Effects of Geometry and Material Properties on Energy Absorption of Axially Crushing Honeycomb Structure*

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Abstract
The axial crushing behavior of the honeycomb structure of hexagonal-cell was studied with laying emphasis on the effects of the cell geometry and the material properties on its characteristics as an energy absorber. First, the axial crushing behavior of aluminum-alloy honeycomb was investigated by the experiment with taking the effect of the number of cells on that behavior into account, and then the effects of the perturbation and the work-hardening rate on the behavior were also examined by the numerical model. The numerical model without any initial imperfection did not show the actual buckling behavior so that the perturbations of the coordinates of nodes were introduced. The work-hardening rate affects the behavior of localized deformation and reduces the downslope just after the first peak in the load – displacement relation. Furthermore, a series of numerical analyses with varying geometric parameters was carried out, and the calculated results were compared with those obtained by some mathematical models. The calculated results and the mathematical models showed that the mean buckling stress for regular hexagonal honeycomb is dominated by the ratio of cell wall thickness to side length. The effects of the changes in the oblique side length and the branch angle on the mean buckling stress were also examined, and the former was qualitatively represented by the extended Wierzbicki model.

Key words: Honeycomb Structure, Energy Absorption, Progressive Buckling, Cell Geometry, FEM

1. Introduction
The honeycomb structure crushes with flat load-time-history and long stroke in the axial direction of constituent cells so that it is a suitable energy absorber while it is preferably used as a core material of the sandwich panel because of its high specific strength. In general, the honeycomb structure has various geometric patterns and has been extensively studied as a 2-dimensional cellular structure about its various macroscopic properties(1). For practical use, the hexagonal honeycomb structure of the highest specific strength is the most important. Wierzbicki studied the theoretical model of its progressive buckling on the basis of the rigid-perfectly plastic material approximation and the energy considerations and found simple formulas, which finally give the mean buckling stress as a function of the ratio of cell thickness to cell size(2). Ogasawara et al. also investigated this problem mainly by conducting a series of numerical analyses under various geometric
conditions\(^3\) with using the explicit FEM code LS-DYNA\(^4\) and obtained the similar formula of mean buckling stress by the method of least squares. In our previous study\(^5\), the axial crushing behavior of the honeycomb structure, whose material showed large work hardening and measurable strain rate dependence, was investigated by the numerical analysis and the mathematical model developed from that Wiezbicki proposed.

In this study, furthermore, the axial crushing behavior of commercial aluminum-alloy honeycomb was experimentally investigated with taking the effect of the number of cells on that behavior into consideration. The numerical model was also made with the consideration for the initial imperfection and the work-hardening rate on the basis of the material properties that were obtained by the experiment, and FEM analysis was conducted with using LS-DYNA. The mathematical model, which is able to deal with the changes in the oblique side length and the branch angle, was also proposed. The results of the experiment and the numerical analysis were compared with each other, and the effects of cell geometry on its energy absorption ability were also discussed.

Fig.1 Honeycomb specimen of A3003 aluminum alloy (6x6 cells, without face plates)

Fig.2 Specimens for quasi-static and high-speed tension tests (unit: mm)

2. Axial Crushing Experiment of Honeycomb Structure

2.1 Experimental Conditions

In order to observe the axial crushing behavior of honeycomb, the specimen of A3003 aluminum alloy (the thickness of cold-rolled sheet before fabricating into honeycomb, \(h\), is 0.076mm) were axially crushed by the Instron universal testing device (25T) with the velocity \(V = 2.5 \times 10^{-4}\)m/s. Figure 1(a) shows the schematic of honeycomb structure in the axial direction (the number of cells \(n_c = 6 \times 6 = 36\)). Figure 1(b) shows a honeycomb specimen of \(n_c = 6 \times 6\) with the cell size \(S = 6.35\)mm, the thickness of glued side \(h' = 2h = 0.152\)mm, and the axial length \(L = 25\)mm. In Fig.1(b), there are some extra sides at both the right and left surfaces, which were not removed in the processing. All the specimens were cut out from large honeycomb plates, and the precision of processing was not so good. Here, specimens of the same cell geometry and \(n_c = 10 \times 10, 12 \times 12, 15 \times 15,\) and \(20 \times 20\) besides \(n_c = 6 \times 6\) with and without face plates were examined. The cell geometry is regarded as regular hexagonal tube\(\left(D = D' = S / \sqrt{3}\text{ and } \phi = 2\pi / 3\right)\) while the dimensions will scatter to a greater or less extent, practically.

