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JSSI MANUAL FOR BUILDING PASSIVE CONTROL TECHNOLOGY PART-5 PERFORMANCE AND QUALITY CONTROL OF VISCOELASTIC DAMPERS

Kazuhisa ISHIKAWA[1], Kiyoshi OKUMA[2], Atsushi SHIMADA[3], Hiroshi NAKAMURA[4] and Nobuo MASAKI[5]

SUMMARY

The viscoelastic damper is composed of viscoelastic material sandwiched by two parallel plates or two concentric pipes. Energy dissipation performance of viscoelastic damper depends on temperature, frequency and amplitude. Therefore the characteristics of viscoelastic damper must be confirmed preliminarily by experiments before application to the buildings. However, the standard performances evaluating method and quality controlling method of the viscoelastic damper have not yet been decided.
The authors have been making the manual for design and construction of passively controlled buildings at the JSSI Response Control Committee. This paper introduces the contents of the manual corresponding to the performance dependence properties by various condition, testing and quality control methods of viscoelastic damper.

INTRODUCTION

This paper discusses various issues related to viscoelastic dampers, including dynamic characteristics, test methods, and quality control.

CHARACTERISTICS AND APPLICABLE RANGE

The dynamic characteristics of viscoelastic dampers must be applied in practice as complying with a range that has been confirmed and verified beforehand under various assumed conditions by experiments and other means.

[1] Showa Electric Wire & Cable Co., Ltd., Kanagawa, JAPAN. E-mail: k880188@snt1.swcc.co.jp
[2] Sumitomo 3M Ltd., Tokyo, JAPAN. E-mail: kokuma1@mmm.com
[3] The Yokohama Rubber Co., Ltd., Kanagawa, JAPAN. E-mail: Y851034@mta.yrc.co.jp
[4] Nippon Steel Corporation, Tokyo, JAPAN. E-mail: nakamura.hiroshi4@eng.nsc.co.jp
[5] Bridgestone Corporation, Kanagawa, JAPAN. E-mail: masaki-n@bridgestone.co.jp

Frequency dependence

Fig. 1 gives examples of the hysteresis curve when changing a frequency. The inclination of the hysteresis curve increases with increasing frequency, indicating that the dynamic characteristics of the viscoelastic damper are frequency-dependent. Since the extent of frequency dependence depends on the type of viscoelastic material used, it is necessary to have previously verified the magnitude through experiments. When a building is designed to have a high damping coefficient, it is generally confirmed that a first mode becomes prominent for building vibration; thus, the frequency range should ideally be verified for a range that corresponds to the first natural period of the building. For structures ranging from low-rise to high-rise buildings, dynamic characteristics must be verified in the range from 0.2 Hz to 3.0 Hz.

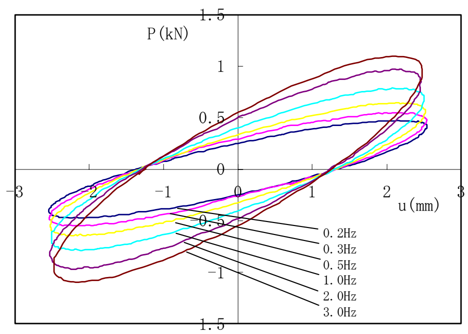
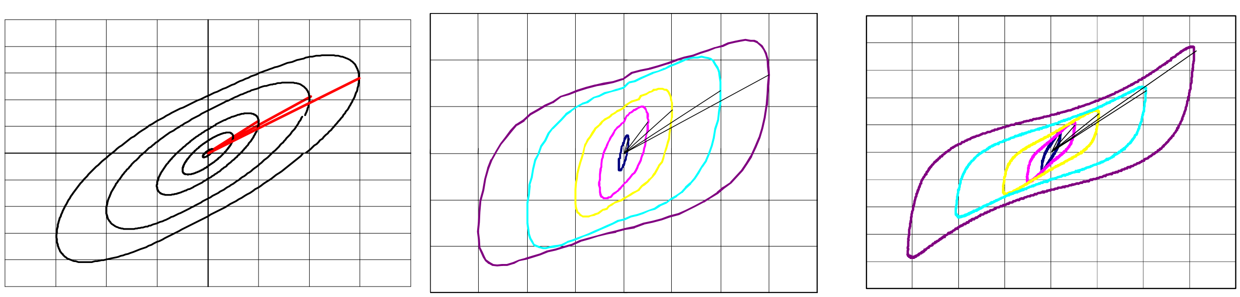


