Forming Process Simulation of Truss Core Panel*

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Abstract
Honeycomb panel is widely used as flooring or wall material in various structure including buildings, aircraft, train and so on due to high stiffness and lightness at present. Honeycomb panel, however, has a disadvantage that adhesive used to glue honeycomb core and top plate may burn by fire. On the other hand truss core panel has equivalent stiffness as honeycomb panel and is expected to be an alternative to honeycomb panel as it is safer for fire. However, in general, difficulty exists to form truss core and forming techniques should be developed for practice use of truss core panel. In this paper, firstly theoretical forming limitation is discussed for tetrahedral truss core. Secondly single stage forming simulation of truss core panel using explicit FEM technique was performed for preliminary investigation to estimate formability and thickness distribution. Finally multi-stage forming simulation was presented and possibility to apply press forming for truss core panel production through the simulation. In addition some results of the simulation was compared with the experiment and good agreement of both results was shown.

Key words: Press Working, Finite Element Method, Formability, Origami-Engineering, Truss Core Panel, Honeycomb, Explicit FEM, Multi-stage Forming Simulation

1. Introduction
Honeycomb panel glued honeycomb core with surface plates, has been widely used for floor and wall materials of buildings, aircrafts, railcars and so on, in many cites up to now as structure with weight saving and high stiffness. The honeycomb panels can be manufactured rather easily for many kinds of core and panel size as usage and have an the feature of high bending stiffness as strength member. They, however, have rather frugal strength against shear deformation and in-plane compressive load. And they may be deathtrap that the adhesive gluing honeycomb core and surface plates is burned as a fire happens. Consequently, from the prospect of application to origami-engineering, we direct our eyes to truss core panels(1)(2) as light saving structure. They have bending stiffness of same level with honeycomb panels, better aspects in shear strength and in in-plane compressive load and over more, possibility being manufactured by only metal plate. The truss core panel is a structural material invented from the research work of space filling feature for regular tetrahedrons or regular octahedrons. Many kinds of usage will be thought out as substitute of honeycomb core(3).

The truss core has a severe problem for forming work in real product development,
though many kinds of the shape will be invented by basis on the space filling theory. It is easy to form the truss cores from plastic, and the prototypes of truss core panels have actually been made with different variations, where truncations are added to the edges of regular tetrahedron or tetrahedron. Core, however, should be formed from thin metal plate when it is used to members of buildings, transport equipments and so on. Then, we have to examine each core shape whether a thin metal plate can be formed to desired shape within forming limit of it, or not. There are several working methods for forming thin metal plate, as like general press forming, hydro-forming and super-plastic forming. But, the production costs by hydro-forming or super-plastic forming are rather expensive so it is desired to work upon cores by press forming at an easy rate. Therefore, in the paper, considering first on the formability of truss core panel with ideal shape geometrically, then we simulate forming core using a nonlinear finite element method, on basis of the truss core shape as having high possibility by press forming. We decide to employ an explicit FEM to be available for large-scale nonlinear analytical simulation and use LS-DYNA(4), a commercial software based on the explicit FEM. In the simulation, first, we simulate the press forming at single stage and calculate the rough distribution of strain in truss core. The result shows the necessity of multi-stage forming, including in preliminary forming stage, to reduce the local strain concentration arose from press forming of truss core. In order to estimate the forming result of the press forming in multi-stage, we carry out the simulation for the model to be expressed exactly the forming stages assumed in the real world. And we compare the simulated result with the prototype that was produced by the press forming in almost same condition to the simulation. The object of the paper is that a feasible forming process for truss core is proposed, based on these results.

2. Investigation for Formability of Tetrahedral Truss Core

Let’s consider to form a thin metal plate with the initial thickness $t_0$. We make press forming a triangular area with an edge length $a$ to a triangular pyramid with a height $h$, as shown in Fig. 1(a).

