IT in Industry, vol. 3, no. 3, 2015 Published online 29-Dec-2015

Modeling and Simulation of Tsunami Pod

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***Abstract*—This paper presents the design of a deployable and foldable tsunami pod for older and disabled people who cannot run to higher grounds during a tsunami attack. In our design, we adopt an ellipsoid structure and use finite element method (FEM) to model the structure. Then, we conduct numerical simulation and confirm the safety based on the von Mises equivalent value and the Head Injury Criterion (HIC). As the result of the first simulation, it is proved that the initial model referring to the commercially available tsunami shelters is weak against the impact force from rigid walls and obstacles and can be strained in the central part. And also, the occupant might hit against the internal wall and get injured. Therefore, a seat and upper and lower bars are added to the initial model. As a result of the second simulation, the von Mises equivalent value for the modified model is decreased, but still above that of the first simulation. The HIC value is decreased largely and is much less than the HIC safety level. This is because the occupant restraint system will prevent the occupant from hitting the internal wall of the pod. Moreover, we optimize the structure for the tsunami pod by minimizing its weight. Finally, we confirm the validity of the optimal model in the original condition of fluid-structure coupling analysis.**

Keywords*— tsunami; von Mises equivalent stress; explicit finite element method; arbitrary Lagrangian Eulerian method; head injury criterion; optimization; origami

I. INTRODUCTION

On 11 March 2011, the magnitude 9.0 earthquake off the coast of Japan triggered a tsunami that struck Tohoku causing severe destruction and loss of lives. Broken evacuation routes prevented people from escaping; older people, seriously injured people, and visitors not familiar with the area would not be able to evacuate to higher places easily. To protect human beings from tsunami disasters has been a challenge for a long time. As a counter-measure for minimizing the damage occurred due to a large tsunami as the last one, fixed tsunami evacuation facility such as tsunami evacuation buildings and floating shelters were proposed [1, 2]. These shelters are limited to urgent and temporary use out of sheer necessity. As a floating type shelter, the spherical shaped shelter which has evacuation space in the upper part and weight and saving space in the lower part was proposed by Shigematsu [1, 2]. And, those motion characteristics was examined under hydraulic experiment with a reduced model. In this paper, we propose a foldable ellipsoidal body as a floating type tsunami shelter and name it "tsunami pod" for its form.

Firstly, we generate the 3D model for simulation by calculating the values of coordinates *X*, *Y*, and *Z* from 2D foldable pattern. Then to verify the safety of the tsunami shelter, we analyze the degree of crash by the von Mises stress in case the tsunami pod collides with walls or obstacles, and also calculate the Head Injury Criterion (HIC) for an occupant at the same time.

II. MODELING OF TSUNAMI PODS

A. *Previous Tsunami Shelters*

After the 3.11 earthquake, several types of tsunami shelters made of carbon fiber reinforced plastic (CFRP) have been produced by Japanese companies. Table 1 shows the specifications of three types of spherical pods. Due to the curved surface, these pods can avoid crashes by obstacles and pressure from outside, and can diffuse stress. As a result, it can decrease the lard at each point, and suppress the explosion and damage to the utmost limit. As shown in Table 1, the safety of each shelter is evaluated based on criteria such as air tightness and oxygen concentration. Furthermore, some companies conducted waterfall tests and floating tests in the sea.

B. *Design of Foldable Ellipsoidal Model for Simulation*

The product "HIKARi" in Table 1 is an assembling type which is carried in with each part split apart. After being carried into the home, they have to put parts together into spherical form and keep it on the balcony in its development state. On the other hand, we devise the pod which can be kept in a foldable state and can be developed instantaneously in case of emergency. An ellipsoid body rotated in one direction is applied as form, while a sphere is rotated in all directions. The

TABLE I. COMMERCIALLY AVAILABLE TSUNAMI SHELTERS

product name	Life Armour	HIKARi	Nore	Super Barrier S4
manufacturing company	Pond Co., Ltd.	Hikari Rezin Co., Ltd.	Shelter JAPAN Co., Ltd.	World Net International Co., Ltd
form on sale	integrated	integrated or assenbly	integrated	integrated
material	CFRP	CFRP	CFRP	steel
form in use	spherical body	spherical body	spherical body	dotriacontahedron
diameter	120cm	120cm	120cm	180cm
weight	80kg	80kg	80kg	500kg
maximum number of occupants	4	4	4	6
withstand load	9t	22.4t	12.5t	
price	400,000 yen	500,000 yen	670,000 yen	2,600,000yen
priduct photo				

ISSN (Print): 2204-0595
ISSN (Online): 2203-1731)

folding way for a sphere has already been studied [3] and it is possible to fold an ellipsoid body. Here, we use the mechanism which makes it possible to develop an ellipsoid body in case of emergency and be folded for storage after use. In this paper as the first report, we assume that there is no influence on strength by being developed and folded. Its size is designed as 1200 mm for the major axis and 800 mm for the minor axis, and examine the case where one occupant boards a shelter.