Fig. 1 Frequency dependence

Displacement dependence

The dependence of viscoelastic dampers on displacement amplitude can be divided broadly into (a) linear types, (b) softening types, and (c) stiffening types as shown in Fig. 2. Linear types (a) do not depend on displacement amplitude; their dynamics characteristics are nearly constant. Softening types (b) and stiffening types (c) depend on the displacement amplitude, and their dynamics characteristics vary the magnitude thereof.



(a) Linear Type (b) Softening Type (c) Stiffening Type

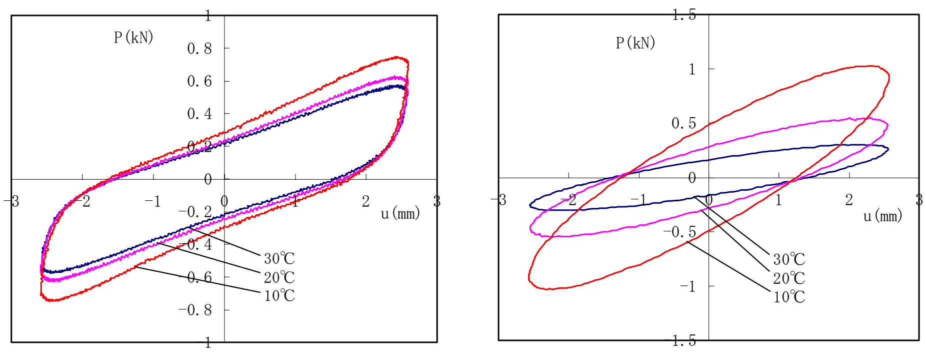
Fig. 2 Example of hysteresis curves

Since the yield strength at the limit of the viscoelastic damper depends on the type of viscoelastic material, experimental verification of the yield strength limit must be performed beforehand, and a working displacement amplitude range carefully set when designing an actual damper.

Temperature dependence

Viscoelastic dampers vary from extremely low to high temperature dependence. These characteristics are determined by the type of viscoelastic material used therein. Fig. 3 gives an example of a hysteresis curve for varying temperatures.

Working temperatures are governed by the environmental temperature of a building in which the damper is installed, while environmental temperatures are determined by the location where the damper is installed (i.e., inside or outside the building), including whether the installation location exposes the damper to direct sunlight. In Japan, when dampers are used indoors, the temperature range is generally assumed to be 10°C to 30°C throughout the country. Thus, the dynamic characteristics of the dampers selected for use should be verified for at least this temperature range. For dampers used in machine rooms with extremely high temperatures or in areas of extreme cold, dynamic characteristics must be tested for the respective temperature ranges. For dampers used outdoors, working temperatures must be carefully set according to the environmental temperature.



