied the effect and distribution of defects on honeycomb in-plane deformation modes. The location and the number of defects influence the deformation modes and this influence is significant under low impact velocity.

Among these works, many factors affecting the distribution and shape of in-plane compressive honeycomb crush bands are proposed. It is important to the investigation of honeycomb deformation modes and mechanical properties.

In this paper, we use the finite element method to avoid the influence of imperfections. We summarized and studied the factors that can affect the deformation modes of honeycomb under in-plane compression, including material constitutive models, boundary constraints, cell wall thickness-to-length ratio $h/l$ and aspect ratio.

2. FEM model
In this investigation, both elastic and plastic deformations are researched. Honeycomb is usually made of traditional metal like aluminium or steel. With the development of material science, some materials with hyper-elasticity or pseudo-elasticity like Shape Memory Alloy (SMA) are also used in the manufacturing of honeycomb. Considering the effect of plastic hardening parts, the ideal elastoplastic model and bilinear model are studied in this section. The ideal elastoplastic model represents the traditional material such as Aluminium. The bilinear model represents the material with good plastic performance such as SMA. They are setting as the Plastic Kinematic (MAT3). The elastic parameters are same in the two models. The difference is the hardening model for the ideal model is 0 and the bilinear model is 1043 MPa. The material constitutive models are shown in Table 1. All material parameters are from uniaxial tensile tests.

| The material constitutive model | Hardening model $E_p$ (MPa) | Density $\rho$ (U/mm$^3$) | Elastic model $E$ (MPa) | Poisson Ratio $\nu$ | Yield stress $\sigma_y$ (MPa) |
|--------------------------------|-----------------------------|---------------------------|-------------------------|----------------------|-----------------------------|
| Ideal elastoplastic model      | 0                           | $2.7 \times 10^{-9}$      | 39213                   | 0.33                 | 181.5                       |
| Bilinear model                 | 1043                        |                           |                         |                      |                             |

The FE model built by Patran is shown in Figure 1. In this model, there are 15 regular hexagon cells in vertical direction and 14 cells in horizontal direction to keep the aspect ratio nearly equals to 1. Therefore, the effect of aspect ratio is reduced. The length and depth of walls in a single cell are $l = d = 10$mm. The thickness of cell walls is varied from $h = 0.2$mm to $h = 1.4$mm. The cell walls are defined as self-contact and the friction coefficient between adjacent cell walls is set to $f = 0.17$. All nodes are fixed in the direction vertical to paper. The length of single mesh is $l_m = 1$mm to ensure the accuracy. The impact is provided by a moving “Rigid wall” in vertical direction. The original velocity is $v = 1.0$m/s, which is considered as a Quasi-static compression. No-slip, friction coefficient $f = 0.17$, 

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\( f = 0.57 \) and no-friction four situations are considered as the boundary constraints between the specimens and the “Rigid wall”.

\[ f \]

Rigid wall

Honeycomb

Rigid wall

Figure 1. Finite element model.

3. The main factors affecting honeycomb deformation modes

3.1. Material Constitutive Models

Different material constitutive models have different plastic behaviors. The material models of honeycomb mainly influence on the homogeneity and the symmetry of the crush bands by affecting the plastic hardening parts and the constraints of inner cells. In this section, the honeycomb compression processes are simulated with the no-slip boundary in horizontal direction and the cell wall thickness is setting as \( h = 0.4mm \).

Figure 2 and Figure 3 are the compressed deformation modes of honeycombs with ideal elastoplastic material model and bilinear model. \( L = 242.49mm \) means the dimension in vertical direction of honeycomb. Using \( \delta / L \) to describe the displacement. The crush bands appear at both two specimens. However, the crush band in Figure 2 is asymmetric compared with that in Figure 3. The reason of this phenomenon is ideal elastoplastic model lack plastic hardening part. So, the bending bands become undamped hinges when the stress is over the yield stress. Cells with these undamped hinges do not need greater forces when the deformations continuum. For this reason, deformed cells cannot provide symmetric mechanical constraints to surrounding cells. Deformed cells using bilinear model require greater forces after yielding, which provides symmetrical and homogeneous constraints to the inner cells. The difference in constraints makes the deformation modes diverse.

\[ \delta / L \]

Figure 2. Deformation mode of honeycomb with ideal elastoplastic material model.

(a) \( \delta / L = 10\% \); (b) \( \delta / L = 30\% \); (c) \( \delta / L = 50\% \); (d) \( \delta / L = 70\% \).
3.2. Boundary Constraints

The boundary constraints contain the freedoms of motion and the horizontal frictions on the boundary. The frictions in horizontal direction affect the slide of boundary cells, which influences the initiation of crush bands and deformation modes of honeycomb compressed in vertical direction. No-slip, friction coefficient $f = 0.17$, $f = 0.57$ and No-friction four boundary constraints are considered. FEM models using bilinear material model are studied. Generally, the friction coefficients of metal are less than 0.2. The situation with the friction coefficient equal to 0.57 is setting to illustrate the influence of friction increase.

