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EXPERIMENTAL STUDY ON A TEMPERATURE CONTROL SYSTEM FOR VISCO-ELASTIC DAMPERS

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SUMMARY

Among many visco-elastic dampers (VEDs), linear ones seem better than nonlinear ones, because it is quite easy to simulate linear behaviors by making use of a simple generalized Maxwell model. However, their mechanical properties are usually quite sensitive to environmental temperature. The resistance of some damper is known to goes up and down a lot as the temperature decreases or increases. It may give bad influence on seismic behaviors of buildings especially when the temperature is quite low. Therefore, We developed the temperature control system for VEDs. First part of the paper describes in random wave vibration tests were conducted using an actual size damper to confirm the mechanical properties of a visco-elastic damper in a temperature regime of 0 to 40ºC. The second part deals with the winter field-testing on full-scale visco-elastic damper with temperature control system. Although it is an extremely simple system, it is possible to maintain the target damper temperature of 20ºC while keeping each part of the visco-elastic substance within about 5ºC. Finally, Using a temperature-controlled damper and a damper kept to normal conditions at the standard temperature of 20ºC, vibration tests were conducted to examine the effect of the temperature control on the mechanical properties of VEDs. In these tests it was indicated that there was very little effect of temperature control on the mechanical properties.

1. INTRODUCTION

The mechanical properties shown by the strain-stress relationship of visco-elastic dampers (VEDs) clearly exhibit different types of dependencies on, for example, frequencies, strain, and temperature (Ishikawa[1]). There are roughly two types of visco-elastic dampers, based on whether or not there is a strain dependency. One of these types shows non-linearity in the strain-stress relationship when used within the frequency regime of a building, so it is called the "non-linear visco-elastic damper." The other type shows a linear strain-stress relationship, so it is called a "linear visco-elastic damper." Linear visco-elastic dampers having low strain dependency include the diene series.

If a dynamic model, such as the generalized Maxwell model, is drafted to express a distinctive frequency dependency, then it becomes relatively easy to perform earthquake response analysis on the

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building where the linear visco-elastic dampers are applied; thus, such dampers have very desirable properties for aseismic design (Soda[2]). However, in order to popularize linear visco-elastic dampers as an effective means for providing safety during a seismic event, the temperature dependency of their mechanical properties must be resolved. For this purpose, the authors developed a temperature control method for the linear visco-elastic dampers which uses sheet heaters as a means to ameliorate temperature dependency (especially low temperatures) while obtaining high attenuation performance and making easy use of a high-accuracy dynamic model.

In a previous study, a small 30kN-class two-layer damper was used for basic investigations of temperature control. By maintaining the damper at the target temperature, it was possible to distribute the temperature uniformly over the visco-elastic substance (Soda[3]). Then, a field experiment conducted with a medium-sized 90kN-class four-layer damper confirmed that it was possible to apply the temperature control method to dampers with multiple visco-elastic layers (Hagiwara[4]). The present paper reports on the results of an investigation of the scale effect of the temperature control method using an actual size visco-elastic damper. First, the 300kN-class two-layer dampers used in the seismic reinforcement work were used to confirm the temperature dependency of the mechanical properties of an actual size damper. Then, application of the temperature control method maintained the temperature of the damper in an actual winter environment, revealing little scale effect of this method.

2. MECHANICAL PROPERTIES OF AN ACTUAL SIZE DAMPER

2.1 Overview and purpose of experiment

Before a full-scale experiment of the temperature control method, random wave vibration tests were conducted using an actual size damper to confirm the mechanical properties of a visco-elastic damper in a temperature regime of 0 to 40ºC. Regarding the storage modulus γ' and the loss modulus γ'' of each temperature obtained from the experiments, the temperature dependency of the dynamic properties was quantified by deriving the temperature correction coefficient based on a standard of 20ºC. The results were used to compare the mechanical properties of actual size dampers with the mechanical properties that had been revealed by previous research.