(a) Viscoelastic damper A (b) Viscoelastic damper B

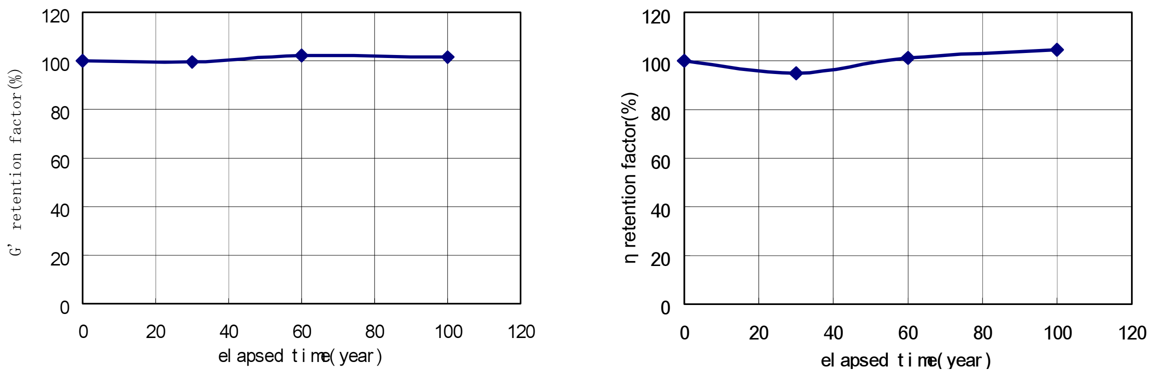
Fig. 3 Temperature dependence

Durability

If steel parts of viscoelastic dampers are treated with sufficient corrosion resistance, it is not necessary to consider degradation. The durability performance of a viscoelastic material part is shown below.

Secular change

Secular change is a phenomenon whereby the viscoelastic material part undergoes a chemical reaction through contact with oxygen and ozone in the air, or ultraviolet radiation, with the result that molecular chains are broken or crosslinks formed, with consequent changes in dynamic characteristics. Secular change can be estimated using an Arrhenius plot based on chemical kinetics. Fig. 4 shows an example of variations in dynamic characteristics over time, obtained from the Arrhenius plot. Since the viscoelastic damper has structurally very few parts exposed to oxygen, ozone, or ultraviolet radiation, degradation by oxidization is unlikely, and variations in dynamic characteristics are likely to be low.



(a) Storage modulus (b) Loss factor

Fig. 4 Example of estimated secular change of viscoelastic damper

Fatigue

Fatigue is a phenomenon in which the viscoelastic is subjected to cyclic deformation that gives rise to a crack at a certain point, after which the crack grows gradually, eventually resulting in a breakdown of the viscoelastic material. Fatigue can be expressed as an S-N curve obtained by plotting the number of cycles of displacement of the viscoelastic material at which breakdown occurs as a function of the displacement amplitude. Fig. 5 shows an example of the S-N curve. In cases where the viscoelastic damper is subjected to cyclic deformations from small vibrations generated by such forces as wind or traffic vibration, fatigue failure must be considered. Normally, the viscoelastic damper has sufficient fatigue life for low displacement amplitudes, and no problems arise. However, in the design of a damper, it is necessary to verify the extent to which the viscoelastic material exhibits displacement amplitude when subjected to minute vibrations, such as those generated by wind, and confirm that fatigue life will not cause a practical problem at that displacement amplitude.

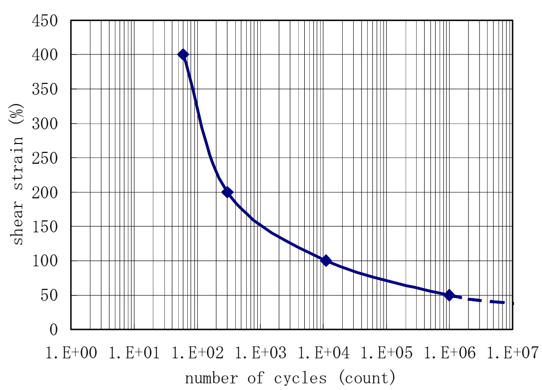


Fig. 5 S-N curve of viscoelastic damper

Fireproofing

If environmental temperature is increased due to fire, the viscoelastic material will soften, decompose, or smolder. To adequately grasp these aspects of a material, it is important to investigate beforehand the softening point of the viscoelastic material or the temperature at which decomposition starts, and the kinds and quantities of combustion gases. If it can be inferred that the environmental temperature at the outbreak of fire exceeded the temperature at which softening or decomposition begins, the damper must be replaced, since the characteristics of the viscoelastic material would have been compromised.