Assuming that the plate is extended uniformly by the press forming, the thickness of the plate will be changed into $t$ after the forming. The volume of the original triangular area with the thickness $t_0$ is given as follows;

$$V_0 = \frac{\sqrt{3}a^2}{4} \cdot t_0 \quad (1)$$

And the volume $V$ of the triangular pyramids with uniform thickness $t$ after the forming is;

$$V = \frac{3a}{2} \left( \frac{1}{12} a^2 + h^2 \cdot t \right) \quad (2)$$

Assuming the volume to be constant because whole the triangular area is exposed to plastic
deformation, we can put Eq. (1) and Eq. (2) to be equal to each other. And let’s define the aspect ratio of $a$ and $h$ ($h/a$) as $\alpha$ and the thickness reduction $\gamma$ as follows, respectively.

$$\gamma = \frac{t_0 - t}{t_0}$$

Then, we can get the following equation;

$$\alpha = \sqrt[3]{\frac{\gamma(2-\gamma^2)}{12(1-\gamma)^2}}$$

We get the curve in Fig. 2 by plotting Eq. (3) against $\gamma$. Figure 2 shows the relation of the aspect ratio against the thickness reduction as the aspect ratio is made only by simple stretching. It is said in general that forming limit may be about 30% of thickness reduction in case of multi-purpose steel plate, though depending on its grade. From this experiential knowledge, the maximum aspect ratio of forming will be about 0.29. It will be impossible to form the ideal regular triangular pyramid in the space filling only by forming with stretching because the thickness reduction is 67% if we form the aspect ratio to 0.81. Then, under the consideration, we simulate a model with aspect ratio to be formable by usual press forming.

3. Geometry and Dimension of Truss Core Panel

We choose the truss core of triangular pyramid with the edge line in the bottom face $82$ mm and the height $23$ mm (the aspect ratio 0.28) as the target of the simulation. Figure 3 shows the dimension of the model. There are different array numbers corresponding to the matrix-like numbers of the truss cores. So, we decide to use the $6 \times 5$ core array here as a simulation model. As shown in Fig. 3, in order to make press forming as a practical member, we change the shape given from geometry to as follows;

(1) Set all the vertices of the triangular pyramids to be flat as they can be spot welded.
(2) Set fillet at the edge lines and the bottom surfaces of all the triangular pyramids as processable.
We simulate for the model mentioned above by using the explicit FEM. The employed element type is a four-node rectangular reduced integral shell element with a viscous type hourglass control\(^5\)\(^6\) and is one used widely in explicit FEM software. The in-plane Gauss integration point is located at the center of an element and the through thickness gauss integration points are three. The material used is the steel plate SPCE for deep drawing and we use the specific values shown in Table 1 and Fig. 4 in the calculation. The Hill ‘48 yield function\(^7\) is used basically,

\[
F(\sigma_{22} - \sigma_{33})^2 + G(\sigma_{22} - \sigma_{33})^2 + H(\sigma_{22} - \sigma_{33})^2 + 2M\sigma_{22}^2 + 2N\sigma_{33}^2 - 1 = 0
\] (4)

where \(\sigma_{ij}\) is stress tensor components, \(F, G, H, L, M\) and \(N\) are parameters of the material. Applying the conditions of in-plane isotropy and plane stress condition\((\sigma_{33}=0)\) to Eq. (4) and assuming the plastic strain velocity complies to the associated flow rule, now we can get the following equation\(^8\).

\[
f(\sigma) = \left(\left(\frac{1}{r+1}\sigma_{11} + \frac{1}{r+1}\sigma_{22} + \frac{2r+1}{r+1}\sigma_{12}\right)^2\right)^{\frac{1}{2}}
\] (5)

where \(r\) is the Landfolk’s \(r\) value. The value \(n\) shown in Table 1 is obtained by fitting the stress-plastic strain curve to the formula by Swift as;

\[
\sigma = K(e_o + e_p)^n
\]

<table>
<thead>
<tr>
<th>Table 1  Material properties (SPCE)</th>
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<tr>
<td><strong>Young’s modulus</strong></td>
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<td><strong>Poisson’s ratio</strong></td>
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<td><strong>Yield stress</strong></td>
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<td><strong>Density</strong></td>
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4. Preparative Analysis

In order to estimate the thickness distribution yielded by press forming, we build a simple model for press forming to a truss core shape by single stage and carry out preliminary calculation for it. Figure 5 shows the model shape. The blank is divided into rectangular shell elements with an edge length of 1.2 mm. As a general condition for press forming, the die is fixed, the punch is moved with enforced velocity after the holder force is set to 156.8 kN. It takes few seconds to an actual forming time but the time step size for the calculation becomes $2.0 \times 10^{-7}$ second from the stability condition of the central difference time integration in case of the explicit FEM. This means the actual forming duration is too long for the explicit forming simulation. In order to make finish the calculation within a practical time, we simulate the motion of the die by being sped-up to several ten times within a range of no having an affect on the calculated results. Figure 6 shows the histories of the holder force and the punch velocity used in actual simulation.