2.2 Overview of the test equipment

The test equipment consisted of a linear guide dynamic loading system (see Figure 1) at Waseda University's Advanced Research Institute for Science and Engineering. Displacement-controlled vibration was applied to a visco-elastic damper using a 1MN actuator to generate shear deformation in the visco-elastic substance. The experimental damper was rotated at a 90-degree angle and placed on its side in constant-temperature tank, resulting in lateral displacement input applied to the damper (Photo 1). By forcing the circulation of heated or cooled air from a constant temperature apparatus, it was possible to keep the temperature of the damper at a certain level within a temperature regime of -10 to 60ºC.

Damper deformation was measured by a contact-type displacement gauge (CDP-50) attached to the top of the damper, while damper resistance was measured by a load cell (TCLP-500KNB) connected to the fitting equipment attached to the top of the damper. It should be noted that the temperature of the test damper vibration was measured using two ϕ0.5 mm sheath-type K-thermoelements inserted into the visco-elastic substance.

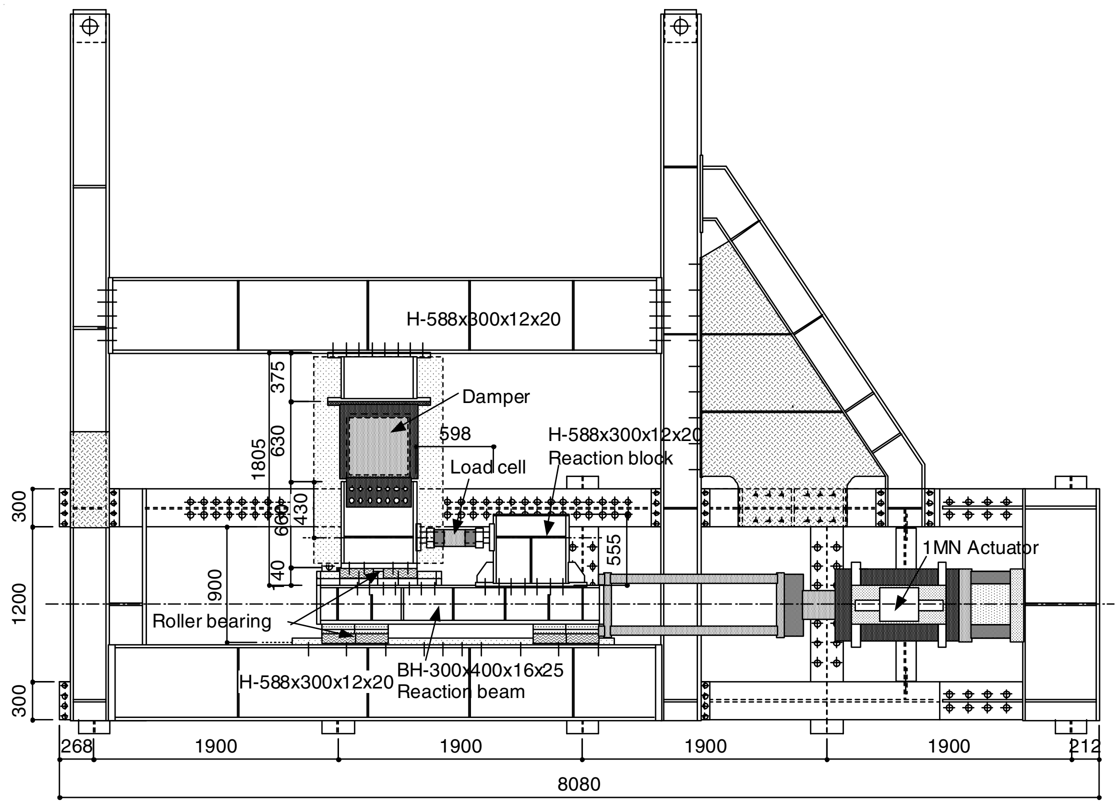
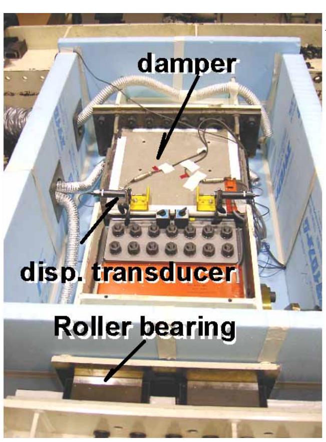


Figure 1 Experimental Equipment

2.3 Overview of the specimen

The specimen used as an actual size damper was a two-layer plate visco-elastic substance of the diene series having shear thickness of d=15 mm and shear area of S, that is S/d of 27 m. The dimensions of all parts of the specimen are shown in Figure 2, while the external appearance is shown in Photo 2.