C. Generation of Initial Mode without Occupant Restraint System

We set the major axis as Z axis and the minor axis as X axis. Consider a spheroid which is obtained from the rotation around the Z axis. Then, we also set the length of diameter for the Z axis as a, and the length of diameter for Y axis as b. The surface of the spheroid form is given in (1a), and each coordinate point can be calculated by (1b), where θ is the latitude and φ is the longitude.

$$\frac{x^2}{b^2}+\frac{y^2}{b^2}+\frac{z^2}{a^2}=1 \tag{1a}$$

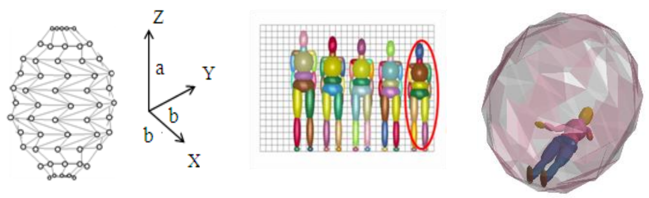
$$x=b\cos\theta\cos\varphi \quad y=b\sin\theta\cos\varphi \quad z=a\sin\varphi \tag{1b}$$

To fold the spheroid form in the direction of Z axis, the foldable and deployable form is generated, as shown as in Fig. 1(a). The small circles in Fig. 1(a) are intersection points, made in the way that the form is divided into ten parts in the latitude direction and longitude direction and the intersection points are connected into folding lines. Those points are called key nodes and are used in generating the mesh model.

We apply dummy model for the 5% lower level female adult in the GEBOD Dummy Model, as shown in the first right side of Fig. 1(b) (LANCEMORE Corporation), developed in the airplane industry. The model for tsunami pod made in the process as above is called the initial model without the occupant restraint system. The total number of nodes and elements for the dummy system is 36138 whose details are 1636 for shell elements and 2648 for solid ones. The model with an occupant is shown in Fig. 1(c). Next, each part is divided into mesh for structure analysis. The way of mesh division for a pod is that after each line of a triangle element is divided into five parts and formed into a square basically and a triangle in the parts around nodes. On the other hand, the part of a rigid wall constructed of shell elements is divided into tetrahedron mesh, and the part of seawater constructed of solid elements is divided into tetrahedron mesh whose volume is around 400 times as large as a pod, as shown in Fig. 2. The boundary conditions for inflow, outflow, and no-slip are set as the fluid part not leaking out. The total process for simulation is from the situation where the seawater (tsunami), shown in the right panel in Fig. 2, gives an initial velocity to a pod to the situation where a pod hits on a rigid wall, as shown in the left panel in Fig. 2, and rise onto that.

D. Fluid-Structure Coupling Analysis

For simulation, we use the software "LS-DYNA" [4] which is a general-purpose finite element program capable of simulating complex real world problems. This simulation is categorized as fluid structured coupling analysis [5] where a fluid force transform a structure of pod and at the same time a transformed structure influences a flow field. In details, seawater and air are set as fluid part, while tsunami pod is set as a structured part. The fluid parts are expressed in Arbitrary Lagrangian Eulerian (ALE) method [6], and the structured parts are expressed in the coordinate system. The ALE method is used in solving simultaneous the conservation rules of mass, momentum, and energy. Each conservation rules are formally written as (2a), (2b), and (2c).



(a) (b) (c)

Fig. 1. Model for tsunami pod with a dummy model: (a) foldable ellipsoidal model, (b) dummy model of GEBOD FEMALE, and (c) foldable ellipsoidal model with a dummy model.