Figure 4 is the deformation modes of honeycomb with bilinear material model and different boundary constraints. Honeycomb deforms homogenously without horizontal friction. With the increase of friction, the crush bands are significant. For the frictions block the horizontal displacement of cells near the boundary, the constraints propagate to the center cells, which makes them deform under a symmetric and harsh mechanical environment. Because of the deformation of center cells, the constraints of surrounding cells change and the crush bands initiate. Otherwise, the “Poisson Ratio” phenomenon is also caused by frictions on the boundary.

3.3. Cell Wall Thickness-to-Length Ratio $h/l$

The thickness and the length of cell walls are the parameters to describe the cell walls’ geometry. In most cases, they appear in the form of the thickness-to-length ratio $h/l$. In this part, the cell wall length is $L = 10\text{mm}$ and the thickness of cell walls varies from $h = 0.2\text{mm}$ to $h = 1.4\text{mm}$. The larger ratio $h/l$, the more difficult the deformation of honeycomb cells. The deformation of cells relates to the initiation of crush bands and affects the deformation mode.

Figure 5 shows the crush bands’ initiation is not only related to the boundary constraints, but also the cell wall thickness. With the similar boundary constraints, the deformations of honeycombs with thicker cell walls are difficult. And the deformation modes are homogenous like the specimens with no-friction on the boundary. The increase of cell wall thickness makes the moment of inertia increase and the bonding modulus of cell walls are advanced. Finally, the moment of inertia is larger than the moment caused by friction and the boundary cells displace in horizontal direction. The motion of boundary cells changes the crush bands and the deformation modes.
Figure 5. Deformation modes with different cell wall thicknesses of bilinear honeycombs with boundary friction coefficient $f = 0.17$ ($\delta / L = 50\%$).

(a) $h = 0.2\text{mm}$; (b) $h = 0.6\text{mm}$; (c) $h = 1.0\text{mm}$; (d) $h = 1.4\text{mm}$.

3.4. Aspect Ratio
The number of cells can influence the honeycombs’ deformation especially the number and region of crush bands. Define the aspect ratio $a/b$ of dimension in horizontal direction $a$ divided by dimension in vertical direction $b$. In this section, the honeycombs using bilinear model are setting as cell wall thickness is 0.4mm and the cell wall length is 10mm. The boundary constraint is No-slip.

Change the aspect ratio from 0.23 to 3.88, the number and width of crush bands are changed comparing with the specimens of aspect ratio nearly equal to 1 in Figure 3. Figure 6(a) and Figure 6(b) are the models based on the model in Figure 3 and decrease cells’ number in horizontal direction or vertical direction. Figure 6(c) and Figure 6(d) are the models based on models in Figure 6(b) and Figure 6(a) but increase the cell’s number in vertical direction or horizontal direction. In Figure 6(a) and Figure 6(d), the number of crush bands increases in vertical direction with the decrease of aspect ratio. Moreover, the whole model is nearly “elastic buckling” in Figure 6(d). The width of crush bands increases with the increasement of aspect ratio in Figure 6(b) and Figure 6(c). For the number of cells increases in vertical direction, the number of crush bands changes from 1 to 2 in Figure 6(a). Because the inner cells lack constraints in horizontal direction, the whole model performs like “elastic buckling” during the process to initiate more crush bands in Figure 6(d). With the increasement of aspect ratio in Figure 6(b) and Figure 6(c), the constraints in horizontal direction increase and then the width of crush bands adds. Changing the aspect ratio influences the cells’ number and horizontal constraints, which affects the honeycomb deformation modes.

Figure 6. Deformation modes of bilinear honeycomb with different aspect ratio.

(a) $a/b = 0.45$; (b) $a/b = 1.90$; (c) $a/b = 3.88$; (d) $a/b = 0.23$. 

(a) (b) (c) (d)
4. Conclusion
In this paper, we summarize and analyse the main factors affecting the deformation modes of honeycomb compressed in vertical direction by finite element method. There are four factors analysed, including material constitutive models, boundary constraints, cell wall thickness-to-length ratio \( h/l \) and aspect ratio. The plastic hardening parts in material constitutive models affect the symmetry of inner cells’ constraints and the shape of crush bands. The boundary constraints especially the frictions in horizontal direction influence the initiation of crush bands. By limiting the motion of boundary cells and setting the centre cells in a harsh and symmetric mechanical environment, boundary constraints make the centre cells deform first and create the crush band by changing the surrounding cells’ constraints. The cell wall thickness-to-length ratio \( h/l \) affects the difficulty of cells’ deformation. The thicker the cell wall, the larger the moment of inertia. When the moment of inertia is larger than moment caused by friction, the boundary cells will slide and then affect the deformation modes. The aspect ratio influences the number and region of crush bands. When the aspect ratio decreases, the number of crush bands will increase and the whole model may become “elastic buckling” because inner cells lack horizontal constraints. When the aspect ratio increases, the region of crush bands will be wider because the constraints on the inner cells are reinforced.

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