Performance test and evaluation method

Setting the fundamental dynamic performance of the viscoelastic damper requires establishing the setting by conducting performance confirmation tests under various assumed conditions, based on an appropriate evaluation method that considers fluctuations in product performance, among other factors.

Tables 1 to 3 list the conditions to be considered, test items, test methods, and methods of evaluating test results. Discussed below is a specimen shape described in Tables 1 to 3; a method for calculating characteristic values of the viscoelastic damper is also discussed.

Table 1 Viscoelastic Material Property

Test Item	Test Method	Specimen	Evaluation Criteria	Note
1.1 Shear and Adhesion Performance	Simple Shear	Single Shear (25×25 ～ 50×50mm Thickness less than 5mm)	Shear Strength (N/mm^2) Shear Strain (%) Fracture State	Temp. : 20°C Tensile Speed : 50mm/min
1.2 Limited Strain	Simple Shear	Single Shear (25×25 ～ 50×50mm Thickness less than 5mm)	Shear Strength (N/mm^2) Shear Strain (%) Fracture State	Temp. : 10°C Tensile Speed : 50mm/min
1.3 Fire Proof	Combustion Test Quantity of Generating Gas	Sheet of Viscoelastic material	Softening point and decomposition Quantity of combustion generating gas	700℃ Combustion

Table 2 Viscoelastic Damper Basically Property

Test Item	Test Method	Specimen	Evaluation Criteria	Note
1.3 Fire Proof	Test shall be conducted under fixed conditions so that the results are free from temperature dependence and strain dependence, and the obtained results are considered comparison data for damper performance test in Table 4.	Damper Shape Specimen (As /d = 1000mm or more L /d = 10 or more)	G' [=Kd '/(A s /d)] (N/mm^2) η [=Cd ・ω/Kd '] h d (If necessity)	Example of test condition Temp. 20℃、Freq. 0.2Hz Strain 50%

Table 3 Viscoelastic Damper Performance in Several Conditions

Test Item	Test Method	Specimen	Evaluation Criteria	Note
3.1 Strain, Frequency, and Temperature Sensitivity	Strain Range : 20～200 % Frequency Range 0.2～3.0 Hz Temperature Range 10～30 °C	Damper Specimen	G' [=Kd '/(As /d)] (N/mm2) η [=Cd ・ω/Kd '] hd (Necessity is accepted) Shape of a histeresis loop. Temp. change of Viscoelastic material	Evaluate G' and η from third-cycle loop principally. (Specify loop number on which evaluation was conducted.) Preferably, hysteresis curves up to 10 cycles are shown.
3.2 Estimation of Secular Change	Evaluation shall be conducted for every element of a matrix composed of the above-mentioned parameters.Secular change estimation curve is derived from accelerated aging test, using activation energy based on .Arrhenius' equation.Test conditions are the same as characteristic check examination.	Damper Specimen	Retention factor of G' (%) Retention factor of η (%) Retention factor of hd (%) (If necessary)	
3.3 Moisture resistance	Method shall comply with dipping test method for vulcanized rubber, JIS K 6258.	Damper Specimen (Single Shear Testing Specimen)	Retention factor of G' (%) (for shear specimen piece, retention factor of strength (%) and retention foctor strain (%))	Water Temp.: 20°C Specify Dipping time
3.4 Fatigability	Frequency 0.3 Hz Initial Temp. 20°C Use Strain in Determined with Consideration of Use Range	Damper Specimen	Create S-N Curve (line representing 70% performance retention to initial value)	Number of Cycle shall be 2x10^6 or more (Speculation for fatigability in allowed)

Specimen Shape

Fig. 6 and Fig. 7 show typical specimen shapes used to evaluate viscoelastic materials. Fig. 6 shows a single shear testing specimen. Fig. 7 shows a double shear type specimen, which is called a damper shape specimen. When necessary to conduct a test with Dynamicloading, use the damper shape specimen of Fig. 7.

