Simulation for Forming and Performance Evaluation of Structures Developed Based on the Concept of “ORIGAMI Engineering”

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Abstract

The “origami” is known as one of traditional Japanese craftwork. Origami is a technique of paper folding in which various complex shapes of birds, flowers and so on can be made from a simple sheet of paper. Origami is also considered as a technique to produce light weight three dimensional structures from two dimensional material. And the 3D structures of origami can be foldable and/or expandable. Recently origami engineering inspired by traditional origami has been advocated by some researchers. Although several excellent structures have been studied ideally and mathematically so far, from a viewpoint of engineering, formability of the origami structure is a very important engineering issue practically even if the structure has excessively elegant shape. There are two major origami structures, i.e., the “octet-truss core panel (shortly truss core panel)” and the “reversed spiral origami tube”. In this paper the formability, strength and crash performance of these origami structures are discussed. The explicit FE code LS-DYNA® is the main solver of these problems. The press forming simulation software JSTAMP is used for formability assessment and the optimization software LS-OPT® is used to study crash performance.

Examples of traditional origami (upper), truss core panel (right) and reversed spiral origami tube (left)

1. Multi-Stage Forming Process Simulation of Truss Core Panel

1.1. Introduction

Honeycomb core panel has been widely used for floor and wall materials of buildings, aircrafts, trains and so on as light weight and high strength for bending structure up to now. However honeycomb panel has several disadvantages. For example it is relatively weak for shear deformation and in-plane compression. It is unsafe for fire accident as flammable adhesive is used to glue honeycomb core and surface plates. So, from the point of view to apply origami engineering, truss core panel is considered as one of hopeful alternative core panel for honeycomb panel. Truss core panel is commonly used as a combination of two panels shown in Fig.1. Ideally two truss core panels having cores of regular triangular pyramids form space filling geometry with regular tetrahedrons and octahedrons[1, 2]. This geometry is very stiff for bending like honeycomb panel, and has better aspects in shear strength and in in-plane compressive load. Moreover honeycomb panel is manufactured through expensive forming process, in contrast, truss core panel has a possibility to be formed through common inexpensive press forming process. The truss core panel is a structure invented from the research work of space filling feature and many kinds of usage will be studied as substitute of honeycomb panel[3].

In the real world, formability of structure is a big problem even though excessively excellent geometry of structure is proposed ideally and mathematically from origami engineering. There are several forming technique to produce real truss core panel, e.g., press forming, hydroforming, superplastic forming, etc. However hydroforming and superplastic forming are expensive for production cost and more inexpensive press forming is preferred. So we consider common press forming technique to form truss core panel in this study.

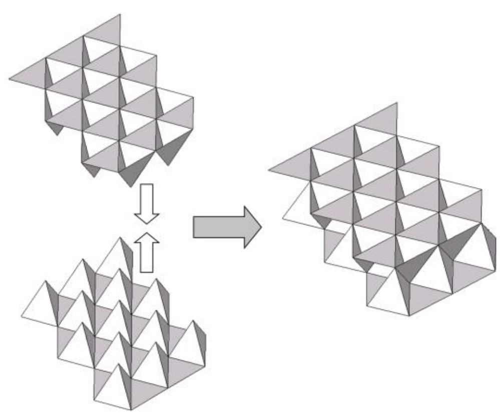


Fig.1 Combined truss core panel

1.2. Preliminary study for forming of triangular pyramid core

Let’s consider to form a thin metal sheet with the thickness t_0. We assume that a regular triangular region with the edge length of a in Fig.2 (a) is formed into a triangular pyramid with the height of h in Fig.2 (b). We also assume that the sheet is stretched evenly and the thickness after forming changes to t. The initial volume of the triangular region V_0 and the volume of the pyramid region of the sheet after forming V are given as

$$V_0 = \frac{\sqrt{3}a^2}{4} \cdot t_0 \quad , \quad V = \frac{3a}{2}\sqrt{\frac{1}{12}a^2 + h^2} \cdot t \tag{1}$$

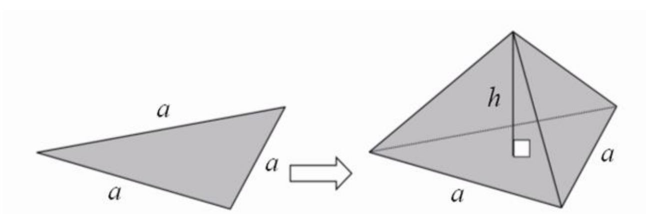
respectively. The change of volume of metals in plastic deformation can be negligible. So we can let $V_0=V$, and let aspect ratio α and thickness reduction γ as

$$\alpha = \frac{h}{a} \quad , \quad \gamma = \frac{t_0 - t}{t_0} \tag{2}$$

From Eqs.(1) and (2) we can derive the relation between α and γ as

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

And we obtain the graph shown in Fig.3 from Eq.(3).The graph shows the relationship between the aspect ratio of the pyramid and the thickness reduction obtained by uniform stretching of the triangular region. Empirically forming limit of common steel sheet is known as around 30 % for the thickness reduction. So we can estimate easily from Fig.3 that formable triangular pyramid shape has aspect ratio up to 30 % when press forming is adopted. Although the ideal core shape is regular triangular pyramids ($\alpha \approx 0.81$), the thickness reduction is about 67 % in this case and it is supposed that forming is impossible from Eq.(3) and Fig.3. Our conclusion suggests that our target of press forming should be the pyramid with the aspect ratio 0.29 against the thickness reduction 30 %.



