


General paper

CRUSH BEHAVIOR OF HONEYCOMB STRUCTURE IMPACTED BY DROP-HAMMER AND ITS NUMERICAL ANALYSIS

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Abstract: Crush behavior of the bare honeycomb structure with hexagonal cell (without the reinforcing plate members bonded on both edges) is studied experimentally and numerically. The dimensions of honeycomb cell used are 3/8in. (9.525mm) and 3/4in. (19.05mm) and the material of foil is an aluminum alloy, A5052. Their foil thicknesses are 0.020mm, 0.033mm and 0.046mm. In experiment, the impact velocity is ranged from 1.98 to 10m/s. As for 3/8in. honeycomb, irregular folding pattern appears just to a little extent in experiment. On the other hand, very irregular buckling pattern is observed in 3/4in. honeycomb. Crush strength becomes slightly larger as the impact velocity increases. The maximum value of acceleration measured by an acceleration sensor attached to the drop-hammer seems to be almost constant when the impact velocity is greater than a certain value, and increases rapidly as the foil thickness increases. Furthermore, numerical simulation is carried out by using the dynamic explicit nonlinear finite element code DYNA3D. In the computation, due to the geometrical symmetry of hexagonal honeycomb core, the 'Y' letter model is proposed. In computation the buckling with folding pattern appears, though, the irregularity in folding pattern is larger in computation than in experiment. Predicted dependence of the crush strength on the impact velocity and the foil thickness is similar to the corresponding experimental result.

Key words: Honeycomb structure, Aluminum honeycomb, Crush behavior, Impact deformation, Numerical analysis

1 INTRODUCTION

Demand of emission and fuel conservation in aircraft and automobile etc. has been increasing, for which lightening their bodies is very effective. Much weight saving is possible by using honeycomb structure. In addition to this, especially in crush situation, the honeycomb structure is very suitable, because it can absorb impact energy with almost constant crush strength. Therefore, the honeycomb structure has been used as the inner member of wall panel of a container of precision devices which might be dropped from the aircraft. Recently experimental study of impact of honeycomb structure was reported[1], where the attention is paid mainly to the energy absorption performance of honeycomb. Experimental and numerical study with regard to the energy absorption by a rectangular thin walled pipe is also reported[2].

In the present paper, bare aluminum honeycomb structure whose cell is hexagonal foil with several kinds of foil thicknesses and of cell dimensions is compressed by a drop-hammer. The maximum impact velocity used is 10m/s and the influence of the impact velocity, foil thickness and cell dimension on the strength of honeycomb structure is examined.

Furthermore, numerical simulations corresponding to the several experiments are carried out by using the dynamic explicit nonlinear finite element code DYNA3D[3]. The main objective of numerical simulation is to develop a proper simplified model of hexagonal honeycomb structure. The numerical results are compared with the experimental results.

2 TEST HONEYCOMB

The dimensions of hexagonal honeycomb cell used are 3/8in. (9.525mm) and 3/4in. (19.05mm) and the material of foil is an aluminum alloy, A5052. An example of test honeycomb is shown in Fig.1. The whole dimension of all the honeycombs used in experiments is 150(mm) high with a square cross section of 150×150(mm) and the foil thicknesses are 0.020mm, 0.033mm and 0.046mm. Test honeycombs and mechanical properties of the foil are listed in Tables 1 and 2, respectively. Aluminum foils are bonded by thermosetting phenol resin at double wall portion and the

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Table 1. Variation of honeycomb grade.
Foil material: A5052.

<table>
<thead>
<tr>
<th>Core grade</th>
<th>Foil thickness, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/4-0.001</td>
<td>0.033</td>
</tr>
<tr>
<td>3/4-0.015</td>
<td>0.046</td>
</tr>
<tr>
<td>3/8-0.0006</td>
<td>0.020</td>
</tr>
<tr>
<td>3/8-0.001</td>
<td>0.033</td>
</tr>
</tbody>
</table>

Table 2. Mechanical properties of foil material.

<table>
<thead>
<tr>
<th>T, mm</th>
<th>U.T.S., MPa</th>
<th>$\sigma_{0.2}$, MPa</th>
<th>e, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.020</td>
<td>347.2</td>
<td>343.0</td>
<td>1.2</td>
</tr>
<tr>
<td>0.033</td>
<td>324.2</td>
<td>300.0</td>
<td>2.5</td>
</tr>
<tr>
<td>0.046</td>
<td>302.0</td>
<td>274.0</td>
<td>2.6</td>
</tr>
</tbody>
</table>

T: Foil thickness
U.T.S.: Ultimate tensile strength
$\sigma_{0.2}$: 0.2% proof stress
e: Total elongation

The thickness of bonding layer is 0.004mm. There exist very small pin holes through foil thickness to release gas generated during the heating process of bonding.