![Fig. 5 Preliminary forming simulation model](image)

![Fig. 6 Holder force and punch velocity history used in forming simulation](image)

We get the thickness reduction distribution as shown as Fig. 7(a) from the result. We know that the thickness reduction becomes over 60% at the areas of surrounding vertices. It is highly possible that clacks will be occurred because the forming limit of SPCE exceeds. Looking at the distribution of the nodal displacement vectors plotted in Fig. 7(b), we can see that the blank at the flange of the plate flows into the areas of triangular pyramids, but that the blank at the around truss cores does not almost flow to the area of the pyramids near the plate center and the each truss core area is only extended as stretching. Namely, it is known that the each truss core area is formed in only the blank stretching almost and that it is severe forming condition for steel to be formed. As seen from the above, the large strain area comes about a vertex of a triangular pyramid locally in the case of forming by single stage, and we can estimate that the blank has quite different stain distribution at triangular pyramid area from the uniform stain as we assumed in Section 2. From the result, we can
know to need a trial for multi-stage forming as like as we do final forming after doing
pre-forming as the strain distribution around one truss core area becomes uniform.

Fig. 7  Results of single stage forming simulation

5. Multi-Stage Forming Simulation

5.1 Simulation Methods

We can consider many patterns on pre-forming shape to form truss core with triangular
pyramid shape. Here, we try a forming method by two procedures as follows; a blank is
formed to a hemispheric shape till a given height by stretching. Then the blank is formed to
triangular pyramid. Figure 8 shows the model dimensions of the die and the original shape
of the blank. The punch tools consist of the punch for pre-forming (the diameter 74.94 mm
and the height 23 mm), guide pins for positioning (the diameter 71.29 mm and the height
21.05 mm) and the punch with triangular pyramidal shapes (the width 76.06 mm and height
23 mm). The die consists of the upper die with the triangular pyramid shapes, the punch for
pre-forming and the holes corresponding to the positions of guide pins. Figure 9 shows the
order for punch operation and the blank movement in each stage. In the first stage, the
pre-forming punch is set at a given position and the blank held between the die and the
holder, is pressed by the pre-forming punch. In this time, the blank is formed with deep
drawing by only the pre-forming punch and the guide pins and the triangular pyramidal
punch are not still operated. In the next stage, the blank is sent forward 82 mm that is the
pitch between the truss cores, and the hemispherical part formed in the first sage is moved
above the guide pins. As the height and the diameter of the guide pins is slightly smaller
than the ones by the pre-forming punch, the guide pins are only inserted in the formed
hemispherical part and do not contribute to forming. In the second stage, the hemispheres of
The second column are formed by the pre-forming punch. In the third stage, the blank is sent the one pitch forward and the prime hemispherical part is positioned above the triangular pyramidal punch. The part is formed to the triangular pyramid, and in the same time, hemispherical part of the third column is formed by the pre-forming punch. After the forth stage, the previous stages are repeated and the hemispherical part pre-formed is formed to the triangular pyramidal shape in order.

![Multi-stage forming model](image)

The explicit FEM is also used in this simulation, we calculate with faster forming speed rather than actual forming speed in order to shorten the calculation time according to the holding force and the punching velocity given in Fig. 6. We explain on the setting operation in each for the holder, the die and the punch and on the handover operation to the later stage from the former stage.

1. **Blank Holding**
   We set the holder force as follows; it rises linearly within 1 to 2 ms from the beginning of the analysis and reaches constant 156.8 kN, in the each stage.

2. **Forming**
   On the time when the holder force is constant, the forming is done with giving enforced displacement to the die or the punch. In the actual forming, the holder and the die holding the blank both descend to the fixed punch and the blank is formed. In the simulation, the die and the holder holding the blank are fixed and the punch is moved down as not to act large
mount of inertia to the blank in stage because of forming in high speed in the simulation. There make no difference whether the upper die moves or the lower die does, it is a relative event.

(3) Sending Blank and Handover for Forming Result

The stage sending the formed blank as much as one pitch of the truss core, is done by manual using the pre-processor. As the blank mesh is used the same through whole the simulation, then the displacement, the thickness and the stress to be gotten in the previous stage, all continue in the next stage for every nodes and elements.