(*a*) Initial geometry (*b*) Formed geometry

Fig.2 Ideal deformation of regular triangle to triangular pyramid

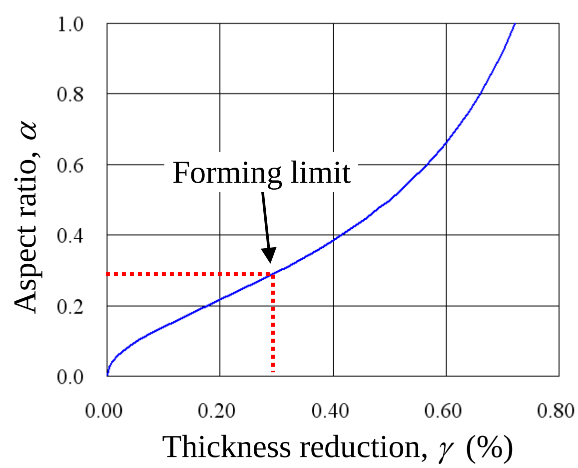


Fig.3 Aspect ratio (h/a) versus thickness reduction

1.3. Geometry and material properties of truss core panel

We determined the target of the triangular pyramid core with the edge length of the bottom 82 *mm* and the height 23 *mm* (aspect ratio = 0.28) in our simulation. The dimension of plate and the number of cores are variable according to the purpose of use of the truss core panel. We defined the truss core panel including 6 x 5 core array as Fig.4. We modified the vertex of the pyramids as flat for spot weld and made fillet at the edges to be able to form by press forming. Belytschko-Tsay shell element with three through-thickness integration point is adopted and *MAT_TRANSVERSELY_ANISOTROPIC_ELASTIC_PLASTC (*MAT_037) is used. The material properties are summarized in Fig.5.

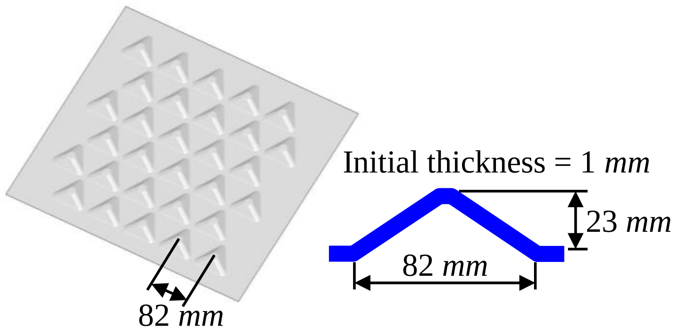


Fig.4 Geometry and dimensions of truss

Young's modulus	= 206 *GPa*
Poisson's ratio	= 0.3
Yield stress	= 159.74 *MPa*
Density	= 7.84×10^3 kg/m^3
r	= 1.815

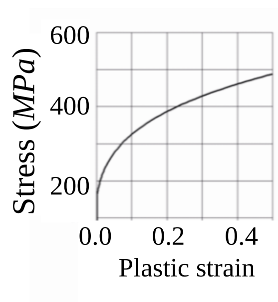
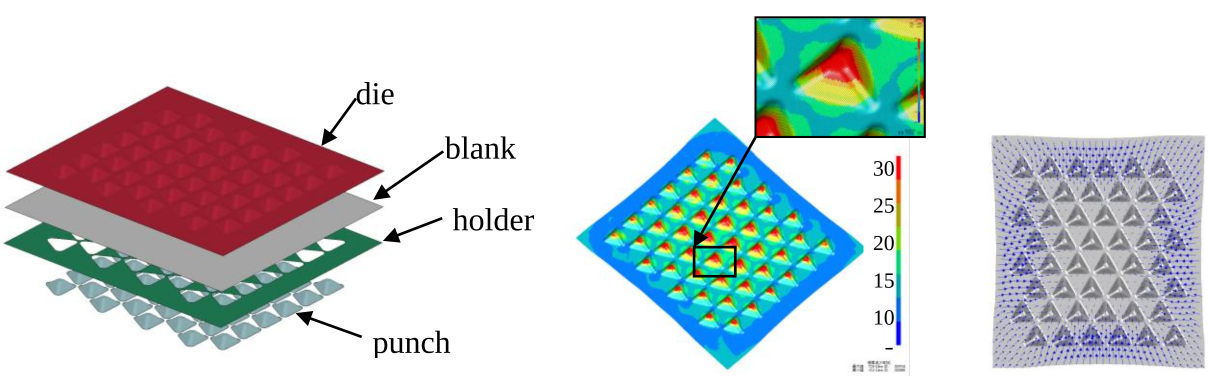


Fig.5 Material properties and stress-strain curve

1.4. Single stage forming

First, simple single stage forming simulation was performed and reviewed shortly. Figure 6 (*a*) is the model and Fig.6 (*b*) and (*c*) are its result. In this case each core stretches individually, then extreme thickness reduction over the forming limit occurs. Sheet cannot flow into the cores especially around the center of the sheet. Therefore this simulation shows clearly that the single stage forming cannot be applied to form the truss core panel.

