CHARACTERISTICS OF SUPER HIGH DAMPING VISCO-ELASTIC DAMPER FOR EARTHQUAKE AND WIND-INDUCED VIBRATION

Brian Lim1 and Tatsuji Matsumoto2

ABSTRACT

In this paper, the dynamic characteristics of newly developed visco-elastic damper of having greatly improved damping performance compared to the conventional visco-elastic one will be shown. The visco-elastic damper explained here could absorb super minute deformation region such as wind induced vibration which occurs daily basis not only huge earthquake vibration which comes once every 50 years or more. The equivalent damping coefficient $H_{eq}$ when giving only 0.05mm deformation in case of static frequency 0.01Hz shows the wonderful value of 0.15. Temperature dependency which had been the conventional weak point of a visco-elastic damper, has also improved dramatically with $H_{eq}$ (-10 degree C / 20 degrees C) =1.21 and $H_{eq}$ (40 degree C / 20 degrees C) =0.90. Moreover, with $H_{eq}$ (0.1Hz / 3.0Hz) =0.94, the conventional weak points which strongly depended on velocity and little effect for long-period type earthquake have overcome. The new damper demonstrates the effectiveness for a wind induced vibration. Since the secular degradation after the aging test equivalent to 60 years based on the heat aging examination is so small as $H_{eq}$ (60 years after / initial value) >0.90 that long-term durability is also approved.

Keywords: Dynamic Characteristics, Visco-elastic Damper, Super Minute Deformation Region, Wind Induced Vibration, Long-period Earthquake, Temperature dependency, Frequency Dependency

INTRODUCTION

Unlike other material based dampers, since visco-elastic damper has the spring element in addition to the damping element, it has the function which restores the object structure to the original position after deformation. Moreover, visco-elastic damper has been broadly used for many years due to small secular degradation of material and the character of no need to replace after an earthquake or long time use of repetition. However, the conventional viscous damper such as frequency-dependent, especially at low frequency region, and the value of shear modulus G is so small and the damping characteristic at high temperature region is not comparatively good. Therefore, since the design corresponds to the entire environment, the worst conditions usually need to be considered on design. As a result, the required cross-section area of visco-elastic damper becomes large and affects economical efficiency including the attachment time. Thus, above mentioned characters were fetters to market the visco-elastic material as dumping component.

On the other hand, since the only viscous dampers such as oil damper can give the damping element purely to an object structure, the handling on design could be easy. However, especially under high temperature environment, the damping force becomes remarkably small because the temperature dependency is large. Moreover, due to strong dependency on frequency, although it is comparatively

1 Manager, VSL Intrafor Hong Kong, Hong Kong, brain.lim@hk.vsl-intrafor.com
2 Manager, SRI Hybrid Limited, Kakogawa, Japan, t-matsumoto.az@srigroup.co.jp
effective for the continentally earthquake which the high frequency components are dominant, the
damping effect becomes feeble in case of a skyscraper where the natural period is relatively large and
when the input earthquake wave which long-period components are still dominant like the case of the
oceanic earthquake. Moreover, on structure, since it has mechanical clearance, it does not function to
minute deformation and furthermore the periodical maintenance works are definitely necessary
including the oil leaking checking and some aging problem also happens by the long term use.

Conventionally, most general damping device as the earthquake-proof safety of the high-rise
building was low yield steel. Low yield steel damper has advantage in size and cost and also
temperature and frequency dependability are better compared with the conventional damper. However,
at the time of the small earthquake or typhoon which occur small deformation frequently, since the
low yield loss has the limit of accumulation plasticity modification, it must be designed under the
condition that the deformation may change only within the limit of elastic modification. That is, it is
said that low yield steel is almost no use for small vibration. Moreover, since the replacement will be
required when accumulation plasticity deformation is exceeded, the maintenance after small
earthquake is basically indispensable. Furthermore, since yield load becomes larger every cycle so the
input load must exceed previous yield load every time. As a result, the design of the circumferential
component must be carefully considered.