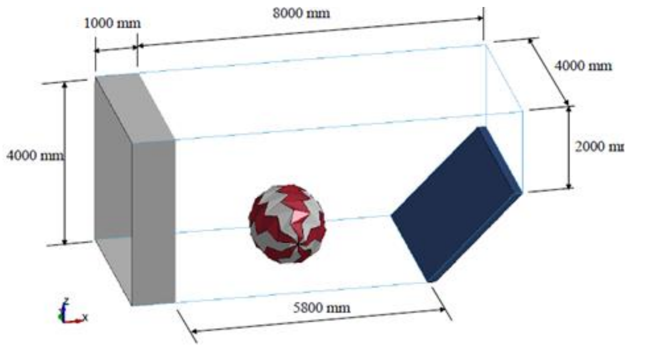


Fig. 2. The simulation model including a pod, tsunami on the right, and rigid wall on the left.

$$\frac{\partial\rho}{\partial t}+\rho\,\mathrm{div}(\mathbf{v})+(\mathbf{v}-\mathbf{w})\,\mathrm{grad}(\rho)=0 \tag{2a}$$

$$\rho\frac{\partial\mathbf{v}}{\partial t}+\rho(\mathbf{v}-\mathbf{w})\cdot\mathrm{grad}(\mathbf{v})=\mathrm{div}(\boldsymbol{\sigma})+\mathbf{f} \tag{2b}$$

$$\rho\frac{\partial e}{\partial t}+\rho(\mathbf{v}-\mathbf{w})\cdot\mathrm{grad}(e)=\boldsymbol{\sigma}\!:\!\mathbf{D}+\mathbf{f}.\mathbf{v} \tag{2c}$$

Here, ρ is fluid density, $\mathbf{v}$ is velocity vector of fluid, $\mathbf{w}$ is velocity vector of mesh, e is energy per unit mass, $\boldsymbol{\sigma}$ is Cauchy stress tensor, $\mathbf{D}$ is deformation velocity tensor, and $\mathbf{f}$ is body force. In the simulation, seawater (fluid part), as shown in Fig. 3(a) touches the tsunami pod (structured part), and then the mesh of seawater and air are deformed internally, Fig. 3(b), and finally the mesh is restored to the initial position, Fig. 3(c). In this procession, the advection term including $(\mathbf{v}-\mathbf{w})$ in (2c) is calculated.

The applied penalty method generally used in the contact calculation for structure analysis is applied to the coupling calculation method with structured part (tsunami pod) and fluid (tsunami). As shown in Fig. 4, those contact points are placed

ISSN (Print): 2204-0595
ISSN (Online): 2203-1731)

on the contact positions with structure part and fluid one. The contract points are shifted following to the fluid transfer. However, the virtual spring between the transferred point and the former one is generated. The force exerted by the extended spring expresses the pressure which a structure is exerted by fluid. The spring stiffness k for the virtual string is given in (3).

$$k = p_f \frac{KA^2}{V}, \tag{3}$$

where K is a volume modulus for the fluid element, A is the average area of the structure element, V is the volume of the fluid element, and p_f is a scale factor. Under this condition, the force P which the structure body receives is expressed as (4).

$$P = kd, \tag{4}$$

where d is the intrusion of fluid into the structure body. This coupling method has short time steps for an explicit method, and the intrusion into fluid for one step is little.

E. Conditions and Video Image Shots of Simulation

CFRP [7] is a compound material which has a layered structure. As a product specification for CFRP, a tensile strength and bending stress (nominal stress) are mentioned. Therefore, in this paper, a pod is estimated as a simple elastic body, and the load provided on its structure is estimated by von Mises stress to compare with the strength of an actual product. The thickness of a tsunami pod for simulation is set to 4.0 mm which is the minimum among the products made of CFRP. For the properties of CFRP as material, Young's modulus is 294 GPa, Poisson's ratio is 0.12, and density is 1.8×10^{-9} ton/mm^3. A tsunami velocity is calculated as follows. A tsunami velocity in transmitting on the sea is in proportion to the √ of sea depth. However a tsunami velocity we apply into simulation is the one after flowing into the land which is slower than to the one on the sea for shallower and obstacles. The velocity for simulation is calculated as 8 km/s by the distance which certain objects move for a given period in the video taken in the Tohoku earthquake on March 11, 2011. The boundary conditions for inflow, outflow, and no-slip are set as the fluid part to prevent water from leaking out.