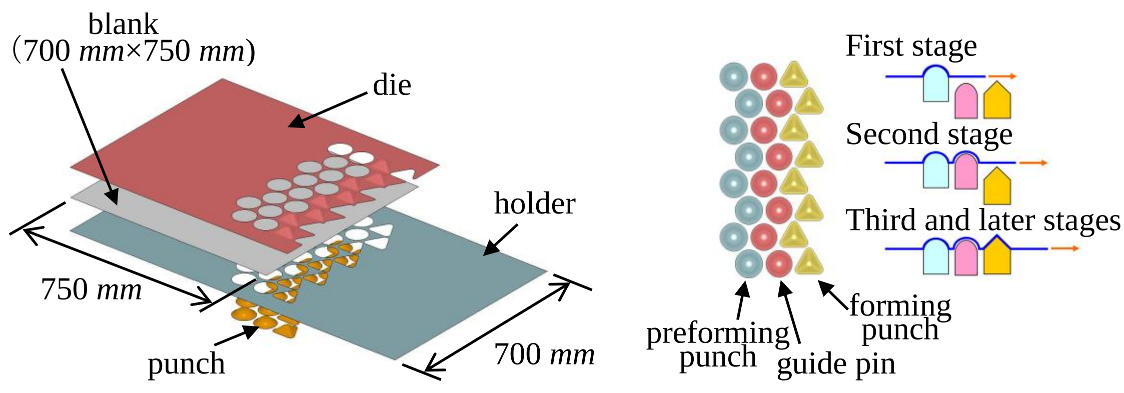


(*a*) FE model (*b*) Thickness reduction (%) (*c*) Nodal displacement vector

Fig.6 Single stage forming simulation

1.5. Multi-stage forming

Second, multi-stage forming process was evaluated using simulation. In this forming process there are two punches, i.e., preforming punch and forming punch. In the preforming stage the cores are formed into hemisphere shape in which each core may be stretched uniformly. After preforming the forming punch is activated to form each core into final pyramid shape. This idea was investigated using the simulation. Figure 7 shows the FE model and tool setup for the multi-stage forming and forming sequence is shown in Fig.8. The result shows that the maximum thickness reduction is under 30 % and the truss core panel can be formed using this multi-forming procedure in our simulation. Later forming trial was performed and it confirmed our estimation based on the simulation.



(*a*) FE model (*b*) Punch and blank motion

Fig.7 Multi-stage forming simulation

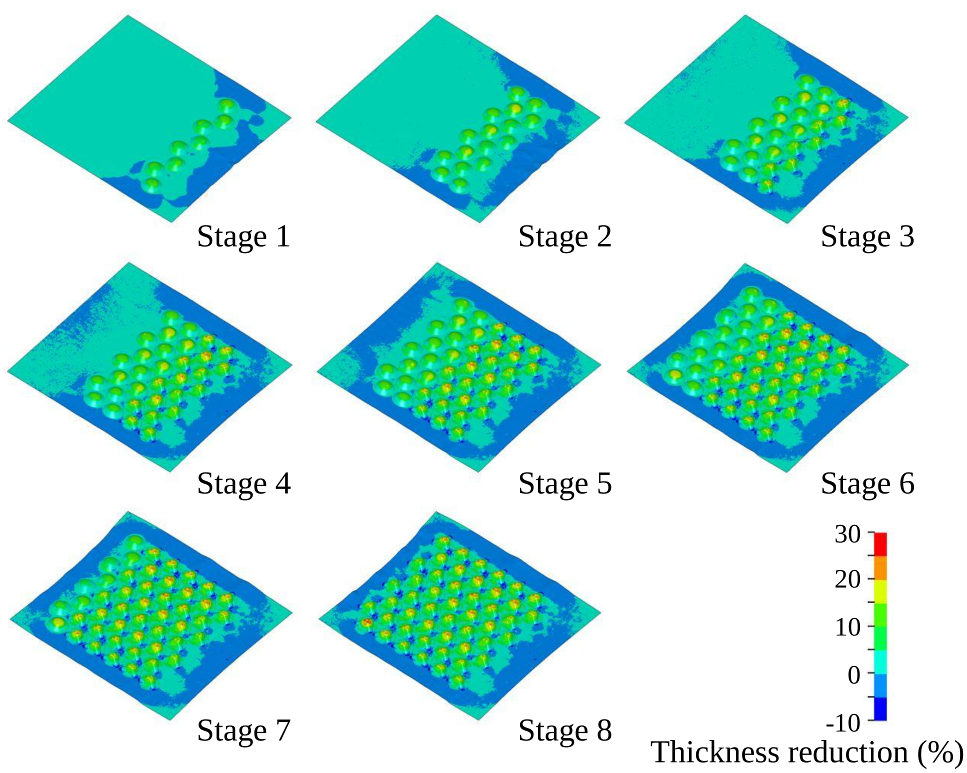


Fig.8 Forming sequence of multi-stage press forming of truss core panel

2. Bending Strength of Truss Core Panel with Work Hardening Effect

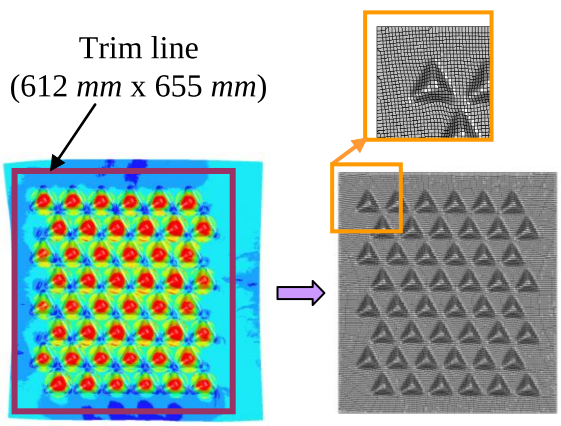
Our purpose of the development of truss core panel is replacement of conventional honeycomb panel as a light weight and high strength structure. For this purpose the bending strength of truss core panel was compared with that of honeycomb panel through the simulation. The procedure to create a three point bending model of the truss core panel is as follows;

(1) The final shape of the truss core panel obtained by multi-stage press forming simulation was trimmed into 612 *mm* x 655 *mm* rectangular plate as shown in Fig.9.

