Study on Impact Loading Reduction Performance of "Origami Hat"

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1 Introduction

With the enforcement of the revised Road Traffic Act, wearing helmets has become a mandatory effort for all cyclists since April 1, 2023 in Japan. However, there are still many people who do not wear helmets. Therefore, we considered developing a foldable helmet that can be easily carried by applying the concept of origami engineering. Origami engineering is a research field proposed with the aim of developing lightweight, high-strength structural components based on the idea of origami, a traditional Japanese paper craft in which various shapes are created by folding paper-like materials. Under the same conditions of the safety test for industrial helmets, a 5 kg striker was dropped from a height of 1.0 m onto a dummy head wearing the hat in which impact energy absorption material was installed, and the impact load received by the dummy head was computed in the simulation. As a result, it was confirmed that it was possible to reduce the impact load by devising the proper material properties and folding shape.

2 What is an origami hat?

We have developed several foldable hats as regular fashion hats as shown in Fig.1[1][2]. Several origami techniques are used to create these hats. For example, in Fig.1 (a), the so-called "sea cucumber fold" is used. In Fig.1 (b), "bellows fold" is applied. And, in Fig.1 (c), "sea cucumber fold" is used on the side of the crown, and the "bellows fold" is used on the top of the crown and the brim. In this way, by changing the color and folding method, it is possible to create a wide variety of attractive hats. These can be easily folded by folding them in the circumferential direction, as shown in Fig.2.

(a) Sea cucumber fold | (b) Bellows fold | (c) Sea cucumber + bellows fold | (d) Sea cucumber fold without brim

Fig.1: Examples of origami hats using various folding techniques

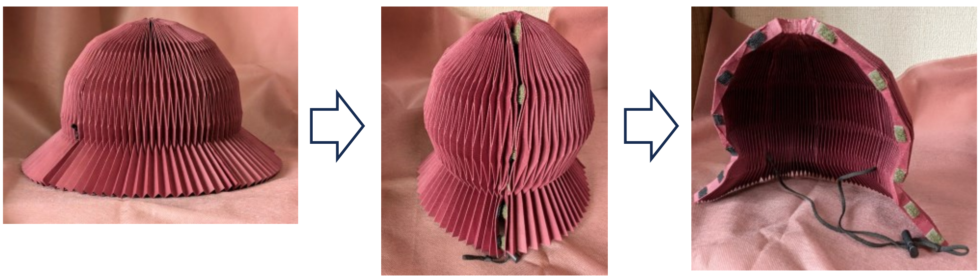


Fig.2: Folding process of origami hat

3 Analysis model configuration and test conditions

When using the origami hat as a cyclist's helmet, it needs to have impact energy absorption capabilities. There are several possible designs that can be used as impact absorber, but here we tried using an air cushion as the impact absorption material. An analysis model for the simulation was constructed based on the conditions of the industrial helmet safety tests as shown in Fig. 3. The origami hat was placed on a dummy head. The hat contains the air cushion. The upper radius, the lower radius and the height of the air cushion are 62 mm, 70 mm and 40 mm, respectively. A discrete linear spring element was attached between the center of gravity of the dummy head and the ground to measure the impact force. A striker with the mass of 5 kg was placed on the head and the hat. The radius of the striker is 48 mm. The striker drops from the height of 1 m from the hat, so its initial velocity at impact is 4428.69 mm/s. The simulation was performed using Ansys LS-DYNA® R13 SMP double precision on Windows 11 Intel Core i7.

4 Material properties

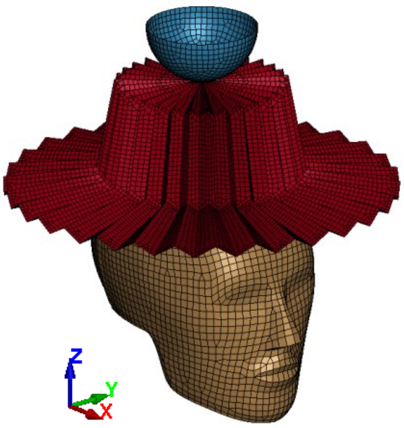
The hat is made of 2 mm thick paper. **`*MAT_PAPER`** in LS-DYNA was used for the definition of the material of the hat, and the values of the parameters were taken from the literature[3]. The air cushion inside the hat is 1 mm thick and is made of an elastic material such as vinyl or rubber. The Young's modulus is 14000 N/mm^2, Poisson's ratio is 0.35 and the density is 1.04 x 10^{-9} ton/mm^3. **`*AIRBAG_SIMPLE_PRESSURE_VOLUME`** keyword was applied for the air cushion to define the relative volume - pressure relation inside the cushion as shown in Fig.4. This relation is expressed using Eq.1.

