The effect of entrapped air on the dynamic response of Nomex honeycomb sandwich structures under flatwise compression

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Abstract
Nomex honeycomb has low relative density, and its high volume-ratio of the entrapped air plays a significant role on its mechanical responses under flatwise compression. We investigated the effect of the entrapped air in Nomex honeycomb by using both experimental test and numerical simulation. Experimentally, both static and dynamic flatwise compression tests were conducted on the Nomex honeycombs with and without facesheets. The air effect was obtained through comparing the test results of the afore-mentioned two different specimens. Numerically, a multi-cell model was developed and proposed using the airbag method to model the entrapped air. The simulation results were consistent with the experimental results, and the energy absorption during the crushing process of the honeycomb was analyzed based on the simulations. We found that the entrapped air has little effect on the collapse strength and stiffness of the nomex honeycomb, however, it has significant effect on the energy absorption capacity of the nomex honeycomb.

1 Introduction
Honeycomb sandwich structures have excellent mechanical properties, such as high strength-to-weight ratio and high-energy absorption capacity, and this makes them are extensively used as protective components. In MD-500 helicopter under low velocity crash, the honeycomb-made energy absorbing device could reduce the impact acceleration levels by a factor of three [1]. Metallic honeycomb possesses excellent kinetic energy absorption properties which can be used as an impact resistance members in structural applications [2].

The strain rate related material flow in the cells of cellular material is part of the origin of energy absorption under flatwise compression[3]. Zhang et al. [4]-[6] studied performance of metallic cellular materials subjected to dynamic compressive loadings but did not consider the air effect. Thomas et al. [7] conducted SHPB tests of closed-cell foams in temperature boxes and discovered that dynamic compressive force of foams will be enhanced by the growing pressure of the entrapped air, which is environmental temperature related. It was found that pressure change of the entrapped air during dynamic compression is a direct source of strain hardening for aluminum honeycombs, whereas it has less influence on the strain hardening of aluminum foams [8]. Xu et al. [9] penetrated the facesheets of aluminum honeycomb sandwich with a certain number of holes to make the cells open. By comparing
it with the closed-cell specimens, they drew the conclusion that the entrapped air could improve energy absorption capacity of aluminum honeycomb sandwich under compressive loads.

Some numerical simulation methods have been proposed for parameter analysis and further study of the effect of the entrapped air. A mesoscopic model of closed-cell polymer foams subjected to dynamic loading was developed using a surface-based fluid cavity tool in ABAQUS [10]. Sun et al. [11] used the similar method in 2D models and studied the air effect of honeycomb sandwiches subjected to in-plane compression. The numerical results showed that the air effect is dependent on cell morphology.

Nomex honeycomb sandwich, widely used in aerospace industry, has a relative density of 0.05 and contains a large percentage of the air entrapped within the cells [12]. Analyzing the effect of entrapped air correctly is of great help to estimate the energy absorption capacity of Nomex honeycomb under flatwise compression accurately. However, specialized tests for assessing the entrapped air effect of sandwich structures with Nomex honeycomb core under static compression are very few, in addition, existing numerical solution method cannot well simulate the air effect within. Comparison between honeycomb (without facesheets) and honeycomb sandwich (with facesheets) is one way to investigate the effect of entrapped air. However, in this method, not only the gas was entrapped by two facesheets, upper and lower edges of the cell walls were also transversely constrained. The constraint of facesheets is an additional variable for the comparison. It is necessary to study its effect on mechanical behavior of Nomex honeycomb under flatwise compression.

This paper investigated the effect of the entrapped air on mechanical behavior and failure mode of Nomex honeycomb under flatwise compression. Specimens with and without facesheets were firstly tested under static and dynamic compressive loads for experimental comparison. Then, a multi-cell model of the honeycomb was proposed for numerical investigation, in which, airbag method of modeling the entrapped air using commercial software LS-DYNA was developed. Finally, a model of honeycomb with facesheets but without the entrapped air was developed and embedded into numerical investigation to estimate the effect of the transverse constraints of facesheets on mechanical behavior of Nomex honeycomb under flatwise compression.