In this paper the various basic dynamic characteristics of newly developed visco-elastic dampers
using the high hardness rubber as the energy absorptive element will be clarified experimentally. Next,
 it is shown that the limit of accumulation plasticity modification does not actually exist in this
dumping device. And finally the damping capability which can absorb from the small disturbance such
as small earthquake and wind-induced vibration to the oscillation of huge earthquake will be shown.

That is, the improved points on the temperature and frequency dependency which had been the
weak point of the conventional visco-elastic dumping device will be explained by clarifying the
dynamics characteristic data of this damper showing the basis which can respond to a broad vibration
in high temperature and long cycle vibration. And finally the experimental data in a minute
deformation region of this damper will be shown to prove its effectiveness in small earthquake not
only the great earthquake which occurs rarely even with high generating frequency.

**EXPERIMENTAL METHOD**

The outline of one-axis two-surface shearing test machine used for the unit damper performance
is shown in Fig.1. The standard visco-elastic damper unit which used high hardness rubber is shown in
Fig.2. A visco-elastic object and two sheets of steel flange are firmly unified by vulcanized adhesion.
In case that it destroys by shear breaking examination, the quality control is made so that visco-elastic
material always carries out material destruction.
Regarding an experiment, two damper units consisting of the same shape is tested as a set each time and the measured force value is divided to half to get a unit damper value. As for each damper unit, cross-sectional shape consisting of square and single rubber layer is used in the experiment. However, practically, it will change to rectangle shape or laminated rubber structure according to required design damping force. During the experiment, the distance between flanges is kept constant. The hysteresis characteristics values are obtained from measured shear forces and horizontal displacement by sinusoidal oscillation using an actuator. The geometric conditions of the tested damper unit are shown in Table 1. Regarding the experiment conditions, the temperature: -10 degrees to 40 degrees, the response region: Frequency: 0.05Hz to 3.0Hz, Strain ratio: 300% or less in order to meet the actual conditions in which the damper is practically installed. As a result, it was verified that this damper has the predetermined hysteresis characteristics value by the performance evaluation test using the various shapes of test model. As the items of the test, basic characteristic, deformation capability, strain dependency, repetition dependency, temperature dependency, frequency dependency and secular degradation by heat aging were examined.

<table>
<thead>
<tr>
<th>Test Sample</th>
<th>Thickness (d)</th>
<th>Width or Diameter (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>φ 25-d5</td>
<td>5 mm</td>
<td>25 mm</td>
</tr>
<tr>
<td>□100-d20</td>
<td>20 mm</td>
<td>100 mm</td>
</tr>
<tr>
<td>□200-d20</td>
<td>20 mm</td>
<td>200 mm</td>
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<td>□300-d20</td>
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<tr>
<td>□300-d30</td>
<td>30 mm</td>
<td>300 mm</td>
</tr>
<tr>
<td>□300-d60</td>
<td>60 mm</td>
<td>300 mm</td>
</tr>
</tbody>
</table>

Regarding the experimental set-up of the system unit, this visco-elastic damper with the same shape put into the steel plate has sufficient rigidity for the system of a wall and brace type dampers respectively as shown in Fig.3 and 4. In the experiment, it was confirmed that the dynamic characteristics is proportional to the number of the visco-elastic damper.

![Fig.3 Experiment sample of wall type](image1)

![Fig.4 Experiment sample of brace type](image2)
EXPERIMENTAL RESULTS AND DISCUSSION

Dynamic Characteristics of Basic Condition

Experiment Result

The basic hysteresis characteristics is obtained from the relations between shear forces and shear displacement as shown in fig.5 by four(4) cycle repetition examination given the shear displacement of the positive/negative direction equal to visco-elastic thickness. The hysteresis loop shows abbreviation parallelogram and the first cycle shows relatively large shear forces though, the trajectory after the second cycle is becoming almost same.