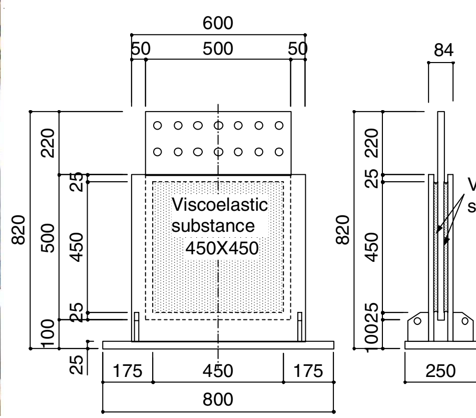


Photo 1 Damper Set-up **Figure 2 Viscoe-lastic Damper** **Photo 2 External Appearance**

2.4 Test items

In the experiment, sine wave and random wave vibrations were applied to the specimen at visco-elastic substance temperatures of 0, 10, 20, 30, and 40ºC. In the random wave vibration tests, there was a total of six input waves: three white noise waves (5 Hz Wave-01, -02, -03) with different phase characteristics having a uniform Fourier spectrum of 0.1Hz to 5Hz and a maximum vibration amplitude of 3mm (20% shear strain), and three white noise waves (10 Hz Wave-01, -02, -03) with different phase characteristics having a uniform Fourier spectrum of 0.1Hz to 10Hz and a maximum vibration amplitude of 1.5mm (10% shear strain). Applied displacement was controlled based on the actual shear deformation that occurred in the visco-elastic substance of the damper specimen.

2.5 Test results

Figure 3 shows the storage modulus γ' and the loss modulus γ'' of each temperature of the visco-elastic substance for the white noise (10 Hz Wave-02) having a uniform band of 0.1 to 10 Hz and a maximum vibration amplitude of 1.5 mm (10% shear strain) in the random wave vibration tests.

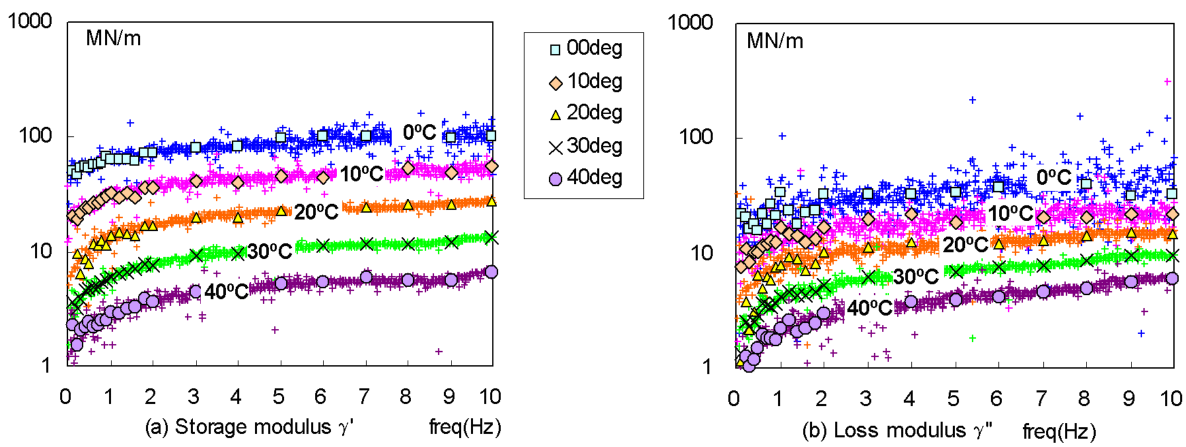
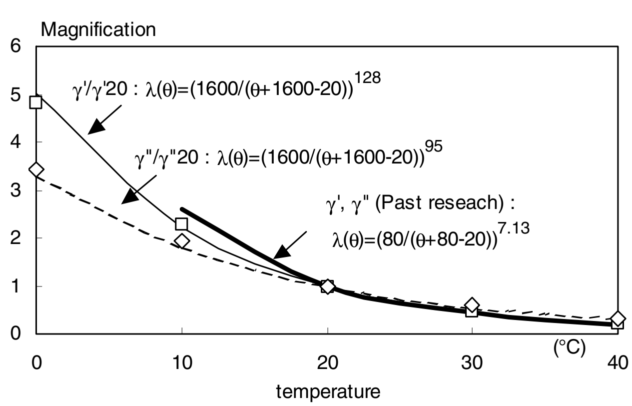