(2) Stress, plastic strain and thickness distribution in the fine mesh of the truss core panel used in the forming simulation were mapped on a coarse mesh for the three point bending simulation as shown in Fig.10.

(3) A sheet of truss core panel was duplicated and combined as Fig.11. Each vertex of the pyramid was attached on the flat surface of the opposite plate using spotweld beam.

Honeycomb panel model of three point bending was also modeled to compare with the truss core panel shown in Fig.12. It should be noted that truss core panel has work hardening derived from press forming whereas honeycomb panel doesn't have this feature.



(*a*) Final result of press forming simulation (*b*) Remeshed model along the trim line

Fig.9 Trimmed model from formed geometry obtained by multi-stage press forming simulation

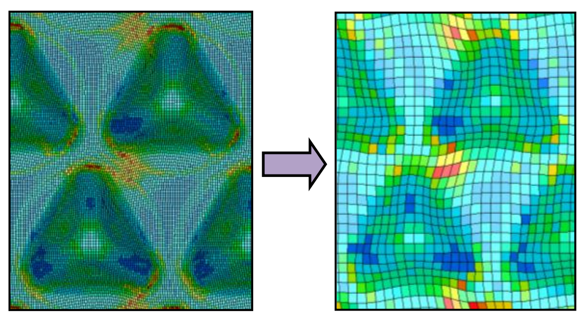


Fig.10 Mapping of stress, strain and thickness distribution from the fine mesh to the coarse mesh

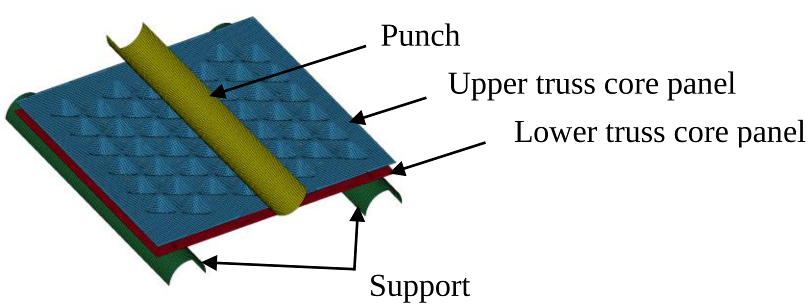
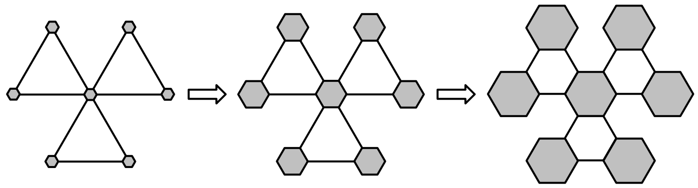
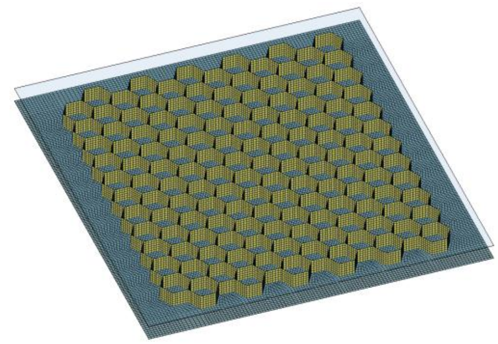


Fig.11 Truss core panel model configuration for three point bending simulation



(*a*) Transformation of truncated triangular pattern to honeycomb pattern



(*b*) Honeycomb panel model equivalent to truss core panel (upper plate invisible)

Fig.12 Honeycomb panel and truss core panel have a similarity

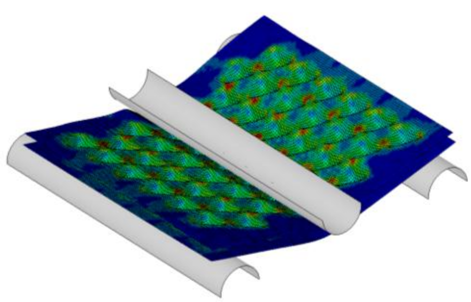
The results of three point bending simulation are shown in Fig.13. Following three cases for truss core panel were performed. and compared with honeycomb panel;

Case 1 : Full integral shell element (elform=16) is used without work hardening

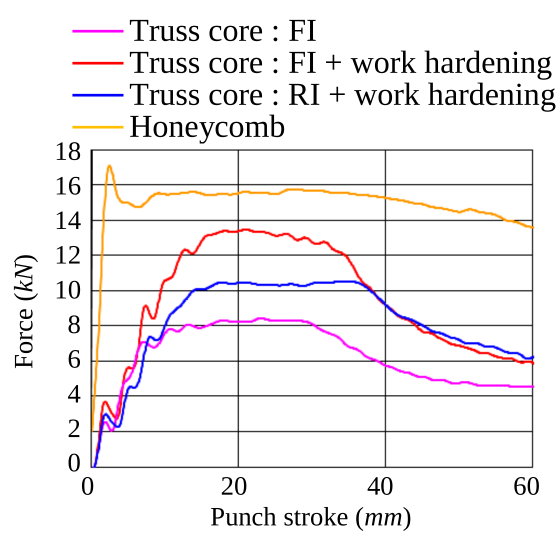
Case 2 : Full integral shell element (elform=16) is used with work hardening