The tension tests of strain rates \(6.0 \times 10^{-4}\) and \(1.7 \times 10^3\) s\(^{-1}\) were also conducted by the testing apparatus Autograph AGS-H (Shimadzu Corporation) and that based on the non-coaxial Hopkinson bar method with specimens made of 10 sheets of cold-rolled A3003
aluminum alloy, which were glued together at the grip part (gray regions in Figs. 2(a) and (b)). Furthermore, dynamic crushing test was conducted only for the specimen of 6×6 cells with using the impact testing machine of drop weight type. The results will be compared with those obtained by the numerical simulation in the subsection 3.3.

2.2 Results of Low-speed Axial Crushing Tests

At the beginning of loading with \( V = 2.5 \times 10^{-4} \text{ m/s} \), each specimen showed the buckling pattern at the side surfaces, however, immediately after that, the deformation localized around the middle in the axial direction. This localized deformation caused the first wrinkle, the wave length of which was much smaller than that of the buckling pattern, at the upper or lower part adjacent to the localized region, and then the progressive buckling continued to the end. Figure 1(c) shows the crushed specimen of 6×6 cells. The wrinkle formed regularly in the middle of the specimen but got out of shape near the edge. Figures 3(a) and (b) show the load \( P \) – displacement \( \Delta L \) relations obtained for the specimens with and without face plates respectively. It was found that the rise of load due to the densification was advanced with face plates. Here, the nominal stress is obtained with dividing the load by the net area of the cross section of cell wall to examine the effect of the number of cells on the crushing behavior. In Figs. 4(a) and (b), the nominal stress – nominal strain relations for different number of cells agree well with each other, so that \( n_c = 6 \times 6 \) seems to be large enough to approximate the periodic boundary condition.

Figure 5 shows the changes of the peak stress and the plateau stress, which is evaluated by averaging values of the nominal stress within the range of the nominal strain from 0.2 to 0.5, with the number of cells at side. Those show the tendency of getting steady states with the increase of the number of cells because the effect of residual sides on the evaluation of area relatively decreases with increasing the number of cells.

Figure 6 shows the nominal stress – nominal strain relations obtained by the quasi-static and the high-speed tension tests. The material hardly shows the work hardening and the strain rate dependence, and the quasi-static relation shows very small total elongation of about 0.017. One can understand that the localization due to small work-hardening rate causes...

3.1 Numerical Model and Boundary Conditions

Figure 7(a) shows a typical finite element model of honeycomb structure (6×6 cells, without face plates) and boundary conditions. The length of model in x-direction is \(2D\cos(\pi/6)\times6 = 6\sqrt{3} D\), and that in y-direction is \(D(1+\sin(\pi/6))\times6 = 9D\). The model is set on the lower rigid wall and is crushed in the axial direction by the upper rigid wall of the velocity \(V = 3.4\text{m/s}\), which was measured in the dynamic crushing test. For the contact of the honeycomb model itself, the coefficient of friction was varied from 0.28 (static) to 0.20 (kinetic) as an exponential of the relative velocity with the exponential coefficient\(^{(4)}\) of 1s/m, and for the contact between the model and the rigid wall, it was set to 0.42.