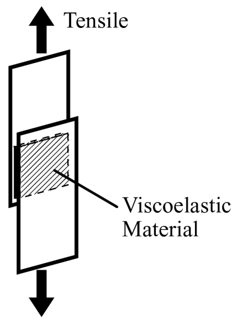


Fig. 6 Single Shear Testing Specimen

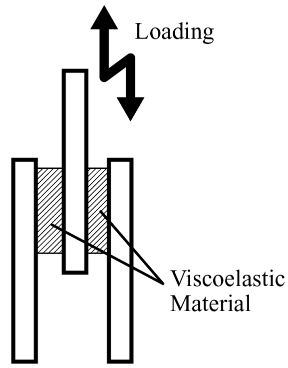


Fig. 7 Damper Shape Specimen

Method of calculating viscoelastic damper characteristic value
As shown in Fig. 8, for sinusoidal strain input

$$\gamma = \gamma_0 \sin(\omega t) \tag{1}$$

stress can be expressed by

$$\tau = \underbrace{G'\gamma_0 \sin(\omega t)}_{\text{Elastic part}} + \underbrace{G''\gamma_0 \cos(\omega t)}_{\text{Viscous part}} \tag{2}$$

Combining the two terms, we reformulate the expression for stress as follows in equations (3) and (4).

$$= \sqrt{G'^2 + G''^2}\,\gamma_0 \sin(\omega t + \delta) \tag{3}$$

$$= \sqrt{1+\eta^2}\,G'\gamma_0 \sin(\omega t + \delta) \tag{4}$$

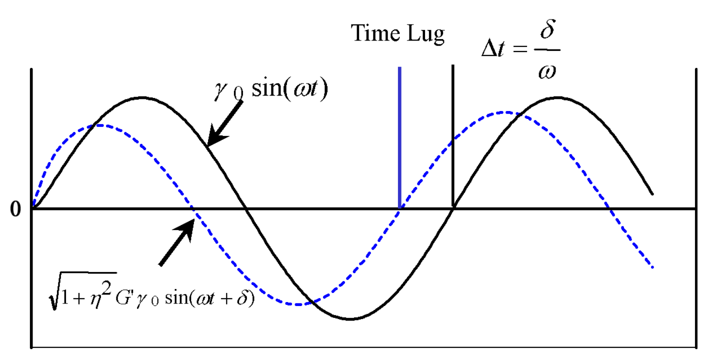


Fig. 8 Time History of Viscoelastic Material

Here, the variables indicate the following:

G' : Storage Modulus [N/mm^2]
G'' : Loss Modulus [N/mm^2]
η : Loss Factor

$$\eta = \tan\delta = \frac{G''}{G'} \quad (5)$$

These symbols are also illustrated on the hysteresis curve in Fig. 9.

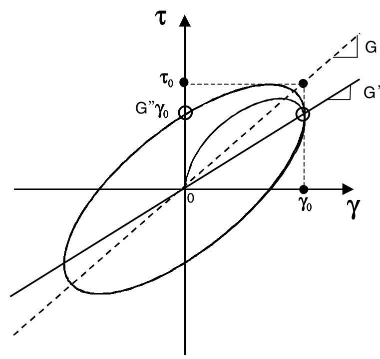


Fig. 9 Histeresis Curve of Viscoelastic Material
(Shown each Symbols meaning)

$$G^* = \sqrt{G'^2 + G''^2} = \frac{\tau_0}{\gamma_0} \quad (6)$$

Stiffness K_d' of the damper part is expressed, with shear area A_s and the thickness of viscoelastic material d, by the Eq.7. When subjected to vibration of angular natural frequency ω_n , viscosity coefficient C_d is expressed by the Eq.8. Further, attenuation constant h_d is expressed by the Eq.9.