Figure 3 Complex Modulus at temperatures of 0, 10, 20, 30, and 40ºC

While the results for γ'' at the visco-elastic temperature of 0ºC are skewed, it does appear that as the modulus of complex elasticity increased from 20 to 0ºC, the rigidity of the frame around the specimen showed a relative decrease. This was the effect of the looseness of the test equipment that occurred during the tests.

2.6 Temperature correction coefficient of the modulus of complex elasticity

Figure 3 shows the storage modulus γ' and the loss modulus γ'' plotted at intervals of 0.1 Hz up to 1 Hz, 0.2 Hz up to 2 Hz, and 1 Hz up to 10 Hz. The averages of γ'/γ'_{20} and γ''/γ''_{20} for each temperature are plotted to obtain the exponential curve in Figure 4.



$$\gamma' : \lambda(\theta) = \left(\frac{1600}{\theta+1600-20}\right)^{128} \quad (1)$$

$$\gamma'' : \lambda(\theta) = \left(\frac{1600}{\theta+1600-20}\right)^{95} \quad (2)$$

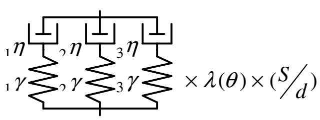
$$\gamma', \gamma'' : \lambda(\theta) = \left(\frac{80}{\theta+80-20}\right)^{7.13} \quad (3)$$

Figure 4 Normalized Temperature Dependency of Complex Modulus

The obtained exponential curve was approximated by the least squares method to produce the regression curves and regression equations (1) and (2). The regression equation (3) for modulus of complex elasticity obtained in a previous paper is also shown.

A comparison of these equations shows that at 20ºC and above, changes in the γ' and γ" of the actual size damper generally agreed with Equation (3) which was obtained in the previous study, but at less than 20ºC, γ" of the actual size damper (S/d=27 m) was less than that of the small specimen (S/d=1 m) obtained from Equation (3). At less than 10ºC, Equation (3) was outside the regression realm. Table 1 shows the six factors of the generalized Maxwell model derived from the least squares method using the γ' and γ" for the standard temperature of 20ºC in Figure 3.

Table 1 Generalized Maxwell Model



$_{1\sim3}\gamma$: Spring elements
$_{1\sim3}\eta$: Dashpot elements
$\lambda(\theta)$: Coefficient at θ℃

	k=1	k=2	k=3
$_k\gamma$(kN/m^2)	12.22	7.834	32.02
$_k\eta$(kNs/m^2)	1.523	24310	0.2972

Using Equations (1) and (2) that determine the temperature correction coefficient from the mechanical model derived for the standard temperature, γ' and γ" were redetermined for each temperature, then in Figure 5 they were superimposed on the test results from Figure 3. The temperature-corrected γ' and γ" obtained from the mechanical model agree very well with the experimental values at each temperature.