Fig. 5 as moving shots for this simulation proves that in the latter process of simulation an occupant hits on the internal wall of a tsunami pod would possibly be injured. To prevent this, we implement an occupant reinforcement system similar to the safety bars used in roller coasters. In the next section, the degree of injury to an occupant is compared between the models without and with the reinforcement system.

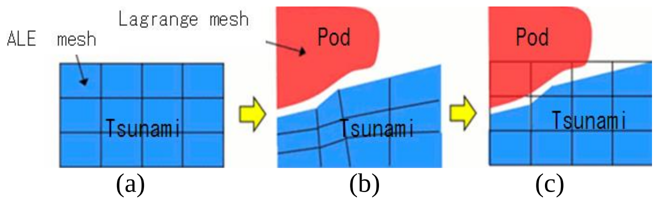


Fig. 3. Arbitrary Lagrangian and Eulerian Method: (a) initial mesh, (b) deformed internal mesh, and (c) restore deformation mesh to the initial position.

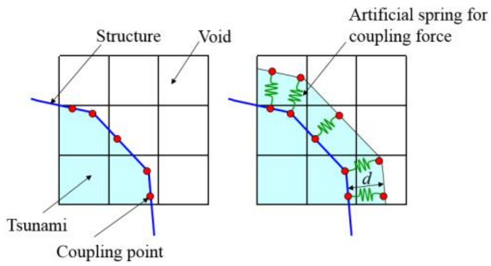


Fig. 4. Fluid structure coupling procedure using the penalty based method: (a) initial configuration, (b) generation of artificial spring at the next step.

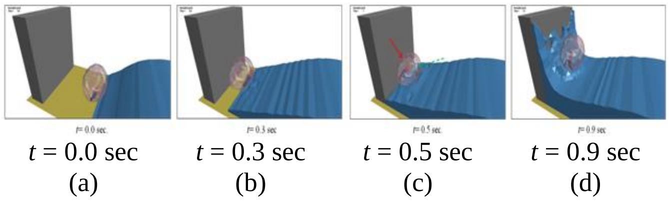


Fig. 5. A sequence of video image shots of simulation.

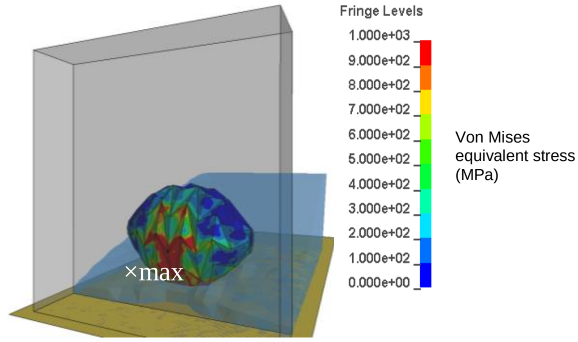


Fig. 6. Color contour for the maximum of von Mises equivalent stress at the moment that a resultant force become maximum in case of the initial model without an occupant reinforcement system.

III. NUMERICAL SIMULATION

A. Verification of Strength of the Initial Model without a Reinforcement

Firstly, the strength is verified in the case of the initial model without an occupant reinforcement system. It would be evaluated as not satisfying safety if any elements of a pod exceeded von Mises equivalent stress for CFRP (1500 Mpa). As a result of the simulation where a von Mises equivalent stress value around the elements of central parts seen from the major axis in the collision, as illustrated in Fig. 6, it is judged that a pod may be damaged.

B. Head Injury Criterion of the Initial Model

The Head Injury Criterion (HIC) is a measure of the likelihood of head injury arising from an impact. HIC is calculated using head acceleration and its duration, as in (5):

$$\text{HIC} = \left\{ \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} (t_2 - t_1) \right\}_{max} \tag{5}$$

where t_1 and t_2 are the initial and final times in seconds, a is acceleration, and $(t_2 - t_1) \leq 0.036\ s$. A big acceleration value for a short duration period is allowed, because the calculated HIC value is the average of every 0.036 second. The value below 1000 is considered as safety where 1 of 6 people suffer a critical injury in the brain. The time transformation of HIC in case of the initial model is shown in Fig. 7. It is proved that the value calculated by (5) is 10 times as the safety level 1000 and it is likely that an occupant could be seriously injured.