Case 3 : Reduced integral shell element (elform=2) is used with work hardening

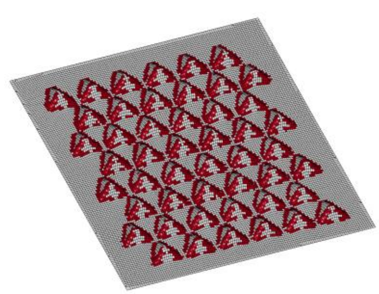
Figure 13 (*b*) is the comparison of force-stroke curves. In this result the work hardening effect improves the strength of the truss core panel dramatically. The honeycomb panel shows highest strength than any cases of truss core panel. But the strength of the truss core panel with full integral shell and work hardening is very close to honeycomb panel. So we suppose that truss core panel can be a substitute for honeycomb panel if production cost is considered. The case of reduced integral shell shows low strength even the work hardening is considered. The reason is



(*a*) Deformation of truss core panel



(*b*) Force-stroke curve



(*c*) Red elements have warpage angle of over 5 degrees

Fig.13 Results of three point bending simulation clear that RI shell doesn't consider warpage stiffness in its formulation[3]. Figure 13 (c) indicates the shell elements having warpage of five degrees and over as red region. It is considered that these elements decrease the bending strength of the panel.

3. Shape optimization of truss core panel to improve impact energy absorption ability

One of important application of truss core panel is the structure of vehicles. Especially as electric vehicle doesn't have exhaust pipes and drive shaft on the floor, the floor is flat and truss core panel can be applied for the floor of electric vehicle (Fig.14). We also expect that truss core panel absorbs impact energy at vehicle crash. For this purpose we tried a shape optimization of truss core to maximize the ability of energy absorption. The model for the shape optimization problem is shown in Fig.15. The definition of the shape optimization are as follows;

(1) Design variables and side constraints

$12.0\ mm \le h \le 18.0\ mm$

$1.2\ mm \le w \le 2.0\ mm$

$3.0\ mm \le r_a \le 6.5\ mm$

$3.0\ mm \le r_b \le 8.0\ mm$

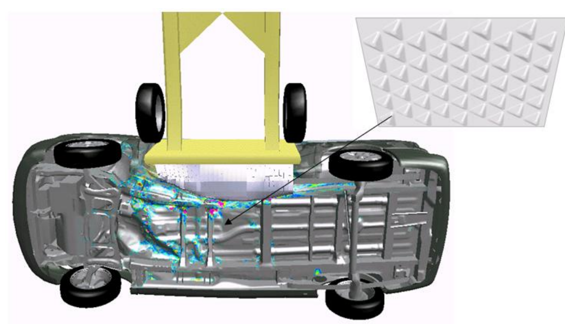
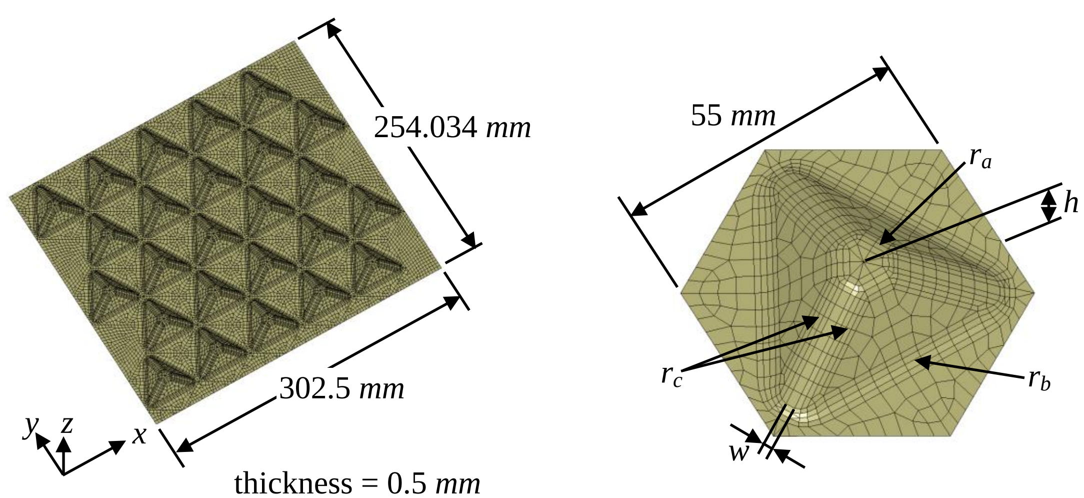


Fig.14 Candidate parts to adopt truss core panel (FE model courtesy of NCAC)[4]



(a) Truss core panel model (b) Design variables h, w, r_a and r_b

Fig. 15 Truss core panel FE model and design variables for shape optimization

(2) Objectives

Maximize absorbed energy E_x for crash in *x*-direction

Maximize absorbed energy E_y for crash in *y*-direction

Maximize absorbed energy E_z for crash in *z*-direction

(3) Constraints

Displacement for crash in *x*-direction, $d_x \leq 156\ mm$ (initial design)

Displacement for crash in *y*-direction, $d_y \leq 117\ mm$ (initial design)

Optimization calculation was driven by LS-OPT and sequential metamodeling using RBF network was used during the calculation. As the result optimal design was obtained at the fifth iteration. The results are summarized in Table 1. The response surfaces of absorbed energy E_x, E_y, E_z vs two important design variables h and r_b are illustrated in Fig.16. In this optimization problem good improvement for the energy absorption for E_x can be seen. However obvious improvement cannot be seen for E_y and E_z. One of the reason is a trade-off relationship between E_x and E_y as shown in Fig.17. Another possible reason is the accuracy of the response surfaces. Following R^2 values show good accuracy for E_x whereas poor accuracy for E_y and E_z.