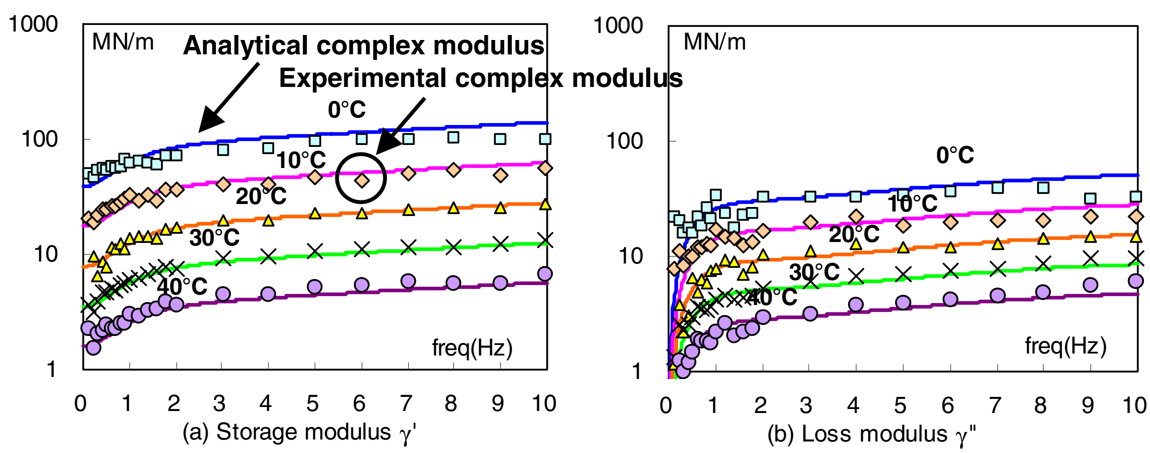


Figure 5 Experimental and Analytical Complex Modulus

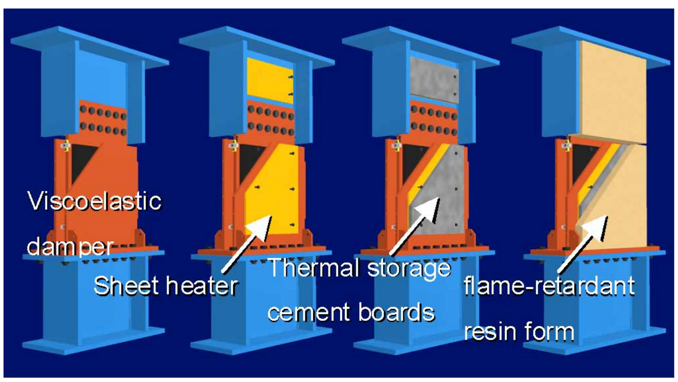
Given the above information, both γ' and γ" curves, at a random temperature in the environmental temperature realm of 0 to 40ºC and the frequency range that should be considered in the aseismic design of a building, were found to be roughly parallel to the γ' and γ" curves at a standard temperature (20ºC in this case). This means that it is confirmed even for the actual size damper that the amount of movement of γ' and γ" values is more or less equal at any frequency from 0 Hz to 10Hz.

In Figure 5, it should be noted that the experimental value is smaller than the value derived from the mechanical model in the somewhat high frequency region at 0ºC. However, as noted in Section 2.5, the effect of looseness that occurred throughout the test apparatus seems to have caused this discrepancy.

3. TEMPERATURE CONTROL EFFECT OF ACTUAL SIZE DAMPER

3.1 Composition of temperature control method

An overview of temperature control system used for the actual size damper is shown in Figure 6. Both sides of the damper and the attachment are covered with sheet heaters, while the sheet heaters themselves are covered with thermal storage cement boards and flame-retardant resin foam to enhance the thermal insulation. The operation of the sheet heaters is controlled by digital thermo-controller. Although it is an extremely simple system, if the surrounding temperature decreases it is still possible to maintain the target damper temperature of 20ºC while keeping each part of the visco-elastic substance within about 5ºC of this. The temperature setting for operations can take the resistance of the damper into account, so it is not necessary to set a target temperature. To simplify the temperature control method (Figure 7), the ON-OFF switch is used instead of the PID control of the heat source. It is also possible to manually adjust the heat setting by using a transformer in conjunction with the heat generator.