In Fig.7(a), the base model of \(D = 3.67\text{mm}, h' = 2h = 0.152\text{mm}, L = 25\text{mm}, 6\times6\text{ cells}\) is shown. Each side of hexagonal cell is divided into 12 equal elements in the lateral direction, and the axial length of element is determined so that each element is the same rectangular close to a square. The base model consists of 109224 shell elements of Belytschko-Leviathan type\(^{(4)}\) and 108315 nodes.

On the other hand, the buckling is an instability phenomenon and is so sensitive to the initial imperfection that the exact buckling behavior cannot be reproduced without any perturbation in the numerical simulation. Figure 7(b) shows the perturbation \(\Delta L'(z)\) (the amplitude \(a_p = 0.035\text{mm}\)), which corresponds to the infinitesimal deformation due to the processing and is introduced to reproduce the localized deformation. The wave length of the perturbation \(l_w = 6.6\text{mm}\) is roughly determined from the observation of buckling pattern in the experiment and is about 8% larger than that of calculated buckling pattern, about
Furthermore, another perturbation $\Delta_x'(z) = a_i \Delta_x' \sin(\pi z / L) \ (i = 1 \sim 3)$, which corresponds to the scattering in the dimensions and is also assumed to change in the $z$-direction, is added to $x$, $y$ and $z$ coordinates of node $n_i$ in the honeycomb model. Here, $\Delta_x'$ is the pseudo-random number that is obtained by the linear congruential method within $|\Delta_x'| \leq 1$, and the amplitude $a_i = 0.015\text{mm}$. So, the total amplitude of perturbation is less than $0.05\text{mm}$ in $x$, $y$ and $z$-directions.

### 3.2 Material Model

The specimen material of cold-rolled A3003 aluminum alloy is modeled as an isotropic elastic/plastic material based on the von Mises yield criterion. The flow stress $\sigma_y$ is represented as a function of the equivalent plastic strain $\varepsilon_{eq}$, for example, as follows:

$$
\sigma_y = f(\varepsilon_{eq}^p) = k_0 + k_1 \exp \left(-\frac{\varepsilon_{eq}^p}{k_2}\right) + k_3 \exp \left(-\frac{\varepsilon_{eq}^p}{k_4}\right) + \left(\frac{H}{\varepsilon_{eq}^f} - \varepsilon_{eq}^f\right),
$$

where $<x> = x$ if $x \geq 0$, and $<x> = 0$ if $x < 0$. $H$ is the work-hardening rate after the rising part, and $\varepsilon_{eq}^f$ is the failure plastic strain in the quasi-static tension test. $k_0$, $k_1$, $k_2$, $k_3$, and $k_4$ are the material constants for expressing the rising part. Those values for the cold-rolled A3003 are shown in Table 1, and Fig.8 shows the true stress – equivalent plastic strain relation calculated by Eq.(1) as compared with that obtained by the experiment. In Table 1, $\rho$ is the density, $E$ is Young’s modulus, and $\nu$ is Poisson’s ratio. In Fig.8, the curve calculated by Eq.(1) with $H = 589\text{MPa}$ is also shown, however, the load – displacement relation calculated with $H = 70\text{MPa}$ is closer to the experimental result than that calculated with $H = 589\text{MPa}$, as shown in Fig.12(c). In the numerical analysis, the piecewise linear approximation model (Type 24(4)) was used.

<table>
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<th>$\rho$(kg/m$^3$)</th>
<th>$E$(GPa)</th>
<th>$\nu$</th>
<th>$H$(MPa)</th>
<th>$\varepsilon_{eq}^f$</th>
<th>$k_0$(MPa)</th>
<th>$k_1$(MPa)</th>
<th>$k_2$(MPa)</th>
<th>$k_3$(MPa)</th>
<th>$k_4$(MPa)</th>
<th>$\sigma_{0.2}$(MPa)</th>
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<td>0.0135</td>
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<td>$4.89 \times 10^4$</td>
<td>-52.4</td>
<td>$3.66 \times 10^3$</td>
<td>209</td>
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</tbody>
</table>