C. Verification of Strength on the Modified Model with Reinforcement and Its HIC Value

It is confirmed from the video image shots that an occupant is moving about heavily and hits on the internal wall of a pod and would be injured in the head. A tsunami pod is rotated 360 degrees while an automobile collides head-on. Therefore, compare to an 4 point fixed seatbelt for an automobile, a reinforcement for an upper body and a lower body to imitate the safety bars for a roller coaster is designed, as shown in Fig. 8(a). Fig. 8(b) is the modified model implemented with our designed reinforcement and seat. The parts of a seat and a reinforcement are set as a rigid body consisting of 5914 nodes and 5858 shell elements totally. While a seat and pod is set as rigid bodies.

The thickness of an outer wall is increased from 4.0 mm to 6.0 mm for reinforcing its structure. As a result of the simulation by the modified model with an occupant reinforcement system, von Mises equivalent value in some elements of a pod in collision exceeds the strength of CFRP and fails to improve the condition of damage, as shown in Fig. 9. On the other hand, the HIC value is decreased by more than 90% to 61, as shown in Fig. 10, which is well below the safety level 1000. Table. II summarizes the comparison result datum between the initial model and the modified model.

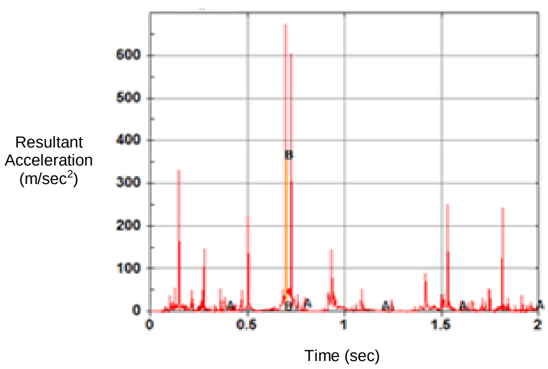
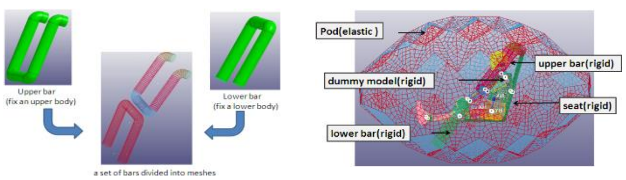


Fig. 7. Resultant acceleration for the head of an occupant in case of the initial model without an occupant restraint system.



(a) (b)

Fig. 8. Model with an occupant restraint system (a) upper and lower bars, (b) modified model.

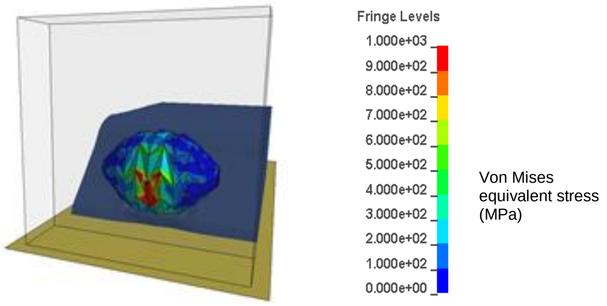


Fig. 9. Color contour for the maximum of von Mises equivalent stress at the moment that a resultant force become maximum in case of the model with an occupant restraint system.

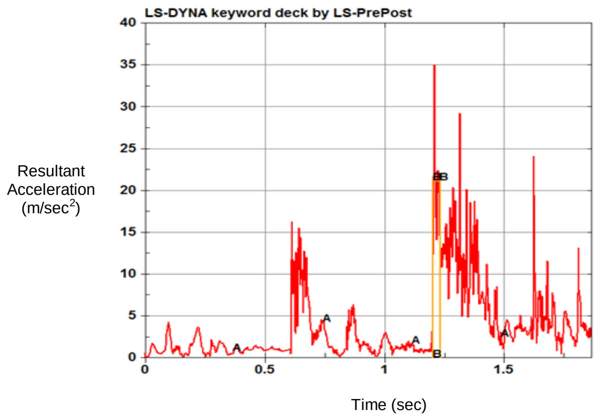


Fig. 10. Average resultant acceleration for the model with an occupant restraint system every 0.036 second.

