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Study on Hysteresis in Sustainable Two-Layer Circular Tube under a Lateral Compression Load

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***Abstract*—**Recently, there have been a lot of earthquakes in Japan. It is necessary to promote seismic isolation devices for buildings. The devices have been hardly diffused in attached houses, because the devices are very expensive. We should develop a low-cost seismic isolation device for detached houses. We suggested a new seismic isolation device which uses a two-layer circular tube as a unit. If hysteresis is produced in the two-layer circular tube under lateral compression load, we think that the two-layer circular tube can have energy absorbing capacity. It is necessary to contact the outer layer and the inner layer to produce hysteresis. We have previously reported how the inner layer comes in contact with the outer layer from a perspective of analysis used mechanics of materials. We have clarified that the inner layer comes in contact with the outer layer under a lateral compression load. In this paper, we explored contact area between the outer layer and the inner layer under a lateral compression load by using FEA. We think that changing the inner layer's thickness is effective in increase the contact area. In order to change the inner layer's thickness, we changed the shape of the inner layer. As a result, the contact area changes depending on the inner layer's thickness. Additionally, we experimented to check whether hysteresis occurs in fact. As a consequence, we can reveal hysteresis in the two-layer circular tube under the condition.

***Keywords*—**Contact area, energy absorbing capacity, hysteresis, seismic isolation device.

I. Introduction

RECENTLY, there have been a lot of earthquakes in Japan. In order to protect people from earthquakes, it is necessary to attach seismic isolation devices to buildings. Tall buildings have attached the devices. On the other hand, almost all detached houses have not attached the devices [1], [2], because the devices are very expensive. Therefore, we should develop a low-cost seismic isolation device for attached houses. Researches related to the seismic isolation devices for attached houses have been studied. Kinoshita et al. proposed an isolation system for the houses using coil spring [3]. Nishimura and Suzuki developed the isolated houses supported by laminated rubber bearings [4]. However, these isolation systems need the seismic isolation pit. The seismic isolation cost increase for the pit. Therefore, we focused on the joint part of wooden houses to develop the device without the pit.

Japanese detached houses are generally made from wood. When wood of the joint part is dented by earthquake, the joint part can absorb the seismic energy [5]. But this function is not sustainability. There is a possibility which this joint part is broken due to the overload. We try to attach a seismic isolation device to the joint part so that this device distributes and absorbs the seismic energy. We have studied a low-cost seismic isolation device using composite material. The composite material is composed of metal square lattice filled with low rigidity material [6]. As the result, it clarified that the composite material has energy absorbing capacity. But, the composite material had little energy absorbing capacity [7].

In this research, we proposed a new seismic isolation device. A two-layer circular tube is a unit of the new device. The tube does not depend on load directions. Furthermore, if friction occurs between the outer layer and the inner layer of the tube, we can equip the tube with absorbing energy capacity due to hysteresis. The inner layer of the tube should come in contact with the outer layer to produce hysteresis. In order to use this device sustainably, the tube must deform in elastic region. We have previously reported how to contact between the outer layer and the inner layer and elastic limits of the tube [8]. In the report, we clarify that the inner layer comes in contact with the outer layer from a prospective of Finite Element Analysis used mechanics of materials [8].

In this report, we analyzed the tubes under lateral compressive load to evaluate contact areas between the outer layer and the inner layer. We think that hysteresis loss increases with increase in the contact area. We consider that changings the inner layer's thickness is effective in increase the contact area. Therefore, we changed the shape of the inner layer to change the inner layer's thickness. Moreover, we carried out experiments and studied hysteresis of the tubes.

II. Seismic Isolation Device

In this research, we suggested a new seismic isolation device. An example of the seismic isolation device is shown in Fig. 1. This device uses a two-layer circular tube as a unit. The two-layer circular tube of the device is shown in Fig. 2. The tube does not depend on the load directions. Moreover, if external force acts on the tube, we think that the inner layer comes in contact with the outer layer of the tube. The inner layer comes in contact with the outer layer, so that friction occurs between the outer layer and the inner layer. Therefore, we think that hysteresis is produced by friction. The tube can have the energy absorbing capacity of hysteresis. We also expect that if the tube deforms in elastic region, the tube have sustainability.