Fig.8 True stress – equivalent plastic strain relation

### 3.3 Calculated Results

Figures 9(a) and (b) show the buckling patterns observed in the numerical simulation and the experiment respectively under the condition of $V = 3.4\text{m/s}$. Here, $t$ means the time from the impact, but the sampling time of the high-speed camera Phantom V9.1 (Vision Research Inc.) and the time increment of contour output in the numerical simulation are $62.5\mu\text{s}$ and $50\mu\text{s}$ respectively so that both in the experiment and in the simulation the closest values for respective moments that the target phenomena happened are shown. The buckling pattern is not so clear as compared with that observed in the low-speed crushing test because there is not sufficient time to develop the pattern.

Figures 10(a) and (b) show the occurrence of the localized deformation in the numerical simulation and the experiment respectively. In Fig.10(a), the localized deformation occurs near the middle in $z$-direction while in Fig.10(b) that occurs at the place where is little...
distant from the bottom (enclosed with a red broken line). Only in the experiment, all the faces are waved irregularly so that there is a possibility that the inertial force besides the initial imperfection affects the crushing behavior. The honeycomb structure has relatively large dimensions so that the measuring system, which consists of the impact and load sensing blocks and the specimen, also becomes large inevitably and causes the transient vibration. Therefore, the calculated behavior of the localized deformation is rather close to that observed in the low-speed crushing test. In Figs. 9(a) and 10(a), the distribution of the equivalent stress is also shown to emphasize the buckling pattern and the localization.

Figure 11(a) shows the honeycomb model crushed up to $\Delta L \cong 11.2\text{mm}$, and Fig. 11(b) shows simulated load – displacement relation as compared with those obtained by the dynamic and the low-speed crushing tests. In Fig. 11(a), the numerical simulation reproduces the progressive buckling, and in Fig. 11(b) the curve evaluated by the simulation qualitatively agrees with those obtained by the experiments. Because the specimen material hardly shows the work hardening and the strain rate dependence, the curves obtained by the dynamic and the low-speed crushing tests agree well with each other although the former shows large oscillation due to the inertial force. The increase in simulated plateau stress might
come from the lack of consideration for the debonding at glued sides\(^{(3)}\), the initial imperfection and so forth.

### 3.4 Effects of Perturbation and Work-hardening Rate on Crushing Behavior

The honeycomb model without initial imperfection will yield the progressive buckling from the upper or lower end immediately, and the localized deformation, which was observed around the middle in the experiment, does not occur. The crushing behavior is also affected by the work-hardening rate. Figures 12(a), (b) and (c) show the effects of the perturbation and the work-hardening rate on the load – displacement relation. In Figs. 12(a) and (b), the amplitude of perturbation \(a_p\) or \(a_r\) is varied for the base model of \(a_p = 0.035\text{mm}\) and \(a_r = 0.015\text{mm}\), and the relationship shows little change with varying \(a_p\) from 0.025mm to 0.045mm or with varying \(a_r\) from 0.005mm to 0.02mm. On the other hand, the relationship without any perturbation apparently differs from any other relationship with the perturbation. This means that the crushing behavior after the bifurcation buckling is stable within the range of perturbation examined here.

In Fig.12(c), some load – displacement relations are evaluated with varying the work-hardening rate \(H\) from 70MPa \((= 0.001E)\) to 1.05GPa \((= 0.015E)\), and the downslope at the falling part just after the first peak greatly decreases with the increase of \(H\). That is because high work-hardening rate will delay the occurrence of the localized deformation. The work-hardening rate of the cold-rolled A3003 is very low and was determined to be 70MPa, as shown in Table 1.