3 EXPERIMENTAL PROCEDURE

An impact testing machine which enables us to give the maximum drop-hammer speed of 10m/s is used and its general view is shown in Fig.2. The impact velocity is ranged from 1.98 to 10m/s. According to the capacity of energy absorption of honeycomb and impact velocity, two types of drop-hammer with the weight of 800N(mainly made of steel block) or 200N(mainly made of aluminum plate) are used. The measurement device of compression force and the drop-hammer are illustrated in Fig.3, in which the base plate on the load cell is held by the four sliding guide posts.

As illustrated Fig.3, a piezoelectric acceleration transducer is attached to measure the maximum acceleration of the sensor(transducer) during impact deformation. The load- and the acceleration-time curves are recorded by a digital storage type oscilloscope, then recorded by XY-recorder. Firstly, using the 800N drop-hammer, when the initial impact velocities of drop-hammer are set to 3.13m/s and 1.98m/s for 3/8in. and 3/4in. honeycomb respectively, the effects of foil thick-
thickness and cell dimension on the compression stress are examined. Next, with respect to the 3/8-0.001 honeycomb, the effect of impact velocity on the compression stress is examined using the 200N drop-hammer, while the corresponding quasi-static tests are also performed.

4 EXPERIMENTAL RESULTS AND DISCUSSIONS

Examples of crushing patterns are represented in Fig. 4. In the case of 3/8in. honeycomb, folding pattern appears almost periodic and regular. On the other hand, 3/4in. honeycomb shows very irregular folding patterns, where the double wall along which two foils are bonded is partially torn off and partial breakage occurs. Buckling pattern becomes irregular as the rel-

Fig. 4. Examples of crushing patterns.
Hammer weight: 800N

Fig. 5. Example of stress-time curve.
Dimension of honeycomb cell: 3/8in.
Foil thickness: 0.033mm
Impact velocity: 3.13m/s

Fig. 6. Relationship between stress and foil thickness.
Hammer weight: 800N

(a) Dimension of honeycomb cell: 3/8in.
Impact velocity: 3.13m/s

(b) Dimension of honeycomb cell: 3/4in.
Impact velocity: 1.98m/s
An example of stress-time curve obtained in experiment is given in Fig.5 where stress defined here is simply the load divided by the whole cross-sectional area of the specimen. Initial peak stress is followed by almost constant crush strength (overall compressive stress during multi-folding due to buckling). Figure 6 shows the relationship between the stress and foil thickness. The crush strength seems to have almost linear relation with the foil thickness, while the peak stress shows somewhat nonlinearity in 3/8in. honeycomb. The discrepancy between peak stress and crush strength becomes larger for thicker foil. The relative difference between peak stress and the crush strength in 3/4in. honeycomb is larger than that in 3/8in. honeycomb. Moreover, the crush strength in 3/4in. honeycomb is less than a half of that in 3/8in. honeycomb though the foil density in 3/4in. honeycomb is just a half of that in 3/8in. honeycomb. This may be due to the fact that mutual constraint to buckling of foil walls is weaker in a coarser honeycomb structure. Therefore, from the view point of structural lightening, the honeycomb with smaller cell dimension is recommended as a better energy absorber.

Figure 7 depicts the relationship of the peak stress and crush strength to the impact velocity. The peak stress and crush strength have a tendency to become larger as the impact velocity increases. On the other hand, the peak stress in quasi-static test shows a remarkably high value, the reason of which is not clear at present.

The relationship between the maximum value of measured acceleration and foil thickness for the case of 3/8in. honeycomb under the impact velocity of 3.13m/s is shown in Fig.8. In this case, the acceleration sensor is attached on the 800N drop-hammer as shown in Fig.3. In Fig.8 the positive value is taken in the direction of deceleration of drop-hammer. Note that at least the maximum value of the measured acceleration which appears at the instant of impact is considered to be that of the drop-hammer, though the acceleration varies oscillatorily with time, being may affected by the eigen number of vibration of the sensor itself. The maximum value of acceleration increases rapidly as the foil thickness increases. Figure 9 presents the relationship between the maximum value of acceleration and impact velocity for the case of 3/8in. honeycomb, whose foil thickness is 0.033mm. Of course, this maximum value is affected by the structure and the mass of the drop-hammer. The maximum value of acceleration seems to be almost constant with respect to the impact velocity by hammer.
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Fig. 10. 'Y' letter model of honeycomb structure used in computation. (At A, B and C, the wall edges can move only in out-of-plane direction.)