This device is attached to the joint part of the detached houses using the pins of the foundation and the column. The joint part applied the device is shown in Fig. 3. If earthquakes

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occur, the seismic energy is transmitted from the foundation to the column through the connecting pins and this device. We consider that this device absorbs the seismic energy at that time. Therefore, we guess that the detached house's vibration becomes lower. We consider that the energy absorbing capacity changes depending on the size and the number of the two-layer circular tube. In order to design the device, we should reveal properties of the tube. First, we researched the tube under a lateral compression load to understand the most basic properties of the tube. In this paper, all of tubes are the same in size. The outer layer is made of stainless steel and the inner layer is made of acrylic plastic.

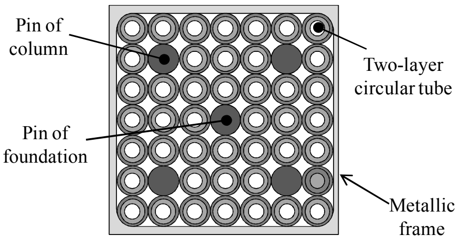


Fig. 1 An example of a proposed seismic isolation device

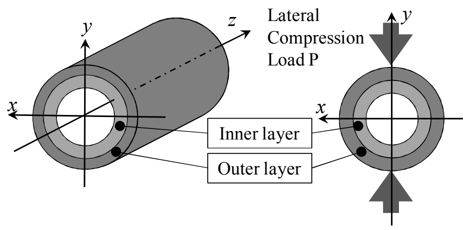


Fig. 2 Two-layer circular tube

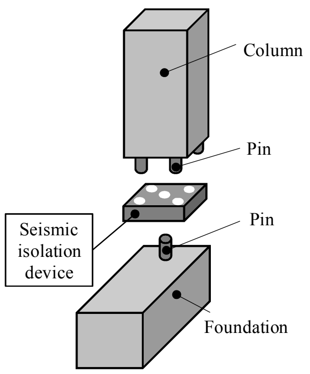


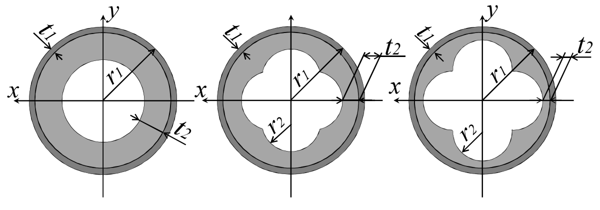
Fig. 3 The joint part applied the seismic isolation device

III. Frictional Contact Analysis of Two-layer Circular Tubes

We checked the contact area between the outer layer and the inner layer under a lateral compression load by using Finite Element Analysis (FEA). Furthermore, we changed the inner layer's thickness to increase the contact area. Therefore, we analyzed three types of the two-layer circular tubes.

A. Analysis Objects and Methods

The objects of this research are shown in Fig. 4 and Table I. First, we analyzed a normal two-layer circular tube whose the inner layer is uniform in thickness. Next, we analyzed other tubes which are processed the inner layer into flower-shaped the inner layers. In order to increase contact areas between the outer layer and the inner layer, the inner layer must come in contact with the outer layer much. Therefore, we change the inner layer's thickness t_2 to it. The tubes of flower-shaped the inner layer is assumed flower-shaped two-layer circular tube. There are two flower-shaped two-layer circular tubes. One is thick flower, the other is thin flower.