R^2 for $E_x = 0.897$, R^2 for $E_y = 0.465$, R^2 for $E_z = 0.086$

Table 1 Optimal design

	Base line model	Predicted response		Real response	
		Value	improvement (%)	Value	improvement (%)
E_x (*J*)	719.76	764.27	6.19	769.29	6.88
E_y (*J*)	603.81	596.83	-1.16	604.758	0.16
E_z (*J*)	186.24	186.29	0.03	186.93	0.37
d_x (*mm*)	156.28	142.31	8.94	139.93	10.46
d_y (*mm*)	117.58	115.49	1.78	105.92	9.92
h (*mm*)	15.000	17.037	-	17.037	-
w (*mm*)	1.690	1.505	-	1.505	-
r_a (*mm*)	5.000	3.217	-	3.217	-
r_b (*mm*)	5.000	8.000	-	8.000	-

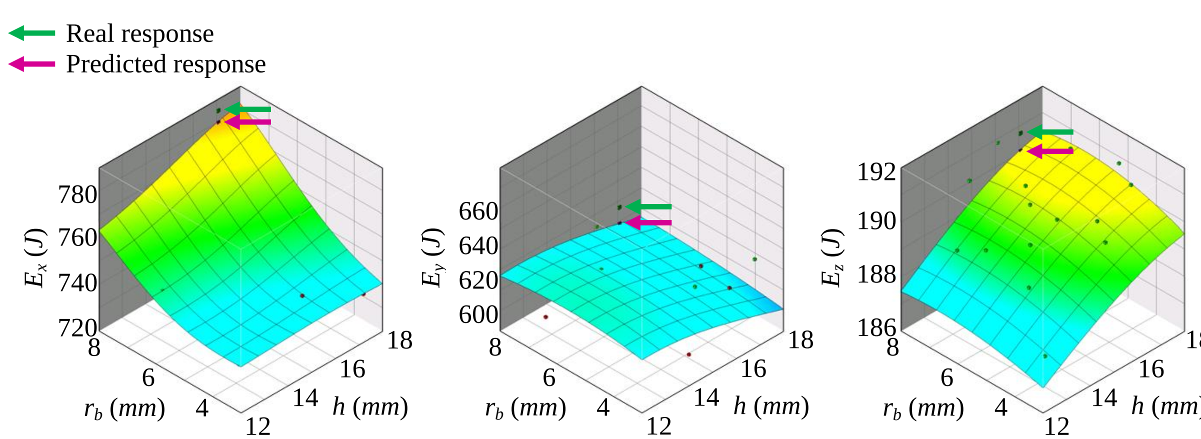


Fig. 16 Response surface of absorbed energy vs design variables h and r_b using RBF

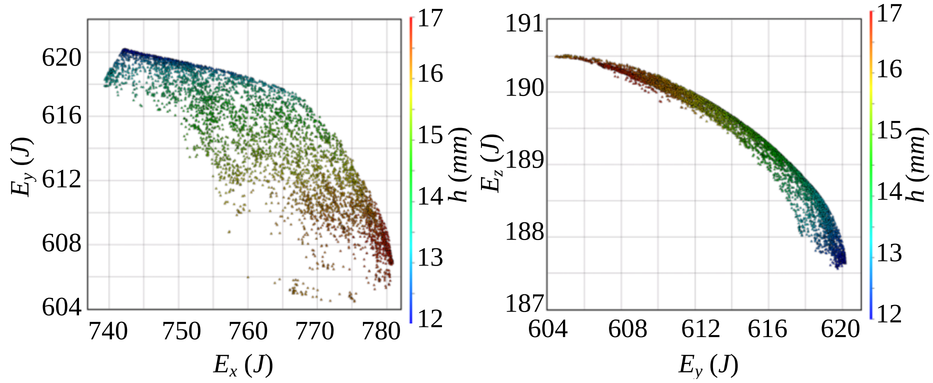


Fig.17 Trade-off relationship between E_x and E_y (left) and E_y and E_x (right)

4. A study for buckling characteristics of reversed spiral origami tube

4.1. Introduction

Reversed spiral origami tube is a tubular structure formed from a folded sheet (Fig.18). A geometric condition to form a closed tube is given as

$$\alpha = \frac{2\pi}{2N}$$

where a is an angle between the lines of mountain fold and valley fold depicted in Fig.18[5]. N is the number of division through the circumferential direction. If the tube satisfy above condition, the tube can be folded easily along the center axis. So if this tube can be made from metals like steel, it is supposed that the reversed spiral origami tube can be used as a kind of crash tube to absorb impact energy. In this study forming process and crash performance were investigated using simulation.