![Fig.12 Effects of perturbation and work-hardening rate on load – displacement relation \((D = 3.67\text{mm}, h' = 2h = 0.152\text{mm}, L = 25\text{mm}, 6\times 6\text{ cells}, V = 3.4\text{m/s})\) ](image)

### 3.5 Effects of Geometry on Mean Buckling Stress

In the numerical analysis, the mean buckling stress is obtained as an indicator of the energy absorption ability by averaging the nominal stress evaluated by the net area of the cross-section of cell wall up to the end of the nominal strain. (For the honeycomb structure without face plates, both the experiment and the simulation were finished before the load rising due to the densification.) Furthermore, three models for the mean buckling stress, which are calculated by the following Eqs.(2), (3) and (4) respectively, were also used. Here, \(\sigma_{0.2}\) means the 0.2% proof stress (see Table 1).
\[
\sigma_m^w = \frac{3}{k_p + 1/2(h'/h)^2} \left\{ \pi k_p I_1(\varphi) I_2(\varphi) \right\}^{1/3} f(\varepsilon_p^w) (h/D)^{2/3}, \quad (2)
\]

where \( k_p = k_p + 1/2(h'/h)^2 \), \( k_p = D'/D \), \( \varepsilon_p^w \equiv a_w (h/D)^{1/3}, \)

\[
I_1(\varphi) = \frac{\pi}{(\pi - \varphi/2) \tan(\varphi/4)} \int_{\pi/2}^{\pi} \cos \alpha \left[ \cos(\varphi/4) - \cos \left( \varphi/4 + \frac{\pi - \varphi/2}{2} \right) \right] d\alpha,
\]

\[
I_2(\varphi) = \frac{1}{\tan(\varphi/4)} \int_{\pi/2}^{\pi} \cos \alpha \left( \sin \gamma / \tan(\varphi/4) \right) d\alpha,
\]

\[
\sigma_m^w = 16.56 \sigma_{0.2} (h/S)^{5/3} \times \left( \frac{\sqrt{5/4}}{2Dh} \right)^{2/3} \approx 4.306 \sigma_{0.2} (h/D)^{2/3}. \quad (3)
\]

\[
\sigma_m^o = 10.70 \sigma_{0.2} (h/S)^{1.90} \times \left( \frac{\sqrt{5/4}}{2Dh} \right)^{2/3} \approx 2.894 \sigma_{0.2} (h/D)^{0.94}. \quad (4)
\]

\( \sigma_m^w \) is obtained by replacing the constant yield stress in the expression of the nominal stress derived from Wierzbicki’s mean buckling load with \( \sigma_m \) in Eq.(1). Although Wierzbicki finally solved for the case of \( \varphi = 120^\circ \), \( k_p = 1 \) and \( h'/h = 2 \), \( \sigma_m^w \) is formulated for arbitrary \( \varphi, k_p \) and \( h'/h \). The extension for arbitrary \( h'/h \) was introduced by Chen et al.\(^{69}\). Wierzbicki showed that the average plastic strain yielded in the formation process of one wrinkle, \( \varepsilon_p^w \), is in proportion to the cube root of \( h/D \) in the case of \( h = 2h' \), and for this material the constant \( a_w = 0.525 \) was adopted by taking the behavior of simulated plastic strain into consideration. \( \sigma_m^w \) comes from the original mean buckling stress proposed by Wierzbicki\(^{29}\), and \( \sigma_m^o \) is obtained by Ogasawara et al.\(^{29}\) from the least squares approximation of data evaluated with FEM simulations. In this study, \( \sigma_m^w \) and \( \sigma_m^o \) are changed to the values per the net area of the cross section of cell wall by multiplying the ratio (occupied area) / (net area).