(a) Normal (b) Thick flower (c) Thin flower

Fig. 4 FEA and experimental objects

TABLE I
Materials and Sizes of the Two-layer Circular Tubes

		Normal	Thick flower	Thin flower
Outer layer	Material		Stainless steel	
	Young's modulus E_1 (MPa)		1.93×10^5	
	Poisson's ratio υ_1		0.28	
	Yield stress σ_{a1} (MPa)		205	
Inner layer	Material		Acrylic plastic	
	Young's modulus E_2 (MPa)		3.14×10^3	
	Poisson's ratio υ_2		0.35	
	Yield stress σ_{a2} (MPa)		50	
	Outer radius r_1 (mm)		10	
	Outer layer's thickness t_1 (mm)		0.8	
	Flower's radius r_2 (mm)		4	4
	Inner layer's thickness t_2 (mm)	4	2	1
	Length L(mm)		30	

The analysis condition and the mesh models are shown in Figs. 5 and 6. FEA software ANSYS 14.5 (ANSYS Inc.) was used for the analyses. The FEA models were 2-D symmetrical models. The analyses were carried out as plane stress problem. Element type was solid element with 8 nodes and the mean element size was 0.2 (mm). Boundary condition was as shown in Fig. 5. The coefficient of friction μ was set to 0.5 as contact condition. The constraint displacements were set at nodes on upper side of elastic body 1 in y axial direction. The constraint displacements also were set so that the tubes deformed in elastic region. The allowable y axial deformation amounts δ_{ya} of (a) Normal, (b) Thick flower and (c) Thin flower were 0.081 (mm), 0.117 (mm) and 0.122 (mm). We used the contact pressure P to judge the contacts between the outer layer and the inner layer.

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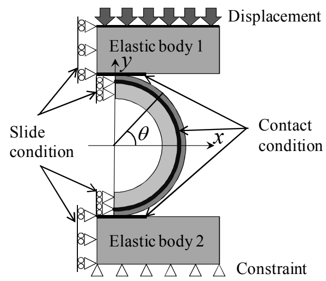
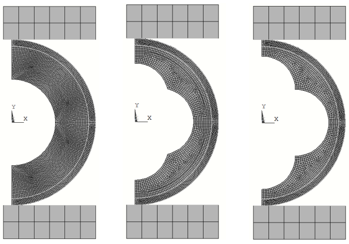


Fig. 5 Analysis condition

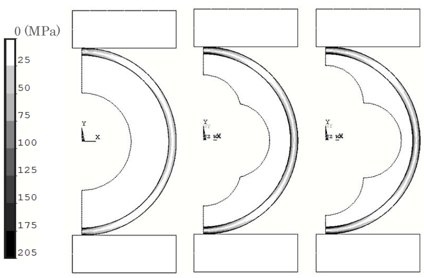


(a) Normal (b) Thick flower (c) Thin flower

Fig. 6 FEA mesh models

B. Analysis Results and Considerations

Von Mises stress σ distributions and the contact pressures P of each two-layer circular tube are shown in Figs. 7 and 8. According to Fig. 7, the stress σ became larger within contact area and the maximum stress σ_{max} occurs at angle θ of 90 (°). According to Fig. 8, the contact points of (a) Normal, (b) Thick flower and (c) Thin flower are 36 points, 43 points and 55 points, respectively. Therefore, we found that the contact areas of the flower-shaped tubes are larger than the normal tube. We also found that the contact area of (c) Thin flower is larger than (b) Thick flower. However, the contact pressures P of the flower-shaped tubes are smaller than the normal tube. The rigidity of the inner layer changes depending on the inner layer's thickness t_2. The thicknesses t_2 of the flower-shaped tubes are smaller than the normal tube. The inner layer's thickness t_2 becomes smaller, so that the rigidity of the tube gets lower. We think the contact pressure P decreased due to the reduction in the rigidity of the tube. Therefore, we speculate that the contact pressures P of the flower-shaped tube are smaller than the normal tube.