As for hysteresis loop data for evaluation, one cycle from the maximum shear displacement point of third cycle is chosen which the dynamic performance becomes quasi-steady status. Very high rigidity is shown in the minute modification domain like low yield steel, however, unlike steel which has only pure elastic component in this region, the visco-elastic damper has large damping component as mentioned later. Regarding frequency and temperature condition, as long as there is no special description, frequency is 0.1Hz of sign wave and temperature is 20 degrees hereafter.

The Definition about the Hysteresis Characteristic Value

The definition for the hysteresis characteristic value of this damper is illustrated in Fig.6. Especially important parameters, equivalent shear modulus $G_{eq}$ and equivalent damping coefficient $H_{eq}$, are defined by Eqs.1 and 3 respectively. $G_{eq}$ is coefficient which is not concerned with the shapes of the visco-elastic body but shows the characteristic of material. The equivalent stiffness $K_{eq}$ obtained from the maximum displacement and the maximum load is divided by $S/d$ (the cross-section area / the thickness of visco-elastic object). Equivalent-damping coefficient means the damping forces transposing the nonlinear recovering character of the visco-elastic body to the equivalent liner recovering and damping forces.

$$G_{eq} = \frac{K_{eq}}{(S/d)} \quad [kN/\text{mm}^2]$$  \hspace{1cm} (1)

$$K_{eq} = \frac{P_{\text{max}} - P_{\text{min}}}{X_{\text{max}} - X_{\text{min}}} \quad [kN/\text{mm}]$$  \hspace{1cm} (2)

$$H_{eq} = \frac{1}{4\pi} \cdot \frac{\Delta W}{W}$$  \hspace{1cm} (3)

$$W = \frac{1}{2} \cdot X_{\text{max}} \cdot P_{\text{max}}$$  \hspace{1cm} (4)
where $S$: sectional area of visco-elastic body, $d$: thickness of body, $P_{\text{max}}$: maximum forces of hysteresis loop, $P_{\text{min}}$: minimum forces of hysteresis loop, $X_{\text{max}}$: maximum displacement of hysteresis loop, $X_{\text{min}}$: minimum displacement of hysteresis loop, $\Delta W$: absorption energy (the area of hysteresis loop) [major sampling points are 1000 or more.] and $W$: absorption energy (the area which is surrounded by the line perpendicularly taken down from the intersection of $X_{\text{max}}$ and $P_{\text{max}}$, $K_{eq}$ and the X-axis.)

**Deformation Capability**

In the deformation capability examination, shear deformation was given to the damper at the constant velocity of 5.0 mm/sec. The design target value of the deformation capability characteristic was 400% or more of thickness $d$ of the visco-elastic body. Then it was confirmed that there is no fall (negative slope) of shear forces in 400% or less of shear strain. Fig.7 shows the deformation capability characteristic in the case of □300mm and d20mm. In this examination, the test discontinued at the position where shear strain exceeded 400% due to the capability of the examination facilities. However the shear forces are presumed to be still on the way of right slope and have sufficient capability. With regard to shear forces, after the minute deformation region showed very high stiffness, it changed gently to approximate 200%. In the region of 200% or more, hardening phenomenon occurred with the increase of shear strain. As a result, shear forces increased rapidly.

**Strain Dependency**

In strain dependency examination, four cycles of displacement with both positive/negative direction equivalent to ±0.5% - ±300% of thickness $d$ of visco-elastic damper was input into an examination body and calculated a hysteresis characteristic value using the hysteresis loop of third cycle respectively.