TABLE II. RESULT COMPARISON BETWEEN THE INITIAL AND THE MODIFIED MODEL

	Initial model without reinforcement	Modified model with reinforcement
Thickness(mm)	4.0	6.0
Max von Mises(Mpa)	4678	2969
HIC	9642	61

IV. OPTIMIZATION OF STRUCTURE FOR TSUNAMI POD

A. Conditions for Optimization

Applying the modified model with a reinforcement, the following optimization is attempted. Those ranges for each design valuable are as follows; 1125 < major axis (a) < 1200, 630 < minor axis (b) < 840, 2.0 < thickness (t) < 6.0, 240 < Young's modulus (E) < 450. The HIC is excluded in the considerations because it has already satisfied safety in the result of the simulation applying the modified model with a reinforcement.

Under the above conditions, each design valuables are calculated to minimize the mass of a pod. The velocity is set as constant 4 m/sec in the *X* axis. For shortening a calculation time, a dummy model is set as a rigid body, and apply

ISSN (Print): 2204-0595
ISSN (Online): 2203-1731)

decoupling analysis in optimization, and later the validity of the obtained optimal model is verified by coupling analysis. Incidentally, the calculation time for 1 step in decoupling analysis is one-half as short as the one in coupling analysis.

We use a software named LS-OPT [8] applying Radial Basic Function (RBF) as response surface function. Initially, 5 sample points are input and an optimum solution is searched while generating response surfaces of an objective function and a constraint function by RBF network. The condition of finishing a calculation is the case where the optimal value this step and the one last step satisfies (6). If (6) is not satisfied, more 5 sample points are added and calculated again.

$$\frac{\mathit{Optimal\ value\ this\ step} - \mathit{Optimal\ value\ last\ step}}{\mathit{Optimal\ value\ this\ step}} \leq 0.01 \qquad (6)$$

B. Result of optimization

Table III is the summary of design valuables, maximum von Mises equivalent value among elements, whether a constraint condition is satisfied or not, and the image which is output at each step in optimization. The item “maxvonmises” is expressed as “○” in case maximum von Mises value does not exceed the strength of CFRP and as “×” in the opposite way. In the fourth step, the constraint donation is satisfied. However, the mass is twice as large as the initial model not to satisfy the objective function. Then, the calculation is repeated and to converge in the sixteenth step.

The variables of the obtained optimal model are 41.3kg (-24%), the length of major axis is 1200 mm (-23%), the length of the minor axis is 840 (-21%), the thickness is 5.0 mm, Young’s modulus is 245 GPa. The maximum von Mises value is 1299 MPa (-43%) which does not exceed the strength of CFRP 5000 to satisfy the constraint condition. The comparison between the initial model and the optimal model is summarized in Table IV. It means that by optimization the structural performance is improved while attaining the lightening by 52% which satisfied the condition of not being damaged well.

C. Validation of optimal model

The optimal model is implemented with a dummy model and is calculated by fluid structure coupling analysis in LS-DYNA. The maximum von Mises value among the elements of a pod is 496 MPa, as shown in Fig. 11, which is 70% smaller than that of the optimal model obtained by decoupling analysis in LS-OPT and also one-sixth smaller than the modified model with a reinforcement obtained by coupling analysis in LS-DYNA. On the other hand, HIC is 56 which is 8% lower than the modified model with a reinforcement. Therefore, the reliability of the optimal model is guaranteed.

V. Conclusion

In this paper, as a structure for a tsunami shelter, the ellipsoid body foldable and deployable structure is adopted. The tsunami shelter structure is named tsunami pod. Then, the model of a tsunami pod is generated, and its strength evaluation and safety examination is conducted. The design and analysis steps taken for this research are written as follows.

TABLE III. OPTIMIZATION PROCESSES FROM TIME STEP FROM 1 TO 16 (MAJOR AXIS, MINOR AXIS, THICKNESS, AND YOUNG MODULUS AS DESIGN VARIABLES AND VON MISES EQUIVALENT STRESS AS CONSTRAINT CONDITION AND MASS AS OBJECTIVE FUNCTION ARE LISTED EVERY 16 TIME STEP. AND, THOSE IMAGES FOR EACH MODEL ARE SHOWN IN THE BOTTOM)