Table 3. Mechanical properties of honeycomb materials used in computation.

<table>
<thead>
<tr>
<th></th>
<th>Foil (assumed)</th>
<th>Bond (assumed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, g/cm³</td>
<td>2.7</td>
<td>2.0</td>
</tr>
<tr>
<td>Young's modulus, GPa</td>
<td>72.0</td>
<td>1.29</td>
</tr>
<tr>
<td>Shear modulus, GPa</td>
<td>28.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Yield stress, MPa</td>
<td>300.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Hardening modulus</td>
<td>0.01</td>
<td>0.0</td>
</tr>
<tr>
<td>Bulk modulus, GPa</td>
<td>60.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

5 NUMERICAL SIMULATIONS OF CRUSH BEHAVIOR

5.1 Computational Method

Numerical simulations are carried out by using a public domain of the dynamic explicit nonlinear finite element code DYNA3D[3] whose post-processor, graphics program to display deformed shapes, is newly developed. In computation, due to the geometrical symmetry of hexagonal honeycomb structure, a 'Y' letter model is proposed and used (see Fig. 10). As seen in the figure, one of the branches of the 'Y' letter wall is considered to be bonded doubly. The honeycomb cell dimension is set to 3/8in. (9.525mm). The dimension of each element is 0.25 and 0.33mm in longitudinal and lateral direction, respectively. Further, the lateral length of the elements of single walls near double wall is 0.17mm and the angle between them is half of branch angle (120°).

Material properties of the foil are set to be similar to the ones of 0.033mm thickness foil which is assumed to be an isotropic elastic-plastic material. The adhesive of the double wall is assumed to be much weaker than the foil material, whose thickness is set to be 0.004mm similar to the test honeycomb used in experiment. The height is 20mm, which is shorter than the actual honeycomb. However, this height is considered enough to realize the actual deformation pattern and to calculate the crush strength, because, as seen later, calculation runs only as far as several wrinkles by buckling appear, giving almost stationary buckling mode. The static and dynamic friction coefficients between the tool and foil, and foil and foil are set to be 0.3 and 0.2, respectively. The mechanical properties of materials used in computation are listed in Table 3. The drop-hammer and the supporting base plate under the honeycomb are assumed to be an elastic body with density of 7.82g/cm³ and Young's modulus of 210GPa.

5.2 Results of Numerical Simulations and Discussions

Deformed patterns obtained by computation are given in Fig.11. Corresponding to them, the compressive overall stresses with time are shown in Fig.12. In this figure, the horizontal straight lines show the averages of the crush stresses. In Fig.11, crushing patterns with folding appear similar to the experiments. However, irregularity in folding period is a little larger in computation than in experiment (see Fig.4(a)). Moreover, there exists the case where the folding begins at the middle portion in height of the specimen.

The amplitude of the oscillation of compressive overall stress is larger in computation than in the experiment. The reason may be that imperfection of various degree is included in each 'Y'-letter wall of the actual honeycomb which would cause mutual interference of each amplitude of stress oscillations, resulting in reduction in overall amplitude in the experiment. Further, the peak stress in computation is higher than that in experiment, due to similar reason as above. The averaged crush strength by computation is rather close to that by the experiment (see Fig.7), though oscillation in stress obscures somewhat this conclusion. Therefore, it may be said that the 'Y' letter model used here is proper to analyze the buckling behavior of hexagonal honeycomb.

6 CONCLUSIONS

Using a drop-hammer type impact testing machine, with respect to the bare aluminum honeycomb structure whose cell is hexagonal aluminum foil, the effect of foil thickness, cell dimension and impact velocity on the compressive overall stress has been examined experimentally. Furthermore, numerical simulations corresponding to the several experiments have been carried out and the results were compared with the experimental ones.

Buckling pattern became irregular as the relative cell dimension to the foil thickness increased. Crush strength was almost proportional to the foil thickness. The honeycomb with smaller cell dimension was considered more proper as an energy absorber from the viewpoint of structural lightness. The maximum value of deceleration of the hammer was found almost con-
stant to the impact velocity.

To predict the deformation pattern and compressive overall stress by computation, 'Y' letter model for hexagonal honeycomb was used. Crushing patterns with multi-folding similar to the experiment appeared. However, the irregularity of folding period was larger than that in experiment. Crush strength was predicted accurately in a practical sense, if averaging the oscillatory behavior of it with time was done appropriately.

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REFERENCES