**Super Minute Deformation Region**

In the examination of super minute deformation region, the strain ratio was measured at ±0.5% to ±100% using the examination sample with 25mm diameter and 5mm thickness. The piled up hysteresis loops of the minute deformation region in the frequency of 0.25Hz are displayed on Fig.8. $H_{eq}$ of ±0.5% of strain ratio is as large as 0.25, and $G_{eq}$ is as large as 12N/mm². As a result, the large absorption energy could be obtained. The relation between shear strain ratio and $G_{eq}$, $H_{eq}$ are shown in Fig.9 (a) and (b) respectively. Although $G_{eq}$ decreases rapidly with the increase of shear strain in a relative small amplitude domain, in the domain of 10% or more, it decreases gradually. On the other hand, although $H_{eq}$ shows a peak value at ±12.5% of shear strain with the increase of shear strain, the region where the shear strain ratio is relatively large shows almost constant values.
Relatively Large Deformation Region

Regarding the examination of relatively large deformation region, we gave 50 to 300% of strain ratio of thickness d of the visco-elastic body to the examination sample. Frequency is 0.1 Hz sign wave and temperature is 20 degrees. □ 300 mm and d20 mm case is shown in Fig.10 as an example of superposition of the hysteresis loop in each distortion. Fig.11 (a) and (b) show the strain dependency of \( G_{eq} \) and \( H_{eq} \) for various shapes of test sample respectively. In \( G_{eq} \) values, the difference by shape is hardly observed, rather the values are almost same with the increase of strain ratio. The influence by the form difference also hardly appeared in \( H_{eq} \). The value of \( H_{eq} \) increased with the increase of strain ratio rapidly at first and then it gradually increased until 200% of strain ratio showing a peak value at 200% and then decreased gently after 200% of strain ratio.

Temperature Dependency

Temperature dependency was measured for every 10 degrees in the range of -10 degrees to 40 degrees. Measured frequency is 0.1 Hz (sign wave), the examination sample is □ 100 mm and d20 mm. Superposition of the hysteresis loop of third cycle in each temperature is shown in Fig.12. Although the area of a hysteresis loop becomes smaller with the increase of temperature, the area large enough is
presented also in 40 degrees. The temperature dependency of \( G_{eq} \) and \( H_{eq} \) is shown in Fig.13 (a) and (b) respectively. Here it was approved that the newly developed damper has greatly improved compared to the conventional viscoelastic material in terms of the temperature dependency of \( G_{eq} \), and temperature dependency especially on \( H_{eq} \).

**Frequency Dependency**

Frequency dependency was examined in the range from the frequency of 0.1 Hz to 3.0 Hz under 20 degrees of temperature with the test sample of \( \square \) 100 mm and \( d \) 20 mm. The directions of positive/negative displacement equivalent to \( \pm 25\% \) of visco-elastic damper thickness were given to the predetermined number of cycles. The hysteresis loop with frequency of 0.1 Hz and 3.0 Hz are shown in Fig.14 (a) and (b) as representative of experiment results respectively. As a result, the difference was hardly found between both loops in spite of very different frequency conditions. Then the frequency dependency of \( G_{eq} \) and \( H_{eq} \) is shown in Fig.15 (a) and (b) to confirm that both dynamics characteristic values showed the almost constant value at broad frequency region.
**Repetition Dependency**

**Repetition Fatigue Examination for Minute Deformation Region**

The result of the repetition fatigue examination focused on the minute deformation region is shown in Fig.16. Temperature condition was 20 degrees and the size of the examination body used for the experiment is collectively shown. The plot in the figure shows the points of fracture happened and the plot with an arrow mark in right side means that it did not fracture even after giving deformation to the regulated cycles. And the repetition test which resulted in fracture decreased when shear strain is at ±25% or less. Even after exceeding 2 million times, the fracture phenomenon was not confirmed until reaching 10 million times.

**Relatively Large Deformation Region**

Using the test sample (□100mm～□300mm and d20mm～d60mm), the repetition examination in relatively large deformation region were carried out with 40 cycle repetition by inputting 100% and 200% strain rates and calculated the hysteresis characteristic value using the hysteresis loop of 3 cycle, 10 cycle, 20 cycle, 30 cycle and 40 cycle. In addition, input frequency was 0.1Hz sign wave and temperature was 20 degrees. As the result example, the piled up hysteresis loops in □300mm and d20mm are shown in Fig.17. As for the inclination of a loop, i.e., equivalent stiffness, reduction advanced slightly by every cycle and loop area became smaller. Moreover repetition dependency of $G_{eq}$ and $H_{eq}$ are shown in Fig.18 (a) and (b) respectively. When the deformation was comparatively large, both characteristic values decreased with the increase...
of the cycle number but when the ratio of reduction became smaller when repetition time increased.