$$P_{gage} = \begin{cases} \frac{C_N}{V_{Relative}} - P_{atm} & V_{Relative} < 1.0 \\ 0 & V_{Relative} \geqq 1.0 \end{cases} \tag{1}$$

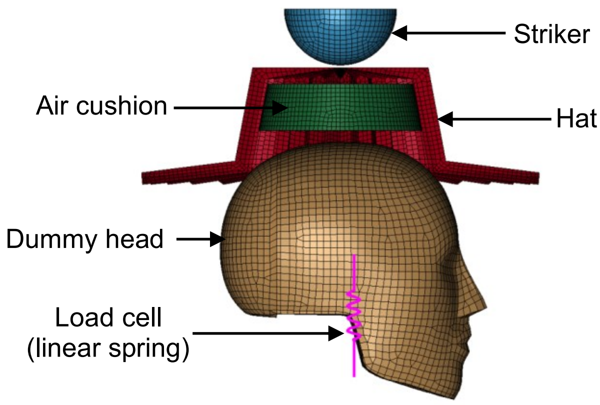
$$V_{relative} = \frac{V_{current}}{V_0}$$

P_{gage} ; Gage pressure (MPa)
V_0 ; Initial volume of airbag = 5.4773 x 10^5 mm^3)
$V_{relative}$; Relative volume
$V_{current}$; Current volume of airbag (mm^3)
C_N ; Parameter, C_N = 0.1 (MPa)
P_{atm} ; Atmospheric pressure, P_{atm} = 0.1 (MPa)

The dummy head and the striker are both rigid material. The spring constant of the load cell is 100000 N/mm.



(a) Model geometry



(b) zx cross section

Fig.3: Analysis model configuration

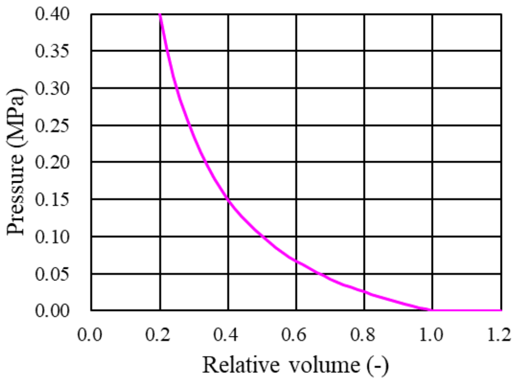


Fig.4: Relative volume - Pressure relation in air cushion

5 Contact definition

The contact definition used in the simulation is summarized in Table 1.

Table 1: Contact definition

Contact ID	Contact parts	Keyword	Friction coefficient
1	hat + head	*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE	fs=fd=0.1
2	hat + striker		
3	hat + cushion		
4	cushion + head		
5	striker + head		
6	hat	*CONTACT_AUTOMATIC_SINGLE_SURFACE	
7	cushion		

6 Results and discussion

The snapshot images of the drop test simulation are shown in Fig.5. The displacements of the dummy head and the striker are shown in Fig.6. The striker reaches the lowest position at 0.019 seconds and then rebounds. The pressure history in the air cushion is shown in Fig.7. The peak pressure also occurs at 0.019 seconds. Figure 8 shows the time history of the sum of the contact force between the hat and head, and the cushion and the head, and the time history of the spring force used as a load cell. The