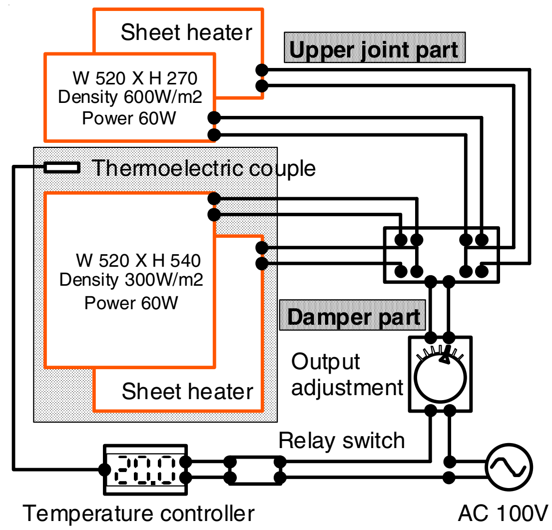


Figure 6 Component of Thermal Insulation System

Figure 7 Temperature Control System

3.2 Overview of the building

The building to which this method was applied is located in the Tsurumi district of Yokohama. Built in 1971, it is an RC structure having four aboveground floors, an eaves height of 15.8 m, and total floor space of approximately 3000 m^2. The lot, which is located by a Tokyo Bay canal, sits on land that was reclaimed in the late 1920s, and the building is supported by RC piles. An investigation of its seismic properties showed its structural seismic index to be about 0.5, so it was seismically reinforced. As shown in Photo 3, a damper frame was installed on the building exterior, and each floor was equipped with six visco-elastic dampers, for a total of 24 dampers. The top and bottom H-steel (400x400x13x21) of the reinforcing frame (Figure 8) were fastened to the girder side of the building with chemical anchors (ϕ20x27), then all the visco-elastic dampers were temperature-controlled using the system described in the chapter 2.

Photo 3 Externals of Applied Building

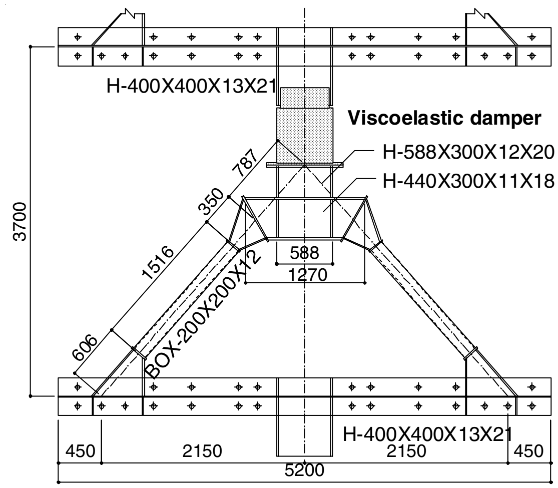
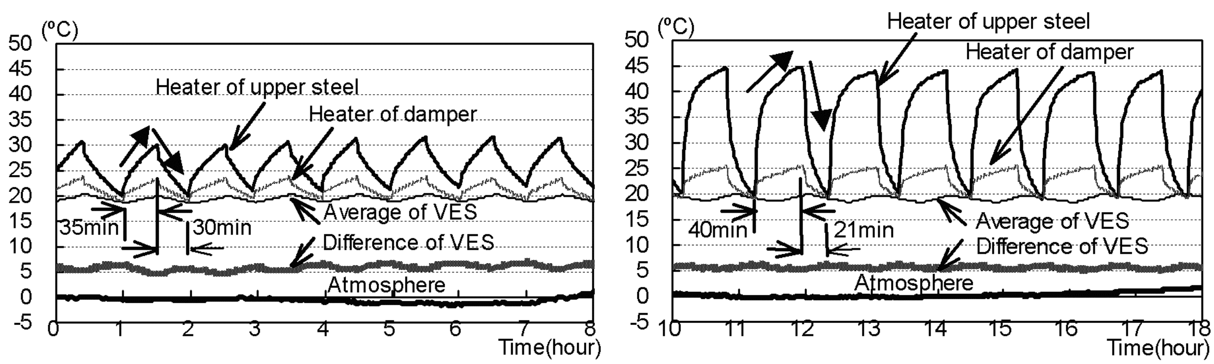