$$K_d' = \frac{A_s}{d} G' \quad (7)$$

$$C_d' = \frac{\eta K_d'}{\omega} \quad (8)$$

$$h_d = \frac{1}{4\pi}\frac{\Delta W}{W} = \frac{\eta}{2} \quad (9)$$

Method of calculating activation energy

To calculate activation energy, the Arrhenius equation based on well-known chemical kinetics in the aging mechanism caused by thermally accelerated aging is used [1][2].

$$K = A \cdot \exp\left(-\frac{E_a}{RT}\right)$$

E_a : Activation energy [J/mol]
K : Velocity constant [time^{-1}]
A : Frequency factor
R : Gas constant (=8.313 [J/mol/K])
T : Temperature [K]

The Arrhenius plot plots experimental data points to a coordinate system, in which the logarithm of the velocity constant is mapped to the longitudinal axis, and 1/T is mapped to the horizontal axis. From the slope of this plot, Ea/2.303R can be found, while log A can be found from the y-intercept.

LIMIT STATE VISCOELASTIC DAMPER

The limit state of the viscoelastic damper is set, based on the results of performance tests, for each of the limit states: end limit, damage limit, and use limit.

End limit state

In the viscoelastic damper, the end limit must be set from two points: fracture of the material and fatigability. A designer must specify the specific purpose of using the damper (to provide protection against earthquakes or wind). If the damper is intended to provide protection against earthquakes, the designer must define a safety ratio ($\alpha 1$) for the limit state from both the strain limit obtained by the one-directional shear test and a strain that forms a stable loop on the characteristic figure, obtained from repeated loading experiments; if the damper is intended to protect against wind, the designer must define a safety ratio ($\alpha 1$) for the limit state after examining a region in which stable hysteresis can be obtained for the number of cycles assumed in actual use, in light of the results from repeated loading experiments.

Damage limit state and use limit state

For viscoelastic dampers, the designer must specify a damage limit value that defines a region in which the damper can be repaired for further use, and a use limit value that defines a region in which the damper can be used continuously. For each damper, the designer must define the damage limit and use limit for assumed input. In actual design, these values are set by the designer after making an overall judgment, and thereafter determining the safety ratio ($\alpha 2$) for the end limit state.

QUALITY CONTROL

Quality control system

In the implementation of quality control for viscoelastic dampers, a quality control system must be clearly defined and quality controlled for each manufacturing process.

Since the quality control practiced by manufacturers is vital in ensuring the quality of a viscoelastic damper, a design administrator, contractor, and manufacturer shall engage in mutual discussion regarding all matters deemed important for quality control. Table 4 gives an example of a manufacturer's quality control method.

Manufacturing process and quality control

In the manufacture of the viscoelastic damper, the design administrator, contractor, and manufacturer must confirm the quality provided by manufacturing instructions formulated beforehand by the design administrator, contractor, and manufacturer.

In the manufacture of the viscoelastic damper, the design administrator, contractor, and manufacturer must engage in sufficient consultation beforehand to confirm the following three items, and prepare manufacturing instructions and production drawings:

1) Specifications concerning device and quantity
2) Manufacturing process and contents of inspection
3) Delivery date and delivery details

gives an example of the contents of manufacturing instructions.

The damping trait is the most important quality characteristic for viscoelastic dampers. Currently, products are shipped after the equivalent damping coefficient and equivalent rigidity in the performance inspection (vibration experiment) are measured; this data is compared to standard and control values to confirm performance.