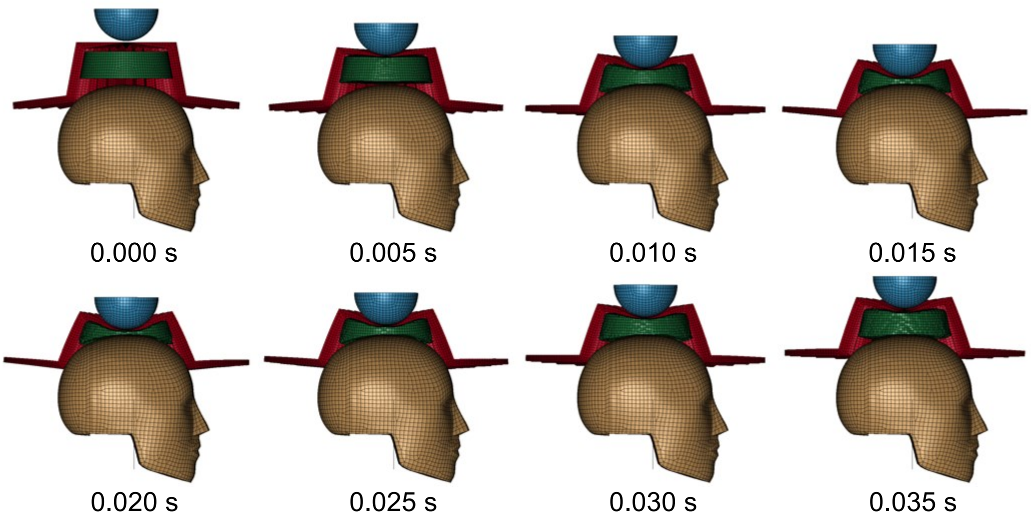


Fig.5: Snapshot of drop test simulation

most important conclusion is that the impact force is below the 4.9 kN safety limit for industrial helmets.

7 Conclusions

In this paper, we were able to demonstrate the possibility that the origami hat we invented could be used as a bicycle safety helmet. The authors have already manufactured and sold origami hats of various designs as regular fashion hats. In the future, we would like to aim for the practical application of helmets that are attractive in design and made of lightweight materials that can be used by many people.

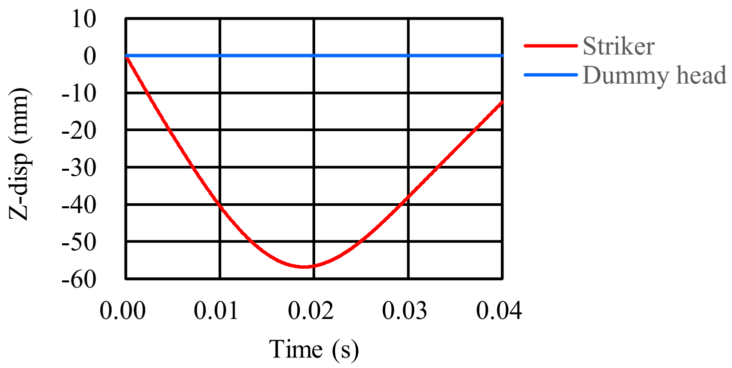


Fig.6: Z-displacement history of rigid body parts

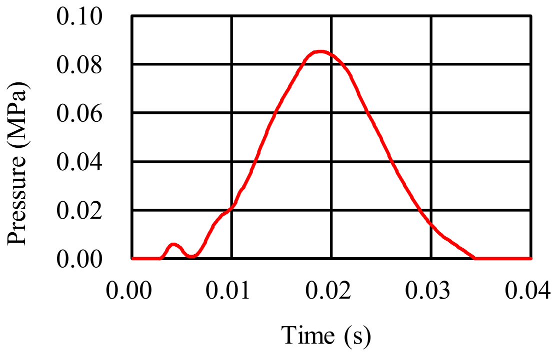


Fig.7: Pressure history in air cushion

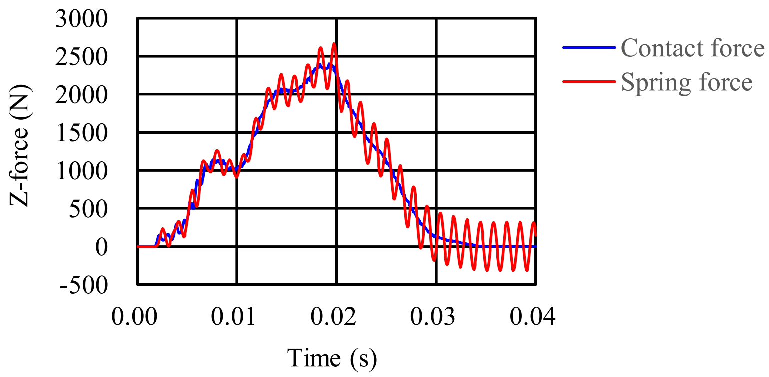


Fig.8: Contact force and spring force history

8 Literatures

[1] Sasaki T., Tokura S., and Hagiwara I. : Development of Stylish Bicycle Helmets, Proceedings of JSCES conference, Vol.29, 2024

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