2 Experimental tests
2.1 Description of specimens

(a) Without facesheets   (b) With facesheets
Two types of Nomex honeycomb specimens, with and without facesheets, were tested. Fig.1(a) shows the specimens without facesheets (honeycomb without facesheets). Fig.1(b) shows the specimens with two 1.5mm thick carbon fiber laminates glued on top and bottom surfaces of honeycomb core (honeycomb with facesheets). The Nomex honeycomb cores with a length of 50 mm, a width of 50 mm and a height of 20 mm are used in the specimens. Since the minimum cross-sectional area should be 2500 mm$^2$ for the honeycomb cores with 3.2 mm cell size according to the standard test method, ASTM C365 / C365M-11 [13]. In this paper, honeycomb with facesheets is also expressed as honeycomb sandwich.

The honeycombs are manufactured by the expansion process of Nomex Type 412 aramid paper [12][14]. Single and double cell walls of the Nomex honeycomb are layered films. The single cell walls consist of one aramid paper layer inside and two phenolic resin layers outside. The double cell walls consist of two aramid paper layers inside and two phenolic resin layers outside. One aramid paper layer is 0.054 mm thick and one phenolic resin layer is 0.008 mm thick. Therefore, the thickness of the honeycomb single cell walls is 0.07 mm, and that of double cell walls is 0.124 mm.

2.2 Dynamic tests

The compressive tests of 5 specimens for honeycombs without facesheets and 5 specimens for honeycombs with facesheets were conducted using the Instron 9350 impact testing system, as shown in Fig. 2. The CeastVIEW software is used in the impact testing system for parameters setting and graphical display. A force transducer of 10t load capacity was installed under the lower end of the platen (shown in Fig.2), and the force transducer was connected to a data acquisition instrument of DH 5960. A cylindrical hammer was installed under the drop weight, and its size is a diameter of 200 mm
and a height of 30 mm. The total mass of movable head is 27 kg.

During test of dynamic compression, the upper hammer moved downwards to impact with the specimen on the lower platen. The specimens were glued on the platen to avoid disconnection with the lower platen and to minimize the measurement error. The impacting velocity is 3 m/s and the impacting energy is about 121.7 J. The data acquisition frequency was set as 100 /ms.

3 Numerical simulation

3.1 Modelling entrapped air by Airbag method

Airbag tool is basically a surface-based control volume (CV) method [16], which can be used to model an air-filled structure. Six cell walls of honeycomb and two facesheets as well as the air entrapped by them are simulated as an air-filled cavity using Airbag tools. Honeycomb sandwich can be regarded as many isolated airbags. The change of pressure, volume and temperature of the air inside the cell can be calculated using a special airbag definition subroutine [16][17][18]. It is assumed that the air inside the cell has ideal properties (pV/T = constant).

Cell walls of honeycomb sandwich are subjected to compressive load and air pressure within the cells as shown in Fig.3. The structure deformation leads to change of the cell volume, which results in change of temperature and pressure of interior air within the cells. Meanwhile, pressure and temperature change of the air also affect folding process of cell walls. This interaction between the honeycomb sandwich and the cell gas is shown in Fig.3, in which different cells are marked as number k and time step is marked as number i. In calculation, the initial air pressure is set as atmosphere pressure. The air pressure is applied in the cells in the first millisecond of the analysis, and then the structure was subjected to compression load.

3.2 Constitutive model of honeycomb core

The material model was composed of two parts. One part was the strength criterion that controls the yield strength according to stress invariants. The other part was the equation of state (EOS) that determines the hydro-pressure in terms of density and energy.

Nomex cell walls consisting of aramid paper and resin coat was modelled as an elastic-perfectly
plastic material. Its compressive strength was assumed to be the same as its tensile counterpart. The plastic kinematic material was used to simulate the cell walls. This model was suited to model isotropic and kinematic crushing plasticity with the option of including quasi-static and dynamic compression. The mechanical properties of Nomex cell walls are tabulated as follows [12].

Table 1 Mechanical properties of cell walls of Nomex honeycomb core

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Density</td>
<td>$1 \times 10^9$ t/mm$^3$</td>
</tr>
<tr>
<td>Young's modulus</td>
<td>2,500 MPa</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Yield stress</td>
<td>86 MPa</td>
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</table>

For modelling entrapped air using the airbag tool, it was presumed that the gas inside the cell has ideal properties ($pV/T = \text{constant}$). Atmospheric pressure was set at $1.013 \times 10^{-1}$ MPa, density was set as $1.29 \times 10^9$ kg/mm$^3$ and initial atmospheric temperature was set as 300 K.