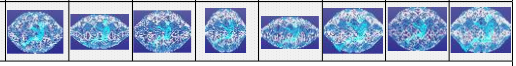
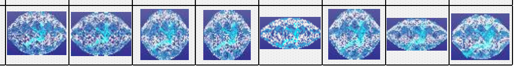
times of roop	1	2	3	4	5	6	7	8
a (scale)	1.00	0.96	1.10	0.75	1.07	0.75	1.10	0.75
b (scale)	1.00	0.75	1.07	1.10	0.79	0.75	1.10	0.75
t (mm)	4.0	6.0	2.4	6.0	5.6	2.0	2.4	2.0
Young's modulus (GPa)	294	450	240	282	240	450	450	261
mass (kg)	85	126	51	135	63	43	74	68
constraint condition(max vonmises(MPa))	× (1861)	× (1746)	× (2747)	○ (1362)	× (1895)	× (2158)	× (2253)	× (2070)
image of model								
times of roop	9	10	11	12	13	14	15	16
a (scale)	0.75	1.06	1.02	1.02	0.87	0.91	0.81	0.77
b (scale)	1.10	1.04	0.77	0.78	0.98	0.76	1.10	0.79
t (mm)	2.8	5.3	2.6	2.6	2.0	5.4	4.1	5.0
Young's modulus (GPa)	240	440	427	240	240	450	432	287
mass (kg)	97	70	76	128	62	85	51	41
constraint condition(max vonmises(MPa))	× (1558)	× (2140)	× (2264)	× (1931)	× (2061)	× (2394)	× (1611)	○(1299)
image of model								

TABLE IV. COMPARISON BETWEEN THE INITIAL VARIABLES AND THE OPTIMUM VARIABLES

	initial variavle	optimal variable
design variable		
major axis(scale)	1.0	0.75
minor axis(scale)	1.0	0.82
thickness(mm)	4.0	3.7
Young modulus(Mpa)	294.0	240.0
Objective function		
weight(kg)	63.72	48.67
Constraint condition		
maximum of von Mises equivalent stress(Gpa)	2969	1299

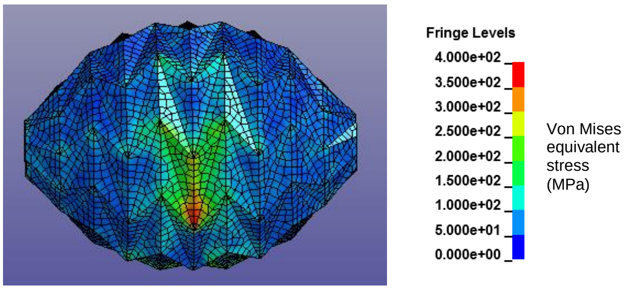


Fig. 11. Color level distribution chart for von Mises equivalent stress when the part of the element is the highest during simulation in the case of fluid-structure.

1) The strength evaluation for several kinds of tsunami shelters have been conducted only by experiment, and 4 points typed seatbelt for an automobile is applied to those shelters, and the injury value in collision has not been calculated. Then, a foldable tsunami pod is designed referring to size, material, the thickness of the present ones, and an occupant is loaded on it. As a result of conducting fluid structured coupling analysis applying the initial model without an occupant constraint system, it is found that both the strength of a pod and the injury

ISSN (Print): 2204-0595
ISSN (Online): 2203-1731)

value did not satisfy safety level. Here, the strength of a pod is evaluated by von Mises condition while treated as isotropic. And, an occupant is shown being rotated 360 degrees in simulation, so we decided that the 4 points typed seatbelt is not appropriate for our designed shelter.

2) Therefore, based on the initial model, setting those variables as thickness, a major axis, a minor axis, and Young's modules, optimization analysis is conducted under the constraint condition of von Mises and the objective function to minimize a mass, and the expected structure which is light weight and strong enough is obtained. In this optimization analysis, decoupling analysis is adopted instead of coupling analysis which takes twice times as decoupling analysis. Next, when the obtained optimal model is verified by coupling analysis, it is clarified that the strength of a pod is evaluated more strictly by decoupling analysis than by coupling analysis.

3) From the above, in this research, we design the optimum specifications for a pod structure and develop the technique of modeling and simulation to examine injury value of an occupant. Also, it is proposed that a rigid seat with two bars which fix separately the upper and lower body of an occupant, as used in roller coasters, should be effective for an occupant constraint system.

Additionally, the Origami typed ellipsoid body is developed which is deployed before use and folded after use in case of emergency. However, we did not discuss its mechanism and ignored the influence of that on the strength of a pod to simplify this research. In the future, we will propose a mechanism to be foldable and deployable for a tsunami pod with CFRP, and optimize the model considering the mechanism.

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ISSN (Print): 2204-0595
ISSN (Online): 2203-1731)