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# SHOCK ABSORBER COMBINING RUBBER WITH STEEL PIPES

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**ABSTRACT :** The authors studied the basic characteristics of steel pipes by experiments and analyses, aiming to determine whether steel pipes can be used as shock absorbers. The results of the study proved that steel pipes have enough energy-absorbing capacity to be used as shock absorbers. The authors then made a nonlinear response analysis to examine the effect of attaching rectangular rubber and steel pipes as shock absorbers to base-isolated bridges. The analysis showed that when steel-pipe shock absorbers alone are used, the collision force acting between adjacent girders of bridges increases rapidly after the steel pipes fail. The authors conducted static loading tests to examine the basic characteristics of shock absorbers that combine rubber with steel pipes. The authors investigated the effectiveness of a new type of shock absorber consisting of steel pipes wrapped with rubber pipes, constructed a load-displacement model to estimate the load-displacement characteristic of the new type of shock absorber from the basic characteristics of rubber and steel pipes, and proved the validity of the model on the basis of experimental results.

**KEYWORDS:** shock absorber, rubber pipe, steel pipe, pounding of girders, base-isolated bridge.

## 1. INTRODUCTION

Shock absorbers are the key devices which enable us to restrict damage to limited parts of the bridge when a large earthquake occurs and then quickly restore the damaged parts. Nagashima and others [1] proposed a shock absorber using shape steel in place of rubber and studied its practicality and effectiveness through experiments and analyses. On the other hand, an analytical study [2] by the authors of this paper indicated that if steel pipes completely fail, there may be a collision force greater than the one that occurs after rubber shock absorbers fail.

Because of the above, the authors examined the basic characteristics of shock absorbers composed of rubber and steel pipes by static experiments. The authors then proposed a new type of shock absorber composed of steel pipes wrapped with rubber pipes, constructed a load-displacement model to estimate the load-displacement characteristic of the new type of shock absorber from the basic characteristics of rubber and steel pipes, and proved the validity of the model on the basis of experimental results.

## 2. STATIC COMPRESSION TEST

### 2.1 Test Method

Four types of test pieces shown in **Figures 1** were made of steel pipes wrapped with rubber.

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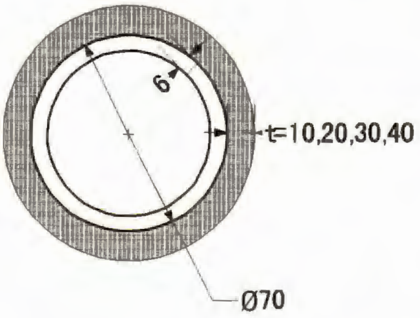


Figure 1. Sizes and shape of test specimens

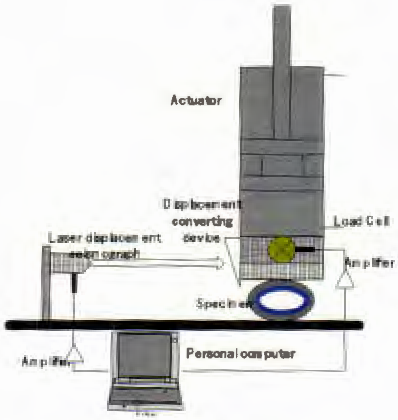


Figure 2. Outline of loading test equipment

The steel was STKM13A, and the rubber was chloroprene rubber (hardness: 60+/-5). **Figure 2** shows an outline of the loading test equipment used for the test. A universal testing machine having a capacity of 300 kN was used for the static compression test. A laser displacement seismograph having a reference distance of 30 mm and a measuring range of +/-5 mm was used for displacement measurement. The vertical displacement was converted into horizontal displacement by a passive reflector attached to the loading plate.