Figure 8 Installation of Damper on Building

3.3 Temperature control effect

Let us look at the damper that was installed on the east side of the third floor. Figure 9 shows the temperature hysteresis in damper parts that were measured with sheath-type K-thermoelements that were inserted in 18 places on the visco-elastic substance. The temperature at the time the measurements were taken on 16 January 2003 was below the freezing point at around 8:00 a.m., rising to only 5ºC during the day, an extremely low temperature for central Yokohama. As a result, the average temperature of the visco-elastic substance was controlled to 20±1ºC, while the difference between the minimum and maximum temperatures at all measuring points on the visco-elastic substance was within a range of 5ºC. This indicates that the temperature was uniformly distributed and stably controlled.



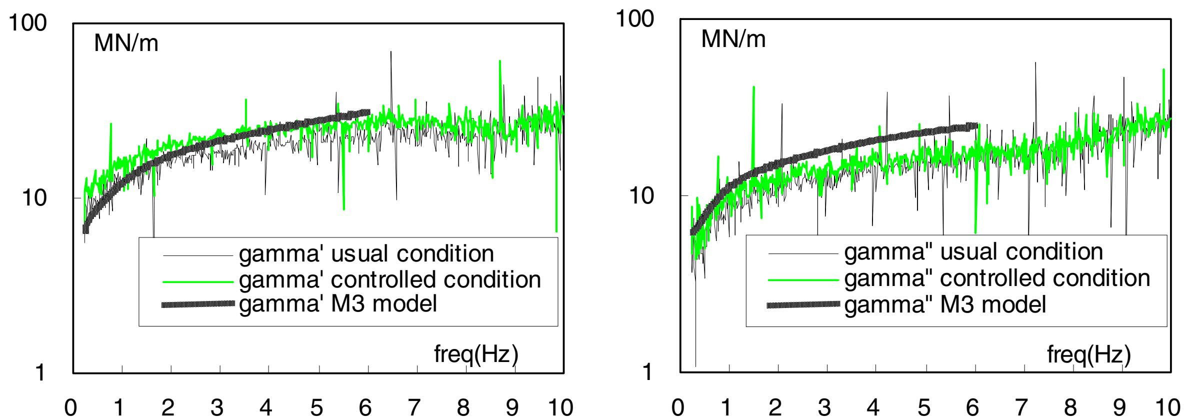
(a) With thermal storage cement boards (b) Without thermal storage cement boards

Figure 9 Time history of Temperature on Damper

The heater turned on and off at roughly 30-minute intervals, and the temperature gradients of the forced heating and natural cooling were almost equal. This was the result of the high heat storage effect of foam resin insulating material used in conjunction with 8.5mm-thick vinyl short fiber cement boards. These were heated slowly at the extremely low temperature of about 30ºC and slowly cooled to reduce electrical consumption. The visco-elastic substance of the damper was installed outside so that it would be the same as the outside temperature. Despite the very severe environmental conditions (0 to 5ºC) throughout the day, the sheet heaters only consumed electrical power at the rate of 3800Wh per day, which comes out to about 53 yen/day based on the current rates. This figure is used as a reference. If the damper had been installed inside the building, the temperature environment would have been less severe, and less electrical power would have been needed. Because four 60W-class sheet heaters were attached to each damper, we can assume that each damper would require 240W of power.

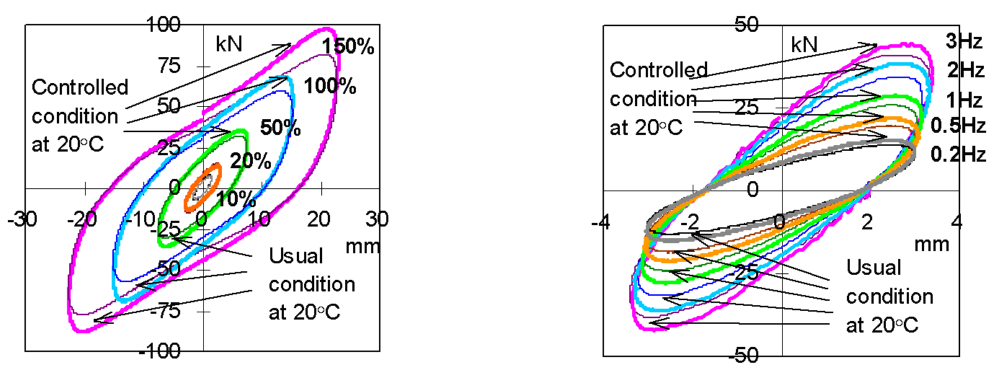
3.4 Effect of temperature control on mechanical properties