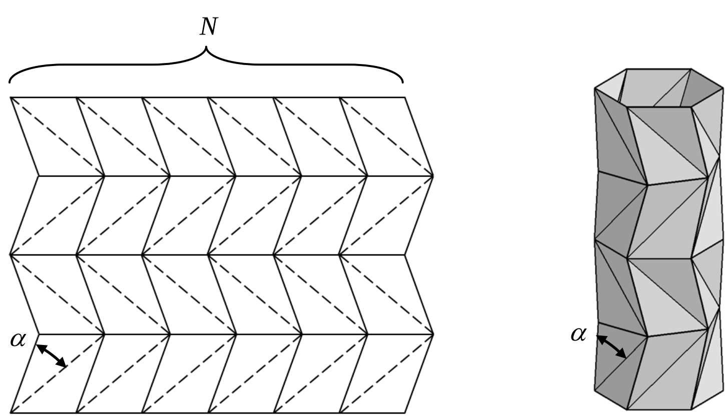
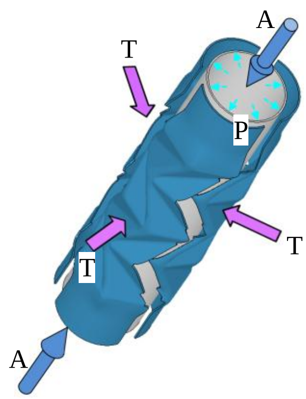


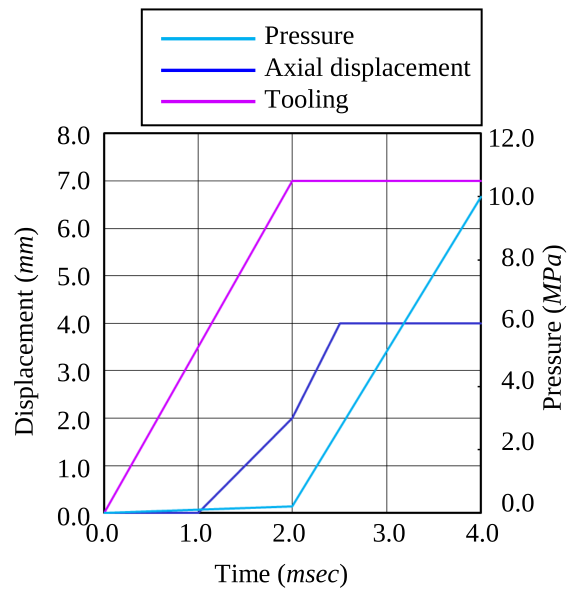
Fig.18 Development view and folded shape of reversed spiral origami tube. Solid lines in the development view are mountain fold and broken lines are valley fold.

4.2. Hydroforming simulation

Hydroforming simulation of the origami tube was performed to study formability. The origami tube is formed from a cylindrical tube by the combination of pressure, axial displacement and tooling shown in Fig.19 (*a*). The main purpose of the simulation is determination of the loading path or history of these three loading condition. If the pressure is too weak and the axial displacement is too large, buckling may occur during the forming. In contrast if the pressure is too large and the axial displacement is too small, the tube may be ruptured. The appropriate loading path could be determined after several trial and error as Fig.19 (*b*). Figure 20 shows the deformation of the tube in the forming process.



(*a*) Loading condition
P : Pressure
A : Axial displacement
T : Tooling



(*b*) Loading path

Fig.19 Loading condition and history for the hydroforming simulation

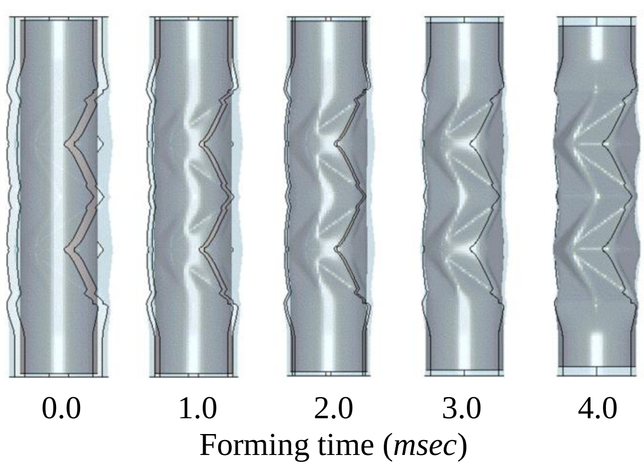


Fig.20 Deformation of the tube during the forming process

4.3. Crush simulation

The reversed spiral origami tube can be folded effectively along the center axis of the tube when axial load is applied. The region of common side member of vehicle which contributes for impact energy absorption is regarded only 70 %, whereas the reversed spiral origami tube can collapse almost 100 %. So there is a possibility to use origami tube as a component of energy absorption mechanism of vehicles if it is designed properly. In this paper a simple crush simulation of the origami tube was performed to reveal the behavior of the tube against axial compression. Figure 21 shows the crush simulation model of the origami tube. The tube is impacted by the rigid impactor with the velocity 13888.89 *mm*/*s*. The result is shown in Fig.22. The force-displacement curve can be divided into seven phases as shown in this figure. The events occurred in each phase can be analyzed as follows;

Phase 1 : Initial peak appears by the impact between the edge of the tube and the impactor.
Phase 2 : High frequency oscillation is observed caused by the buckling of the edge of the tube.
Phase 3 : The layer 1 and 2 in Fig.21 are folded and the force decreases.
Phase 4 : The layer 1 and 2 are compacted completely and the force increases.
Phase 5 : The folding of the layer 3 and 4 is initiated along the fold lines and the high force is kept.
Phase 6 : The layer 3 and 4 are folded and the force decreases.
Phase 7 : All layers are compacted and the force increases.