(a) Normal (b) Thick flower (c) Thin flower

Fig. 7 Von Mises stress σ distributions in the two-layer circular tube which simulated by FEA

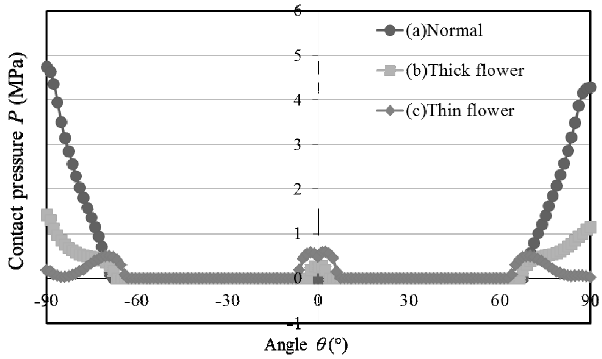


Fig. 8 The relations between the contact pressure P and the angle θ

IV. Lateral Compression Experiments of Two-Layer Circular Tube

We clarified that the inner layer comes in contact with the outer layer under a lateral compression load by using FEA. Next, we experimented to check whether hysteresis actually occur in the two-layer circular tubes.

A. Experimental Equipments and Methods

In this paper, the outer layer is made of stainless steel and the inner layer is made of acrylic plastic. Young's modulus E_1 of stainless steel is larger than one of acrylic plastic E_2. We think that the maximum stress σ_{max} occurs in the outer layer. According to the results of FEA and previous our research [8], the maximum stress σ_{max} occurs in the outer layer at angle θ of -90 (°). First, the lateral compression experiment was carried out on a stainless steel tube with circular cross section in order to derive an allowable y axial deformation amount δ_{ya} of stainless steel in elastic region. A diagrammatic illustration of our experimental equipment is shown in Fig. 9. A strain data logger was a KEYENCE NR-500 and a servo press was a SHIMADZU EHF-ED5. It is difficult to measure the stress σ at angle θ of -90 (°). Therefore, we stuck a strain gauge at angle θ of 0 (°) and measured the stress at the angle. We should derive the maximum stress σ_{max} of stainless steel at angle θ of 0 (°) to consider sustainability of the two-layer circular tubes. We have previously derived a relation between the bending moment M and the angle θ using a single circular tube [8]. The bending moment M distribution in single circular tube is shown in Fig. 10. The yield stress of stainless steel σ_{a1} is 205 (MPa). According to the yield stress σ_{a1} and Fig. 10, the maximum stress σ_{max} at angle θ of 0 (°) is 117 (MPa). A relation between the y axial deformation amount δ_y and the stress σ at angle θ of 0 (°) is shown in Fig. 11. According to Fig. 11, the stress σ is 117 (MPa) at δ_y = 0.24 (mm). Therefore, we set δ_y = 0.24 (mm) as a maximum value to each two-layer circular tube (as shown in Fig. 4). The experimental specimens are the same as FEA model as shown in Table I.