In the experiment, a damper placed in a constant-temperature tank and kept at 0ºC showed a maximum temperature difference of 10ºC with the interior of the visco-elastic substance. Using two types of actual size dampers, i.e., a temperature-controlled damper and a damper kept in a constant-temperature tank at close to normal conditions at the standard temperature of 20ºC, vibration tests were conducted using the same apparatus in Chapter 2 to examine the effect of the temperature control on the mechanical properties of the visco-elastic damper. Figure 10 shows the storage modulus γ' and the loss modulus γ'' that were obtained in a random wave vibration test by inputting white noise having a maximum vibration amplitude of 1.5mm (10% shear strain) of a uniform band region from 0.1Hz to 10Hz. For reference, γ' and γ'' of the M3 model (Soda[2]) used in a previous study are also shown. Figure 11 shows the hysteresis for sine wave vibration tests with constant vibration amplitude of 3mm (20% shear strain) and sine wave vibration tests with constant frequency of 0.2Hz.



(a) Storage modulus (b) Loss modulus

Figure 10 Comparison of Complex Moduli by Random Loading



(a) Frequency of 0.2Hz (b) 20% shear strain

Figure 11 Comparison of Hysteresis Loop by Harmonic Loading

As we can see in Figure 10, γ' of the temperature-controlled damper was an average of 1.2 times higher than γ' under normal conditions, γ'' was about 1.1 times higher. Likewise, the results from the sine wave vibration tests shown in Figure 11 reveal that the resistance of the temperature-controlled damper was somewhat higher than that of the damper under normal conditions. In a low-temperature environment (such as air temperature of 0ºC) with temperature control, the visco-elastic substance of the section near the attachment with the damper was about 10ºC lower than the temperature in the center of the damper, so this was considered to be the effect of a slight rise in rigidity of the damper (compared with the damper at 20ºC). However, even when the damper that was temperature-controlled in a low temperature environment had up to a 10ºC temperature difference with the interior of the visco-elastic substance, the rise in modulus of complex elasticity remained at about 20%, indicating that there was very little effect of temperature control on the mechanical properties.

4. CONCLUSIONS

This paper has reported on the scale effect of a temperature control method using an actual size damper. The main findings were as follows:

1) Random vibration tests with an actual size damper confirmed the temperature dependency of the mechanical properties. As a result, storage modulus γ' and loss modulus γ'' at a random temperature between 0 and 40ºC showed curves that were parallel along the vertical axis to γ' and γ'' curves at the standard temperature of 20ºC. The parallelism of the curves of γ' and γ'' indicated that the amount of movement of γ' and γ'' were roughly equal in the range from 0 Hz to 10 Hz.
2) The 300kN-class two-layer dampers used in the reinforcing work were given a temperature control system. As a result, even under the very severe environmental conditions (0 to 5ºC) throughout the day during the measurement period, the average temperature of the visco-elastic substance was controlled to 20±1ºC, while the difference with temperature inside the visco-elastic substance was within a range of 5ºC. This indicates that the temperature was uniformly distributed and stably controlled.
3) The effect of temperature control on the mechanical properties was examined in vibration tests using an actual size damper. In these tests, even if the temperature-controlled damper showed a maximum temperature difference of 10ºC inside the visco-elastic substance in a low temperature environment, yet the rise in modulus of complex elasticity remained at about 20%, indicating that there was very little effect of temperature control on the mechanical properties.

The above findings indicate that there was little scale effect of the temperature control method of visco-elastic dampers, and confirm the high practicality of the temperature control method.

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