Table 4 Example of quality control method for viscoelastic damper

Manufacturing process	Process name	Control point	Inspection item	Person in charge	Note
Raw material / Metal component / Other component					
◎ ◎ ◎	1. Acceptance inspection				
	Raw materials		Document (weight and material characteristics)	Inspector	Sampling inspection for lot
			Appearance		
	Metal components		Appearance and dimensions	Inspector	Sampling inspection for lot
	Other components		Appearance and dimensions	Inspector	Sampling inspection for lot
○	2. Combination	Weight		Worker	
○	3. Mixture	Temperature, Time and mixer rotational		Worker	
◎	4. Material inspection		Material characteristics	Inspector	Sampling inspection for lot
○	5. Assembly and heating	Temperature and time		Worker	
○	6. Viscoelasitic material injection	Pressure and overflow quantity			
○	7. Cooling and decomposition	Temperature and time		Worker	
◎	8. Filling quantity inspection		Weight before and after filling	Inspector	100% inspection
○	9. Assembly				
◎	10. Size inspection		Length	Inspector	100% inspection
◎	11. Performance inspection		Damping Stroke	Inspector	Sampling inspection for lot
○	12. Coating			Worker	
◎	13. Coating inspection		Layer thickness and appearance	Inspector	100% inspection
○	14. Packing	Package form		Worker	
○	15. Shipping				

○ :Manufacturing process

◎ :Inspection process

Table 5 Example of the items mentioned for instructions

A. Manufacturer's quality control system B. Manufacturing process C. Design specifications (requirements) D. Product specifications (material, form, and size) E. Inspection and testing items, method, designed values (material inspection, performance test, quantity of viscoelastic material inspection, size inspection, and appearance inspection) F. Packing, transport Measures to prevent deformation of viscoelastic dampers in transit (securing method) G. Document to be submitted Size inspection report, material test report (performance test report)

Inspection items and performance confirmation test items

Prior to installation and assembly, the manufactured viscoelastic dampers must be verified for quality by inspection.

The viscoelastic damper manufacturer must conduct the following four inspections/tests and prepare an inspection/test report.

1) Material test of viscoelastic material - performance test with standard specimen - (Damping characteristics and restoring force characteristics are verified.)
2) Viscoelastic material filling quantity inspection (Verification involves weight measurement before and after filling.)
3) Size inspection (Product dimensions are verified to fall within the range of tolerances for design dimensions.)
4) Appearance inspection (This verifies that none of the members has flaws that would degrade functionality.)

A full-scale performance trial should also be conducted separately, if needed, with the mutual consent of the building client, designer, contractor, and manufacturer.

Acceptance inspection

Inspections of the viscoelastic damper at the time of acceptance should consist of an inspection performed by the contractor and appearance inspection (consisting of the three items given below). The contractor may substitute the above-mentioned inspections/tests conducted by the manufacturer for the acceptance inspection. Note that the contractor should report the inspection results to the design administrator, as needed.

1) The contractor should collate a list of members with actual components, and check that the specified types and quantities have been accepted.
2) The contractor should confirm that the viscoelastic material has no leaks or peeling.
3) The contractor should confirm that the members do not have flaws that degrade functionality.

Inspection at execution

The contractor should conduct inspection at the time of execution (consisting of the two items given below), and submit an inspection report to the design administrator.

1) Mounting accuracy
2) Bolt tightening condition (to confirm that the specified bolts are securely fastened at junctions)

Inspection at completion

The design administrator must attend the inspection following installation by the contractor (with the inspection consisting of the four items given below) to confirm that there are no abnormalities when installing the viscoelastic damper.

1) Main body (free of abnormalities in shape and flaws)
2) Rusting (free of red rust)
3) Mounting section (free of gaps between the markings of a bolt and of a nut)
4) Viscoelastic material (free of leaking or peeling)

CONCLUDING REMARKS

In this paper, we have presented an up-to-date proposal concerning the performance, design, and quality control of viscoelastic dampers. We plan to continue preparing a damping structure manual by expanding on the topics touched on in this paper, and by proposing suitable installation plans and maintenance control systems.

REFERENCES

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2. Seismic-Isolation Laminated Rubber Committee of Society of Rubber Industry, Japan, edited, "Seismic-Isolation Laminated Rubber Handbook," Rikoh-Tosho, Jan. 2000