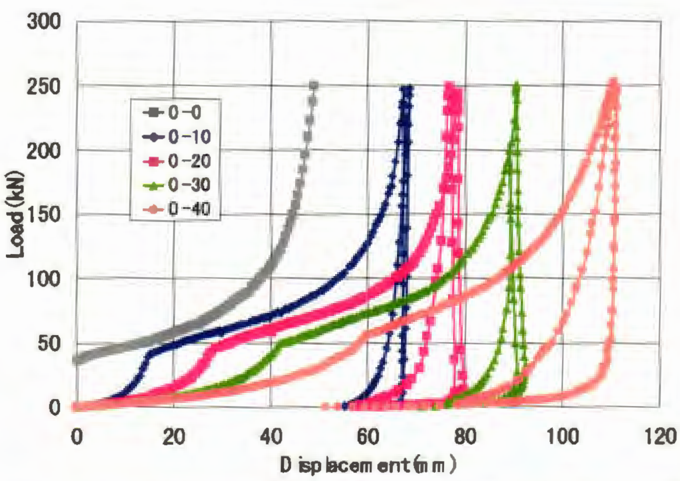


Figure 3. Load-displacement characteristics of steel pipes wrapped with rubber pipes

2.2 Test Result

**Figure 3** shows the load-displacement characteristics of the steel pipes. There was no unstable phenomenon in which rigidity was lowered. Rigidity increased gradually after yielding. After yielding at 40 kN, the pipe was deformed into an elliptic shape and the load value increased as deformation progressed. Constrictions were formed near the center of the pipe, and the load rose radically at a displacement of around 50 mm when the upper and lower constricted parts came into contact with each other. Nagashima and others [1] reported a phenomenon in which rigidity decreased gradually after yielding when the steel pipe was fixed to the loading plates by welding them at the top and bottom. Such a phenomenon was not observed in this test.

(a)Initial shape

(b)Shape with the displacement of 30mm

(c)Shape after testing

Figure 4. Deformation of O-40

**Figure 3** shows the load-displacement characteristics of test. **Figure 4** shows the transitional deformation of O-40. Before yielding, only the rubber was deformed and the rigidity was low (phase I). The displacement measured at yielding was almost in proportion to the thickness of rubber, and the yielding load was higher when the the rubber was thicker. After the steel pipe yielded, the rigidity gradually increased. It could be argued that the compressive deformation of rubber was advanced when the plastic deformation of the steel pipe was in progress (phase II). Unloading was done when the load reached 250 kN because of the limits of the testing machine. In the process of unloading and reloading, the steel pipe had failed already. It can be assumed that the rubber returned to its original dimensions after the load was removed and that its deformation beyond 250 kN (phase III) can be extrapolated from **Figure 3**.

## 3. MODELLING OF LOAD-DISPLACEMENT CHARACTERISTIC

The following describes the modeling of the load-displacement characteristics of the shock absorber composed of steel pipes wrapped with rubber on the basis of basic characteristics and the verification of the model.

3.1 Compressive Deformation Characteristics of Rubber Pipe

Static compression tests were conducted for each rubber pipe with a steel rod fitted into it. The following formulas were used to calculate stress and strain from load P and displacement • .

$$\sigma_{r1} = \frac{P}{R_i H}, \varepsilon_{r1} = \frac{\Delta}{2t_r} \quad (1)$$

where $R_i$ is the inner diameter of the rubber pipe, $t_r$ is the thickness of rubber, and $H$ is the length of the rubber pipe. The relationship between the obtained characteristics and load values was represented using the Mooney-Rivlin stress-strain characteristic formula [3] as follows:

$$\sigma_{r1} = 2\left(\lambda_{r1} - \frac{1}{\lambda_{r1}^{2}}\right)\left(a_{r1} + \frac{b_{r1}}{\lambda_r}\right) \quad (2)$$

where ë$_{r1}$ is equal to 1 + å$_{r1}$, and $a_{r1}$ and $b_{r1}$ are material constants. The method of least square approximation was applied to the obtained characteristics of O-10, which had the minimum thickness of rubber and seemed to have almost no bend resistance as a pipe. The following parameters were obtained:

$$a_{r1} = 0.458, b_{r1} = 0.0223 \text{ (Mpa)} \quad (3)$$

3.2 Bending Deformation Characteristic of Rubber Pipe

To measure the bending deformation characteristics of the rubber pipes, a static compression test was conducted for each of them. The relationship between ã$_1 = P_B/P_y$ and $(t_r/Ro)^3$ was obtained. Here, $P_B$ is the load value with the same displacement as the one when steel pipe wrapped with rubber yields.