3.4 Mesh and boundary conditions

The finite element (FE) models of the honeycombs with and without facesheets are developed using commercial software of LS-Prepost. Through trial studies, we found that the area would have a limited size effect on the calculation results as the area is equal to or larger than that shown in Fig.4. With consideration of high computing resource cost of the airbag method, a multi-cell model covering an area shown in Fig.4 is developed in this study. This model represents 7.12 percent of the tested specimen.

Four-noded shell elements are used to model the Nomex cell walls. Because this kind of element can well simulate the folding process of cell walls and presents high explicit calculation efficiency in large deformation [19]. There are totally 76,800 shell elements for wall grids of multi-cell model.
As is shown in Fig. 5, two analytical rigid surfaces, W1-PLANAR and W2-PLANAR, of 8.9 mm$^2$ and 177.8 mm$^2$ in area represent the facesheets for unit cell model and multi-cell model respectively. The rigid surface, W2-PLANAR, is set to be fixed. The other rigid surface, W1-PLANAR, is set to be impacted by a simulated movable head with a velocity of 3 m/s using the surface to surface contact algorithm in LS-DYNA. Self-contact algorithm is used to define the possible contact among the cell walls. Friction coefficient between the honeycomb cell walls is set to be 0.4 according to the literatures [20][21].

In addition, a model of honeycomb with facesheets but without the entrapped air was developed and embedded into numerical investigation to estimate the effect of the transverse constraints of facesheets on mechanical behavior of Nomex honeycomb under flatwise compression.

4 Experimental and numerical results

Fig.6 shows the experimental and the simulation results with and without the entrapped air under dynamic compression. The force data in the paragraph are obtained using the force transducer and data acquisition instrument in the tests. A typical result is chosen from the 5-repeated dynamic compressive tests for honeycomb with and without facesheets respectively.
Fig. 6 Comparison of the simulated and tested force-displacement curves of honeycomb with and without facesheets subjected to dynamic flatwise compression.

Fig. 6 shows the experimental and the simulation results with and without the entrapped air under dynamic compression. It can be found that the curves can be divided into three stages. The first stage is in displacement between 0 mm and 0.7 mm, which is elastic stage where the force-displacement curves show linear elasticity. 0.7 mm is a turning point, where the force reaches one peak of 5.7 kN called honeycomb collapse force. After that, the force drops significantly to an initial plateau force of about 2.2 kN at displacement of 0.8 mm. Following that, it is a long crushing stage with a slight increase of the force from 2.2 kN to 2.9 kN (without facesheets) and 3.8 kN (with facesheets). When the displacement is larger than 13.5 mm, force rises quickly, which is well in to the densification stage. The test was terminated at the force of 7.0 kN.

In the elastic stage, the results of the models with facesheets agree well with that without facesheets. It is indicated that the entrapped air has a little effect on curves in elastic stage. Therefore, the entrapped air can be neglected in this stage of calculation.

In the crushing stage, the effect of the air increases gradually, as shown in Fig. 6. Difference of the force from results of the honeycomb with and without facesheets becomes obvious when the displacement exceeds 5 mm. Simulated and tested curves of honeycomb with facesheets reach their ends of crushing stage a little earlier than honeycomb without facesheets because of the effect of the entrapped air.

In the densification stage, folding cell walls begin to squeeze with each other. As a result, the force rises quickly. Difference between the curves of honeycomb with and without facesheets is greatest at the beginning. After that, the curves come closer and closer again. Slope of the tested curve in densification stage is lower than that of all the simulated curves as shown in Fig. 6. This phenomenon can be attributed to loss of the entrapped air in large deformation where cell walls are cracked.

