Numerical Analysis of Kraft Paper Honeycomb subjected to uniform compression loading

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Abstract. The objective of this study is to investigate the crushing strength of Kraft paper honeycomb with different thickness of cell wall and different cell size subjected to compression loading. At first, experimental tests were carried out on Kraft paper honeycomb with 10mm cell size and 0.6mm thickness of paper with different mass density (RO). Then, a finite element model was developed in order to study the effect of cell size and thickness of cell wall on crushing properties of Kraft paper honeycomb. Based on the simulation results, the cell size and thickness of cell wall of Kraft paper honeycomb influence the crushing properties of the honeycomb. Crushing strength increases with decreasing the cell size which for the range of the study, cell size 10mm shows the highest strength. Meanwhile, 0.4mm thickness of cell wall results the higher crushing strength of honeycomb. Also, higher density gives higher crushing strength where in this study is found for 2.236 x 10⁶ kg/mm³.

1. Introduction

Over the years, low technology industry such as furniture and load bearing has been increasingly adopting more and more lightweight sandwich panel type of structure in order to reduce the materials cost and light weight. Recently, some manufacturers are aiming to use paper honeycomb panel or structure for load bearing application such as floor, decks, transportation pallet, load bearing wall and partition due to lower cost and low material usage of paper honeycomb compared to solid wood based panel [1–3].

The honeycomb core can have various configurations. The core type and density, thickness of the core and skin and their respective materials properties will determine the structure’s strength and stiffness. Honeycomb, a typical two-dimensional cellular material, its cell can be characterized by four main geometrical parameters including foil thickness, width, length and elevation angle [4]. Petrone et al [5] reported that energy absorption in honeycomb cores depend on the geometrical parameters of the honeycomb, essentially the cell wall thickness to length ratio (t/l) or the relative density of the core. In case of compressive loads, the critical buckling load is dependent on the bending of the cell wall.

Numerical simulation has always been an effective means for crashworthiness analysis of honeycomb structure. FE method is one of most effective approaches for analyzing stress in structure construction. In this way, some important results and conclusion have been reported [6–8]. Aktay et al. [9] modeled a detailed honeycomb structure which showed that fine micromechanical models can
provide better correlation with compression tests in both aluminum and aramid paper honeycomb. However, only limited number of FE model dealt with Kraft paper materials.

FE models developed in this study intend to simulate crushing properties of Kraft paper honeycomb with different cell size and thickness of cell wall. 8 cell of hexagonal cell were considered. The model is isotropic model.

2. Experimental test

In order to investigate the effect of mass density (RO), cell size of Kraft paper honeycomb (s) and thickness of cell wall (t), experimental test was performed which then followed by finite element simulation. Three different mass density (2.236 x 10^3 kg/m^3, 1.564 x 10^3 kg/m^3, 8.58x10^2 kg/m^3) were used in the experimental test. The cell size, thickness of cell wall and height for all specimens was 10mm, 0.5mm and 45mm, respectively. The geometric configuration of a hexagonal cell structure is shown in figure 1. The Kraft paper honeycombs were subjected to quasi-static compression loading by using SHIMADZU Autograph AG-X 250 compression machine. As the bottom plate was fixed and the upper plate was subjected to vertical downward displacement of 22.5mm. The force acting on the specimens was measured by load cell, and the force-displacement curve was plotted. The rate of displacement was 3 mm/min.

![Figure 1. Geometric configuration of a hexagonal cell of honeycomb](image)

3. Finite element modeling

Three-dimensional finite element models of the Kraft paper honeycomb were developed using Ls-Dyna software. The honeycomb model was generated using Belytschko-Tsai shell elements. Due to the complex mechanical behavior of honeycomb, five through integration points were defined for each of the shell elements. The thickness of the shell elements was chosen equal to the actual thickness of the Kraft paper honeycomb used in the experimental test. The binding material between cell walls was ignored in this study since the adhesive has full capability to attach every cell wall. Automatic single surface to surface contact was applied to avoid penetration between cell wall. Bottom nodes of the honeycomb were fixed in all of its degree of freedom. While, Movable plate on the top of honeycomb was modelled as rigid parts via analytical rigid feature and constrained to move only in the compression direction as shown in figure 2. Explicit/solver was implemented for compression analysis.

Through converge analysis completed by employed FE models having different mesh sizes, an element size of 1mm, 1.5 mm and 2mm are found to produce sufficiently accurate stress result for honeycomb with 10mm, 15mm and 20mm cell sizes, respectively (Figure 3).
4. Results and Discussion of Compression Test

4.1. Finite element model validation

The crushing response of FE model was compared with experimental results in order to validate the numerical model. Load-displacement curves of honeycomb which obtain from quasi-static analysis were implemented to determine the force (N), young’s modulus (E) and yield stress (σ_y) of the Kraft paper honeycomb. The elastic modulus was calculated by the ratio stress-strain curve in the elastic deformation region. Figure 4 shows the force-displacement curve of the Finite element analysis for different mass density (RO) where RO1, RO2, RO3 refer to $8.58 \times 10^7$ kg/mm$^3$, $1.564 \times 10^6$ kg/mm$^3$ and $2.236 \times 10^6$ kg/mm$^3$, respectively. Based on the graph, it is observed that initially the structure behaves
elastically and load increases in a steady manner, then an initial peak force occurs followed by decreases in force value. After that, the post buckling phase develops with secondary peaks which directly related to the formation of subsequent local buckling occurrences in honeycomb structure as crushing progresses. The subsequent peaks in stress history have significantly lower magnitudes in comparison with initial peak. Meanwhile, the peak force values are listed in table 1 and compared with experimental results. It is clear in that the obtained values by FE model are in good agreement with the experimental results and the maximum different are about 12%.