5.2 Simulation Results

Figure 10 shows the simulation results for the multi-stage forming. The forming consists of 8 stages in all. It shows the blank shape formed in each stage and the thickness reduction (%) with tint. In the first stage, the first column of the pre-formed hemispheres is formed. The whole hemisphere almost shows uniform stretching because of forming under equi-biaxial tension and the thickness reduction is about 14%.

Figure 11 shows the distribution of the displacement vectors for the blank at the first and the second stages. It is known that the plate is pulled to the direction of the pre-forming die from the front (the right-hand side in Fig. 11) and that the plate is slightly pulled from the back. So, we can see that the deformation is not induced only by stretching but also by behavior near deep drawing. The pre-forming for the second column is done in the second stage and the first column is moved to above the guide pins. There is very few inflow of the plate from the front and the one from the back only exists (the left-hand side in Fig. 11). In the result, the contribution of stretching becomes lager at the second column in the pre-forming and the thickness reduction comes to about 18%. In the third stage, the first column is formed upon the triangular pyramid shape and the thickness reduction is 28%
around the vertices. After the third stage, the pre-forming and the forming are progressed in the same time and get to the sixth stage. Again, the pre-formed parts are formed in the seventh and eighth stages. And the forming process is finished. The maximum value of the thickness reduction is 28.4% through all the stages. The value does not reach to our criterion of crack 30% for SPCE, so we can predict the possibility of the forming of the truss core panel made of SPCE plate using the above forming method.

Furthermore we compare the deformation of the blank calculated by the simulation with the trial piece in detail. The trial piece is formed upon the triangular pyramid sequentially, and the dimension of the truss core, the shape and the thickness are different from these by the simulation, then we cannot compare deformations of the cores quantitatively. However we think that the attitudes of the deformations will be comparable with each other. Figure 12(a) shows the forming shape for the trial piece and Fig. 12(b) for the final shape gotten by the simulation and the outline of the initial blank. The plate is a strip shape and the width is narrower than the length of the sending direction. The strip of the right side in Fig. 12(a) shows the initial geometry, the center is in forming and the left side is the final geometry. As the plate is drawn into the area formed to the truss cores, the plate is shortened in the sending direction with the forming stage progressed. As shown at the lower edge of Fig. 12(b), we can see the shortening of the plate in reverse of the sending direction in the simulation as well as the trial piece. In the trial plate, dents come about at the flange part of the plate by punch hall as shown in Fig. 13(a), and as well in the simulation as shown in Fig. 13(b).
6. Conclusions

By applying the explicit FEM, we simulated press forming of truss core panel with single stage or multi-stage and it was shown that we were able to apply to press forming for manufacturing truss core panel with about aspect ratio of 0.28. And we carried out the simulation for multi-stage forming of all eight stages. In the press forming to be combined preliminary and final forming, the strain path that the plate was effected, was more complicated than one by press forming of conventional single stage, so we have thought quite difficult to predict the final forming status without such the accurate simulation. It was shown to be able to get the real forming shape of truss core panel with multi-stage by the simulation to be modeled manufacturing process realistically, in which the simulation results was compared with the result of the actual press trial forming to be done experimentally now.

As the information gotten from the simulation results, we could know that there was a limit for using only stretching in order to apply press forming to form truss cores panel and that it was necessary to make flow of the material into the sending direction from the back as shown in Fig. 12. In order to arise desirable material flow, we have to weaken the holding force, but there may be possibility to generate imperfection such as wrinkles if the holding force is too weak. Then it is necessary to control the holding force appropriately, with inflow of material without wrinkles.

From the above, the issues in future on manufacturing truss core panel and practical application are as follows;
(1) Design for forming stages, prediction and compensation against defective forming (crack or wrinkle).
(2) Shape of pre-forming punch to uniform the thickness reduction.
(3) Development of press technology to form truss core with the aspect ratio closer to a regular triangular pyramid.
(4) Revealing the relations between the geometric feature, such as aspect ratio and chamfer dimension for edges and vertex, and characteristics including mechanical stiffness, acoustic absorbing capability and so on of truss core panel.
(5) Shape optimization of truss core panel corresponding to intended purpose.
(6) Simulation in consideration of the effect for work hardening, on the estimation for the mechanical stiffness of truss core panel.

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