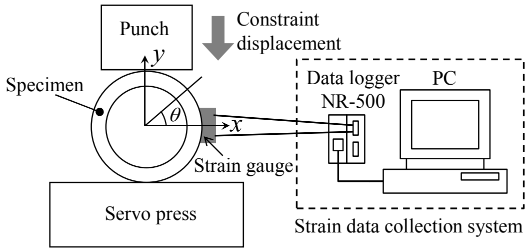


Fig. 9 Diagrammatic illustration of experimental equipment

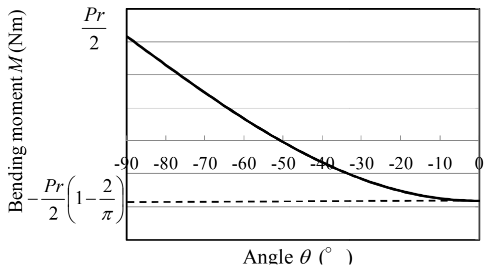


Fig. 10 The bending moment M distribution in single circular tube

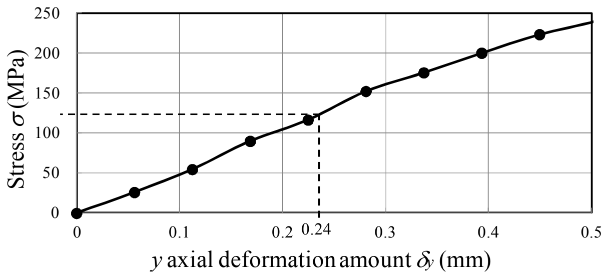


Fig. 11 A relation between the stress σ and the y axial deformation amount δ_y

B. Experimental Results and Considerations

The relations between the load F and the y axial deformation amount δ_y for each two-layer circular tube (as shown in Fig. 4) are shown in Fig. 12. According to Fig. 12, hysteresis was confirmed in all of the tubes. The accumulated energy and Hysteresis loss of (a) Normal are shown in Figs. 13 and 14. The ratios of hysteresis loss to the accumulated energy κ are shown in Fig. 15. According to Fig. 15, hysteresis loss of the (a) Normal is the largest. However, the contact areas of flower-shaped tubes are larger than the normal tube. We consider that the contact pressure P relates to hysteresis loss. The contact pressures P of the flower-shaped tubes are smaller than the normal tube. We guess that hysteresis loss of the flower-shaped tubes get lower. But a difference between (a)Normal and (b)Thick flower ratio of hysteresis loss to the accumulated energy κ is about 3 (%). Therefore, if we arrange the inner layer's thickness t_2 so that the contact area and contact pressure P is larger, we can think that the flower-shaped tube is effective.

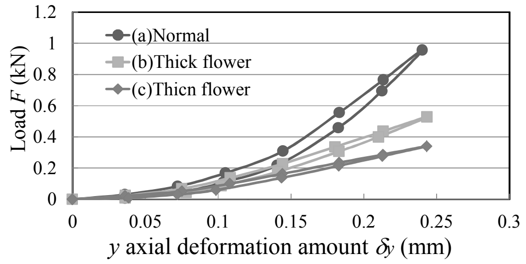


Fig. 12 The relations between the load F and the y axial deformation amount δ_y

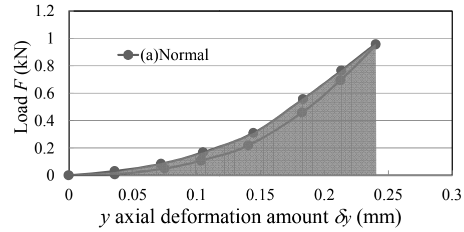


Fig. 13 Accumulated energy of (a) Normal

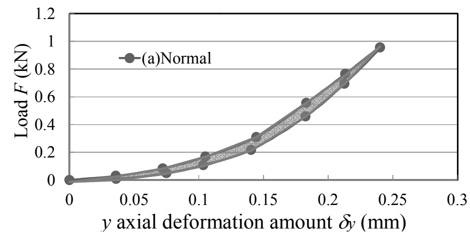


Fig. 14 Hysteresis loss of (a) Normal

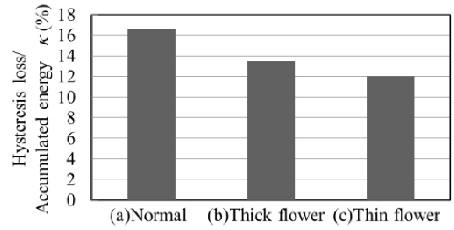


Fig. 15 The ratios of hysteresis loss against the accumulated energy κ

V. Conclusions

We created a new seismic isolation device which uses a two-layer circular tube as a unit. The inner layer of the tube comes in contact with the outer layer under a lateral compression load. In this paper, we investigated the contact area of the tubes. We used the normal tubes and the flower-shaped tubes to verify the relation between the inner layer's thickness and contact area. The contact areas of the flower-shaped tubes are larger than the normal tubes. Furthermore, we carried out the lateral compression experiments of the tubes. We were able to clarify that hysteresis occur in all tubes by using experiments. We think that changing the inner layer's thickness is effective in increase the hysteresis loss.

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