![Figure 4](image)

**Figure 4**: The three-element size of honeycomb for 10mm, 15 mm and 20mm cell size a)1 mm \((s=10\text{mm})\) b) 1.5mm \((s=15\text{mm})\) c) 2 mm \((s=20 \text{mm})\)

**Table 1.** The peak force (N) of Kraft paper honeycomb obtained by FE model and Experimental tests.

| \(\rho\) (kg/mm\(^3\)) | Force (N) | Experimental | FEA | Difference (%) |
|---------------------------|-----------|--------------|-----|----------------|
| 8.584e\(^{-7}\) RO1      | 343.07    | 332          |     | 3              |
| 1.564e\(^{-6}\) RO2      | 478.37    | 423.3        |     | 12             |
| 2.236e\(^{-6}\) RO3      | 650.13    | 597          |     | 8              |

Figure 5 shows the deformation of Kraft paper honeycomb. It observed that the localized fold firstly occurs at the top surface of the honeycomb (free face). The Kraft paper honeycomb initially buckles, and triggers the honeycomb wall to deform. During the first folding process, the second fold start to form simultaneously. With the increase of compression displacement, the cell walls of Kraft paper honeycomb folded in layer by layer up to the compaction of compressed to 22.5mm. Since local buckling occurs early, the honeycomb structure works in a post buckling mode. Castenie et al. [6] found that the stiffener in honeycomb is the vertical edge where it formed by intersection of three cell walls. They reported that, for honeycomb cell, the compression is mainly taken by vertical edge since the buckling of the cell wall occurs earlier. Then the collapse of the stiffened structure corresponds to the buckling of the stiffeners.
Figure 5. Failure mechanism of Kraft paper honeycomb.

4.2 The effect of cell size of honeycomb

In order to study the cell size effect of Kraft paper honeycomb, crushing of honeycomb structure is simulated by changing the cell size of honeycomb to 10mm, 15mm and 20mm (Figure 6). Figure 7 and 8 show the effect of different mass density (RO) and cell size on crushing strength. It is observed in the graphs that the honeycomb cores with small cell size had the larger crushing strength. Meanwhile increasing the density also increase the crushing strength. According to simple compression failure mechanism by Zhang and Ashby [10], the buckling load is determined by the second moment of inertia of the wall and cell side size as follow:

\[
P_{crit} = \frac{K \varepsilon_s t^3}{(1-\nu_s^2)l}
\]  

where, \( K \) is an end constant factor, \( E_s \) is young’s modulus of solid cell wall materials, \( \nu_s \) is Poisson’s ratio of the solid cell wall materials, \( t \) is the thickness of honeycomb materials and \( l \) is the length of cell side. Based on the eq. 1, buckling load decrease with increasing the length of cell wall. When local buckling of the structure is in lower forces values, crushing strength of the honeycomb decline.
Figure 6. Three different cell size of Kraft paper honeycomb

Figure 7. Crushing strength-RO curve for different cell size

Figure 8. Crushing strength-cell size curve for different mass density
The crushing mechanism of different cell size and mass density in isometric and front view were illustrated in table 2. The crushing mechanism is directly associated with cell size and mass density. It can be seen from the figure that the failure mechanism of Kraft paper honeycomb due to the folding of the cell walls and all cell walls folded at the top surface of the honeycomb. Based on Castenie et al [11] reported in their book that the fold shape differed for each material where rounded shape for aluminum and sharp angle for Nomex. This difference of shape can be attributed to the different plasticity of the materials. In this study, Kraft paper honeycomb deformed in sharp angle shape which same as Nomex.

Besides, it also observed that folding length of the Kraft paper honeycomb are different. Honeycomb with large cell size shows larger folding length compare to small cell size. Xu et al [12] reported that for large cell size of honeycomb, the plastic buckling is more to occur in the middle region of the specimens, indicating that the deformation pattern is influenced by the dimension of honeycomb cell.

Table 2. Deformation of FE model of Kraft paper honeycomb with different cell size (isometric and front view)

|       | S = 10mm | S = 15mm | S = 20mm |
|-------|----------|----------|----------|
| RO1   | ![Image](image1) | ![Image](image2) | ![Image](image3) |
| RO2   | ![Image](image4) | ![Image](image5) | ![Image](image6) |
4.3 The effect of thickness of cell wall

The effect of cell wall was studied by changing the thickness of cell wall, \( t \) between 0.4mm to 0.6mm. The cell size for all specimen is 10mm. Nine FE model was developed in order to study the effect of cell wall thickness. From the simulations, the effect of cell wall on crushing strength were illustrated in figure 9 and 10. Based on the graphs, it observed that the crushing strength increase with increasing the mass density. However, crushing strength shows the optimum value at 0.5mm cell wall thickness. According to simple compression failure mechanism as depict in equation (1), the critical buckling load effected by thickness of cell wall. Where, by increasing the thickness of cell wall, critical buckling load increases and lead to larger energy absorption.
4. Summary
In this work, the influence of cell size, mass density and thickness of cell wall of Kraft paper honeycomb was investigated numerically. It is shown that mass density of Kraft paper honeycomb affected the crushing force of the honeycomb. Kraft paper honeycomb with higher mass density had higher crushing force where the simulation results shows the good agreement with the experimental result. Both cell size and cell wall thickness also influenced the crushing strength of the honeycomb. 10mm cell size with 0.4 mm cell wall thickness were recommended in increasing the crushing strength of the Kraft paper honeycomb.

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