In order to investigate the effects of cell geometry on the mean buckling stress, a series of numerical analyses was carried out with varying geometric parameters as shown in Table 2. Figure 13(a) shows the effect of the ratio \( h/D \) on the mean buckling stress for the regular hexagonal honeycomb. The simulated results and the lines of \( \sigma_m^w, \sigma_m^o \) and \( \sigma_m^w \) are included in a relatively narrow band as compared with the results obtained in our previous study\(^{69}\) for 2024-T351 aluminum alloy, which shows large work hardening and measurable strain rate dependence. This gives support to the conclusion in that study that the contribution of work-hardening to the mean buckling stress is not negligible for the material with high work-hardening rate and causes large difference in the evaluation of the theoretical model without the consideration for work-hardening. In Fig.13(a), the results calculated by the numerical simulation for different \( h'/h \) are also shown together, and the data for \( h'/h = 2 \) seems to be a little higher than that for \( h'/h = 1 \). \( \sigma_m^w \) can describe this tendency while \( \sigma_m^o \) and \( \sigma_m^w \) can not be defined. The difference between \( \sigma_m^w \) and \( \sigma_m^w \) for \( h'/h = 1 \) comes from that between \( f(\varepsilon_p^w) \) and \( \sigma_{0.2} \). On the other hand, \( \sigma_m^w \) is closest to the experimental result among those models. That seems to imply that \( \sigma_m^w \) achieves the most realistic evaluation of the debonding at glued sides.

Figures 13(b) and (c) show the effects of \( k_p (= D'/D) \) and \( \varphi \) on the mean buckling stress. In Fig.13(b), the calculated value by the simulation increases with decreasing \( k_p \), and \( \sigma_m^w \) predicts this behavior qualitatively. In Fig.13(c), the calculated value grows with \( \varphi \), however, \( \sigma_m^w \) falls with the increase of \( \varphi \) reversely. The behavior calculated by the simulation agrees with that reported by Yamashita et al.\(^{70}\), too. In Eq.(2), two functions of \( \varphi, I_1 \) and \( I_3 \) affect the behavior of \( \sigma_m^w \), and both of them decreases with the growth of \( \varphi \). \( I_1 \) is related to the dissipation mechanism at moving toroidal surface\(^{29}\). Small \( \varphi \) will enlarge the traveling distance of toroidal surface so that \( I_1 \) might increase. \( I_3 \) is related to the dissipation mechanism at two inclined hinge lines, one imposing the curvature and the other one removing it\(^{29}\). However, small \( \varphi \) seems to lead to easy movement of hinge line. The
behavior of \( I_3 \) seems to be inconsistent with the tendency of structural resistance so that some modification for that will be needed.

### Table 2 List of honeycomb models

<table>
<thead>
<tr>
<th>Model</th>
<th>( D ) (mm)</th>
<th>( k_D )</th>
<th>( h ) (mm)</th>
<th>( h' ) (mm)</th>
<th>( \phi ) (deg)</th>
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<tr>
<td>Base</td>
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<td>0.152</td>
<td>120</td>
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4. Conclusions

The axial crushing behavior of the honeycomb structure of cold-rolled A3003 was investigated by the experiment, and it was found that for the specimen with some initial imperfections the progressive buckling happened after the transition from the occurrence of buckling pattern to the localized deformation. Because that process is reflected in the load – displacement relation, the numerical model with the perturbation was made with the material model whose parameters were determined by the tension test. The material hardly shows the work-hardening and the strain rate dependence. The parameter studies of the perturbation amplitudes and the work-hardening rate showed that the crushing behavior after the bifurcation buckling was stable for the change of perturbation and the work-hardening rate considerably affected the localized deformation behavior. The examination with using the numerical analysis and some mathematical models showed that
the mean buckling stress for regular hexagonal honeycomb is dominated by the ratio of cell wall thickness to side length. The changes in the oblique side length and the branch angle also affect the mean buckling stress so that the mathematical model, which can deal with those changes, was proposed on the basis of Wierzbicki’s model. The proposed model successfully described the effect of the oblique side length while some modification for the dissipation mechanism at inclined hinge lines will be needed for the consideration of the change of branch angle.

References