3.3 Compressive Deformation Characteristic of Steel Pipe

The compressive characteristics of steel pipes were already shown in **Figure 3**. In this study, the Mooney-Rivlin formula was used because the relationship between the load increment and plastic deformation of steel pipes after yielding was similar to that observed in rubber pipes. The following formulas were used to calculate dimensionless load and strain from load P and displacement ▪ :

$$\sigma_s = {(P-P_y)}/{(P_b-P_y)}, \varepsilon_s = {\Delta}/{2R_s} \tag{4}$$

where $P_b$ is the maximum load of the steel pipe and $R_s$ is its diameter. The parameters of the Mooney-Rivlin formula were obtained by the method of least square approximation as follows:

$$a_s = 0.031, b_s = 0.0058 \tag{5}$$

where ë$_s$ is equal to 1 + å$_s$.

3.4 Force Distribution Characteristic (Force Transfer from Rubber to Steel Pipe)

It was assumed that the load transferred from the rubber pipe to the steel pipe is distributed linearly in relation to angle $\theta$ as shown in **Figure 5**. The bending moment at the apex of the circle shown in the figure was obtained as follows from an arbitrary bending moment caused when the loads concentrated on two points opposite each other act as an eccentric load:

$$M_1 = 2A\left[\frac{1}{4} - \frac{\pi}{8}\alpha' + \frac{1}{4}\alpha'^2 + \frac{1}{8}\alpha' \cdot \sin 2\alpha' + \frac{1}{4}\cos 2\alpha'\right]$$

$$A = \frac{1}{\frac{\pi}{2} - \alpha'} \times 0.3183 \cdot R^2 \cdot w_0 \tag{6}$$

When the loads concentrated on two points opposite each other act at the center of the circle, bending moment $M_2$ at the apex of the circle was obtained as follows:

$$M_2 = 0.3183P \cdot R \tag{7}$$

Then, the ratio of $M_2$ to $M_1$ is obtained as follows:

$$\gamma_2 = \frac{M_2}{M_1} - 1 \tag{8}$$

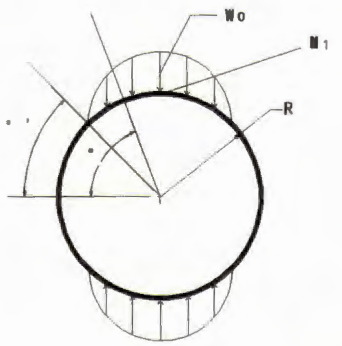


Figure 5. Distribution of force transferred to steel pipe

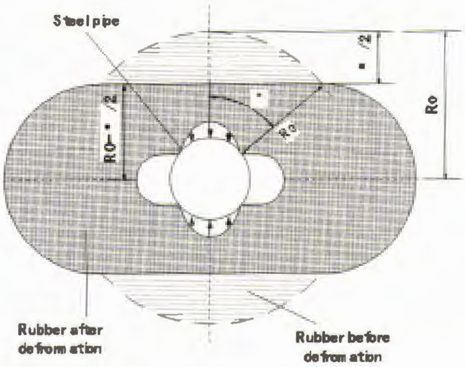


Figure 6. Rubber deformation and transferred-load distribution angle

Next, the relationship between the basic transferred-load distribution angle (á) and rubber deformation amount (Ä) was considered. The basic transferred-load distribution angle á when the rubber was deformed was assumed to be as shown in **Figure 6**. Then, the basic transferred-load distribution angle á was related to displacement Ä as follows:

$$\alpha = \cos^{-1}\frac{R_0 - \frac{\Delta}{2}}{R_0} \tag{9}$$

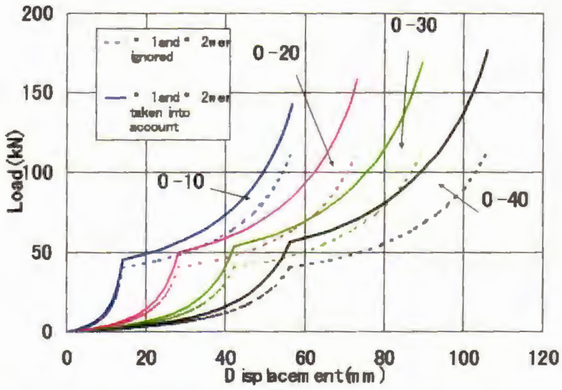


Figure 7. Load-displacement characteristics considering $\tilde{a}_1$ and $\tilde{a}_2$ and those ignoring $\tilde{a}_1$ and $\tilde{a}_2$