**Secular Degradation**

The positive/negative direction displacement equivalent to 100% of the thickness d of visco-elastic sample was given repeatedly and hysteresis characteristic value was calculated using the hysteresis loop of third cycle under Frequency of 0.1Hz sign wave and temperature of 20 degrees with □ 100mm and d20mm sample. The relation of the temperature and time that are obtained from the Arrhenius Law is expressed with Eqs.5. 24 hours aging at 80 degrees corresponds to 8.9 years at 20 degrees from Eqs.5. The hysteresis loops from the initial value to 60-year equivalent aging are collectively shown in Fig.19. Moreover, secular degradation of Geq and Heq are shown in Fig.20 (a) and (b). Although some dynamics characteristic values will change largely in first ten years, they will be almost stable after then.

\[
\ln\left(\frac{t_{20}}{t_s}\right) = \left(1 - \frac{T_{20}}{T_s}\right) \cdot \frac{E_a}{R}
\]

(5)

where \( t_{20} \) : Aging time at 20 degrees, \( t_s \) : Aging time in arbitrary temperature, \( T_{20} \) : 20 degrees, \( T_s \) : arbitrary temperature, \( E_a \) : Activation energy (=27.9 kcal/mol), \( R \) : Gas constant (=2.0 cal/mol • deg)
MODELING OF THE HYSTERESIS CHARACTERISTIC

The approximation equations of the hysteresis characteristic value of this visco-elastic damper were obtained based on the performance evaluation test results and the analysis model was made by the approximation equations as shown in Eqs. 6 and 7. The performance of the damper can be modeled by the popular modified bi-linear model and modified H-D model (Y. Takenaka et al. 2001). In this paper, we show the example of application to modified H-D model which can approximate the hysteresis loop more accurate. $G_{eq}$ and $H_{eq}$ which were obtained by experiments are shown in Fig. 21 (a) and (b) respectively. The approximation curves used for modeling are also shown in the figures. The experiment values obtained from the various shaped samples shown by the plots show good agreement with the approximation curve.

The experiment results performed using the real sized wall type (□100mm, d10mm x 40 pieces) and the brace type (□300mm, d30x16 piece) dampers for buildings is shown in Fig. 22 (a) and (b). Test frequency for the wall type and the brace type are 0.1 Hz and 0.05 Hz respectively. The superposed hysteresis loop obtained from experiment and modeled by modified H-D model are shown and both loops show good agreement.

\[
G_{eq} = 0.0005 \gamma^{-0.7188} \quad [kN/\text{mm}^2] \tag{6}
\]

\[
H_{eq} = -0.0172 \gamma^2 + 0.0648 \gamma + 0.212 \tag{7}
\]

where $\gamma$ : strain ratio.
CONCLUSIONS

The temperature and the response frequency domains of the examination could be said very fair considering where this visco-elastic damper will be installed practically and we can show clearly that this damper has the specified hysteresis characteristic values to be effective for not only a big earthquake but also wind. That is, it is effective whether it is minute vibration or long cycle vibration. The effectiveness in broad frequency region is also confirmed. As a result, amenity for living has been improved. Regarding the aging examination equivalent to sixty (60) years, the hysteresis characteristic value shows that the increase in $G_{eq}$ is just less than 15% and the reduction in $H_{eq}$ is less than 10%. Moreover, it was turned out that its durability is equal to two (2) million repetition times or more at less than ±25% of strain ratio. Finally, it is shown that the hysteresis characteristic of this visco-elastic damper can be modeled by popular modified bi-linear model and modified H-D model and the values obtained from experiments of an actual size scale and model values which were show good agreement.

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