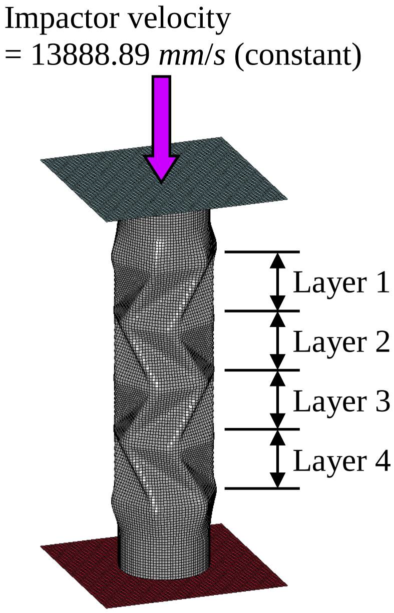


Fig.21 Crush simulation model

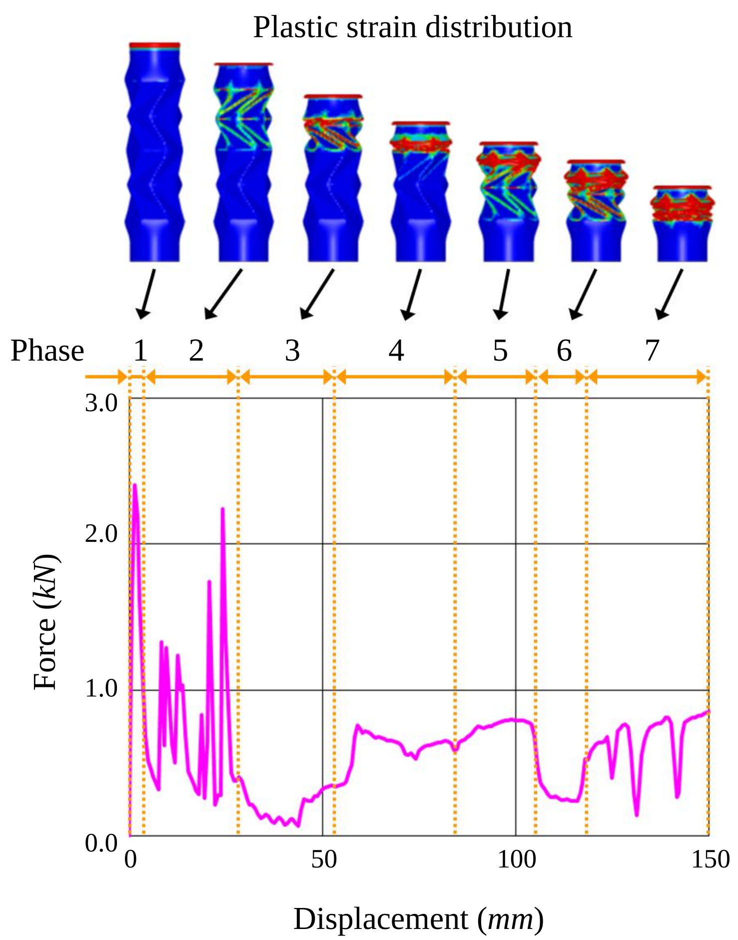


Fig.22 Force-displacement curve of the origami tube

From this result we can conclude that if some design variables, e.g., angle α, the number of division N, the number of layers, etc. are determined correctly, the impact force can be controlled in accordance with the purpose of impact energy absorption.

5. Conclusions

Two interesting structure, octet-truss core panel and reversed spiral origami tube conceived from origami engineering were introduced. The truss core panel is inexpensive for production cost and it was shown that the truss core panel might be an alternative of conventional honeycomb panel as a light weight and high strength structure. For the origami tube it was shown that the tube had a potential ability to control impact force as a impact energy absorption equipment in vehicles. It was quite easy to perform the simulation of the multi-stage forming of truss core panel using LS-DYNA. Because LS-DYNA analysis can pass the result of former simulation easily using dynain file. This capability could also be used in the three point bending simulation including work hardening effect. LS-OPT could create the metamodels very efficiently for the multi-objective optimization problem for the energy absorption ability of the truss core panel.

Excellent capabilities of LS-DYNA and LS-OPT will be a powerful tool for the development of unique structures conceived from origami engineering in the future.

References

[1] T. Nojima and K. Saito, “Panel and Panel Production Method”, Japanese Patent Disclosure 2007-023661 (Panel Production using Octet Truss Structure and Generalized Panels) (in Japanese), (2007)

[2] T. Nojima, “Panel and Panel Pieces”, Japanese Patent Disclosure 2007-055143 (Combined Robust Core Panel) (in Japanese), (2007)

[3] Belytschko, T., and C.S. Tsay, “Explicit algorithms for Nonlinear Dynamics of Shells”, Comp. Meth. Appl. Mech. Eng., 43, 251-276 (1984)

[4] National Crash Analysis Center, Public Finite Element Model Archive, http://www.ncac.gwu.edu/vml/models.html

[5] T. Nojima , “Modelling of Folding Patterns in Flat Membranes and Cylinders by Using Origami”, Journal of JSME, C, 66-643, pp.1050-1056, March, 2000 (in Japanese)