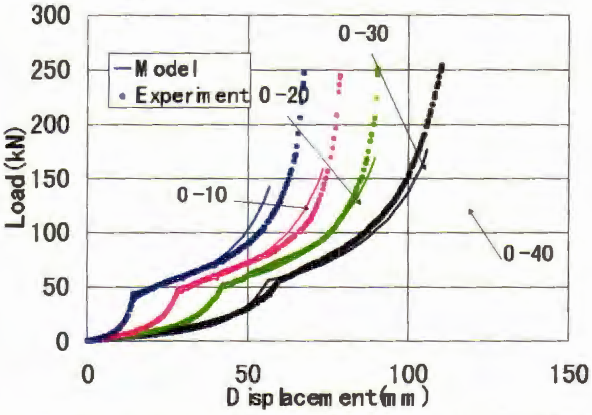


Figure 8. Load-displacement characteristics considering $\tilde{a}_1$ and $\tilde{a}_2$ and those obtained from test results

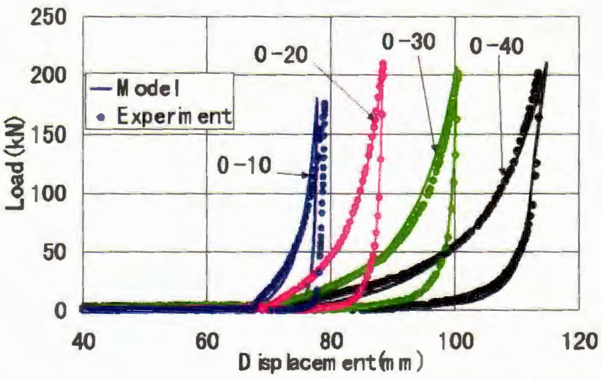


Figure 9. Load-displacement characteristics while unloading and reloading

The following expressions were used to evaluate á' with the diameter-to-thickness ratios of rubber and steel pipes which were the quantitative values related to á':

$$\alpha' = 90 - \beta\alpha \tag{10}$$

$$\beta = \beta\left(\frac{t_r R_i}{t_p R_o}\right) \tag{11}$$

where $t_p$: Thickness of steel pipe.

It was already known that ë$_1$ described before and ë$_2$ defined above make it seem that the yielding load of a shock absorber composed of rubber and steel pipes is higher than the yielding load of the steel pipe by itself. To obtain a â that enables the authors to understand the amount that ë$_2$ contributes to the increase in yielding load, the relationship between â and $(t_r R_i)/(t_p R_o)$ was plotted and â was evaluated using the following expression:

$$\beta = \left(1 - 0.7^{\frac{t_r Ri}{t_p R_o}}\right) \times 0.9 \tag{12}$$

3.5 Compressive Deformation Characteristics of Rubber Pipe Deformed into a Rectangular Shape
The deformation characteristics of rubber pipe while unloading and reloading were evaluated from the results of the static compression test on a rubber pipe deformed into an almost rectangular shape.

3.6 Accuracy of Modeling
**Figure 7** shows two sets of load-displacement characteristics. In one set, ã$_1$ and ã$_2$ were taken into consideration, and in the other set they were ignored. As can be seen, taking ã$_1$ and ã$_2$ into consideration shifts the calculated load by up to 60 percent when ã$_1$ and ã$_2$ are considered. **Figure 8** shows the load-displacement characteristics obtained from the model with ã$_1$ and ã$_2$ considered and those obtained from the test results. Although the large deformation of the rubber pipe during the deformation of the steel pipe was ignored in the model, the model accurately represents the test result. **Figure 9** shows the results of obtaining the load-displacement characteristics of rubber pipes alone and the load-displacement characteristics obtained from the test result. The curves for the same test pieces generally match each other.

## 4. CONCLUSION

In this study, we proposed a new type of shock absorber that consists of a steel pipe having a high energy-absorbing capacity and a rubber pipe to prevent an excessive reaction force. Static loading tests were conducted to confirm the superiority of that type of shock absorber. A model to estimate the load-displacement characteristics of the shock absorber proposed in this paper was constructed, and its validity was proved by comparision with experimental results.

## 5. REFERENCES


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