In a word, the entrapped air has little effect on the collapse strength and stiffness of the nomex honeycomb in elastic stage while it has an obvious enhancement of the compressive force in crushing and densification stages. Therefore, it is necessary to take into account the effect of the entrapped air for honeycomb sandwich subjected to dynamic compression in simulation.
5 Discussion
5.1 Contribution of transverse constraints

Fig. 7 Folding process at various compressive displacement of Nomex honeycomb without facesheets under flatwise compression

Fig. 7 shows the folding process of honeycomb without facesheets at various compressive displacement. It is found that collapse is likely to happen at the top or bottom sides of the honeycomb without facesheets. To estimate the contribution of the transverse constraints of the facesheets on the mechanical response of honeycomb under flatwise compression, a model of Nomex honeycomb with facesheets but without the entrapped air was added in numerical simulations.

Fig. 8 Comparison of the simulated force-displacement curves of Nomex honeycomb subjected to dynamic compression
Fig. 8 shows three force-displacement curves of honeycomb with facesheets, honeycomb with facesheets but without the entrapped air and honeycomb without facesheets subjected to dynamic compression respectively. It is found that the curve of honeycomb without facesheets is larger in the force than that of the others, especially when displacement larger than 6 mm. The curves of honeycomb without facesheets and honeycomb with facesheets but without the entrapped air are similar to each other. The difference of the two curves, mainly exists in crushing stage, is caused by transverse constraints of facesheets on upper and lower edge of cell walls. It is illustrated that the transverse constraints of facesheets has a little influence on the energy absorption capacity of honeycomb with facesheets subjected to dynamic load. The energy absorption capacity of honeycomb with facesheets is mainly improved by the effect of the entrapped air within the closed cells.

5.2 Slopes of crushing stage and energy absorption capacity

![Fig. 9 Slopes of crushing stage of the simulated and tested force-displacement curves of honeycomb subjected to dynamic flatwise compression](image)

Fig. 9 Slopes of crushing stage of the simulated and tested force-displacement curves of honeycomb subjected to dynamic flatwise compression

To study intuitively the effect of the entrapped air on mechanical behavior of honeycomb sandwich under dynamic compression in crushing stage, data from Fig. 6 is taken from 1 mm to 13 mm and then linearly fitted using least square method. Starting points of all the curves fitted are moved to the point of fitted curve of test. Slopes of all the numerical and test fitted curves are given in Fig. 9, where ‘k’ represents slope in linear regression equation. It is shown that curves of honeycombs with facesheets give much bigger slopes than the curves of honeycombs without facesheets. Absolute difference ($\Delta k$) of slopes between results with and without facesheets is calculated. That is $\Delta k=80$ for tested results, $\Delta k=74$ for simulated results respectively. The airbag method provides a good simulation of the entrapped air within the closed-cells of Nomex honeycomb. It is found that the effect of the entrapped air on the compressive force of Nomex honeycomb sandwich structures is negligible at the beginning of crushing stage, but when compressive displacement increases it becomes more and more significant. The compressive force is enhanced by the entrapped air of 1kN at displacement of 13 mm.
Table 2 Energy (kJ) absorbed by Nomex honeycomb

<table>
<thead>
<tr>
<th></th>
<th>Test</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without facesheets</td>
<td>45.8</td>
<td>47.5</td>
</tr>
<tr>
<td>With facesheets</td>
<td>50.3</td>
<td>51.6</td>
</tr>
<tr>
<td>Energy absorbed by the air</td>
<td>4.5</td>
<td>4.1</td>
</tr>
</tbody>
</table>

By choosing the data from Fig.6 from 0 kN to 6 kN, energy absorbed by the tested and simulated Nomex honeycomb is calculated, as shown in Table 2. It is found that the simulated result of honeycomb without facesheets is only 3 percent points higher than the tested result of honeycomb without facesheets. The energy absorbed by the air is also calculated by subtracting the data in first row from the data in second row. It shows that the entrapped air contributes nearly 10 percent of the energy absorption capacity to the Nomex honeycomb sandwich structures. It is concluded that energy absorption capacity of honeycomb with facesheets can be improved by the effect of the entrapped air within the closed cells significantly.

6 Conclusions
1) The entrapped air within the closed-cells has little effect on the collapse strength and stiffness of Nomex honeycomb sandwich structures under flatwise compression.
2) Energy absorption capacity of Nomex honeycomb sandwich structures can be greatly improved by the effect of the entrapped air within the closed cells.
3) The effect of the entrapped air on the compressive force of Nomex honeycomb sandwich structures increases with compression.

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References


