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著者(和文)	Razelle Dennise SORIANO, Dave OSABEL, 佐藤大樹, 太木本仁志, 上野史也, 笠井和彦
Authors(English)	Razelle Dennise Agoba Soriano, Dave M Osabel, Daiki Sato, Hitoshi Takimoto, Fumiya Ueno, Kazuhiko Kasai
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Study of Full-Scale Multi-Layered Viscoelastic Dampers under Long-Duration Harmonic Loading (Part 1: Experimental Investigation of a Viscoelastic Damper in Low Ambient Temperature)

正会員 ○ SORIANO Razelle Dennise[*1] 同 OSABEL Dave[*2] 同 佐藤 大樹[*3]
同 太木本 仁志[*2] 同 上野 史也[*2] 同 笠井 和彦[*4]

Full-Scale Viscoelastic Damper　Long-Duration Loadings　Experimental Investigation　Low Ambient Temperature

1. INTRODUCTION

Properly employed viscoelastic (VE) dampers in tall buildings can effectively dissipate structural vibrations induced by wind or long-period ground motion. Through shear deformation of the steel-laminated viscoelastic material, kinetic energy is absorbed and substantial amount of this energy is converted into heat.

Since viscoelastic materials are characterized to have temperature- and frequency-sensitivities, the performance of the VE damper highly depends on its internal temperature, ambient temperature and loading frequencies. These characteristics had been found in the past experimental studies[1-4)]. Tables 1 and 2 indicate the damper specimens and parameters for the experiment of previous research studies. Gotou[1)], Sato *et al.*[2)] and Nagayama *et al.*[3)] considered full-scale multi-layered VE dampers installed in tall buildings subjected to long-period ground motion, and Sugiyama[4)] considered long-duration wind loading. All these tests conducted were at ambient temperature ranging from 21°C to 30°C.

However, in countries such as Japan, ambient temperature can be below 0°C during winter season or can be about 40°C during summer season. In order to determine the performance of a full-scale VE damper in low ambient temperature, the researchers conducted tests during the winter season in Tokyo, Japan (i.e., in the month of January). This paper reports the damper specimen, test setup and test results for one of the experiments.

2. DAMPER SPECIMEN AND TEST SETUP

The long-duration test was conducted in Tokyo Institute of Technology (Suzukakedai Campus), Japan. To avoid extreme fluctuations of the ambient temperature inside the testing facility caused by out-door wind, all wide-access doors were closed.

Damper specimen VE05 (Table 1) is used in this current study. Each of the 6 laminations is 8-mm thick and is made of ISD-111 type VE material. Total shear area $A_s = 9{,}120$ cm^2.

Material property of ISD-111 type: shear modulus $G = 3.92$ N/cm^2, fractional derivative order $\alpha = 0.558$, at reference temperature $\theta_{ref} = 20.0$°C, $a_{ref} = 0.0056$ and $b_{ref} = 2.10$, and $p_1 = 14.06$ and $p_2 = 97.32$.

Dynamic actuator deformation was set to sinusoidal wave at 0.25 Hz (period $T = 4.0$ s) with peak value of ±10 mm. Amplification mechanism (factor of 2) was provided. Due to some deformation losses (e.g., brace deformation), the actual shear deformation of the VE material was not perfectly double to that of the dynamic actuator. The VE damper was loaded continuously for 6 hours (5,400 cycles).

Table 1. Viscoelastic damper specimens from past studies

Specimen	Length l (mm)	Total shear area A_s (cm^2)	Thickness of one VE lamination t (mm)	No. of laminations n	A_s/t (mm)
VE01	4628.7	26,000	9	10	28,889
VE02	3946.6	13,120	8	8	16,400
VE03	3946.6	18,112	8	8	22,640
VE04	3848.9	26,000	8	10	32,500
VE05	4024.5	9,120	8	6	11,400

Table 2. Harmonic loading conditions from past studies

Test No.	Period T (s)	Amplitude u_d (mm)	Duration t_0 (s)	No. of cycles	Ambient Temp. θ_c (°C)	Damper Specimen	Ref.
1	4.00	20.00	450	112	21	VE01	1
2	2.00	16.00	300	150	22	VE02	2
3	4.00	8.00	1,200	300	22		
4	4.00	16.00	600	150	22		
5	4.00	24.00	400	100	22		
6	6.00	16.00	900	150	22		
7	2.00	16.00	300	150	22	VE03	
8	4.00	8.00	1,200	300	22		
9	4.00	16.00	600	150	22		
10	4.00	24.00	280	70	22		
11	6.00	16.00	900	150	22		
12	4.00	16.00	600	150	22	VE04	
13	2.86	24.96	66	23	22	VE05	3
14	3.61	5.66	25,864	7,172	30	VE05	4
15	3.61	5.66	22,796	6,321	26		
16	7.01	5.66	24,942	3,559	28		
17	7.01	5.66	30,986	4,422	24		
18	4.33	5.66	27,340	6,307	28		

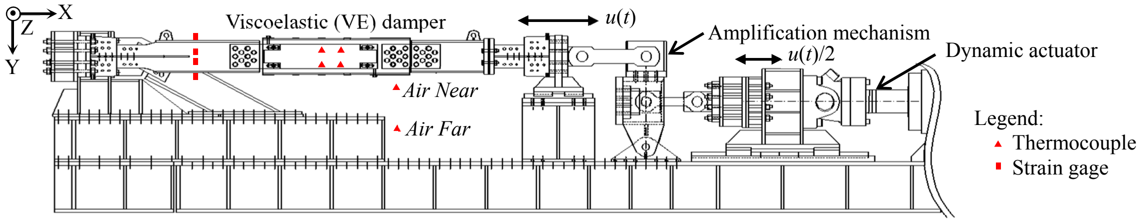
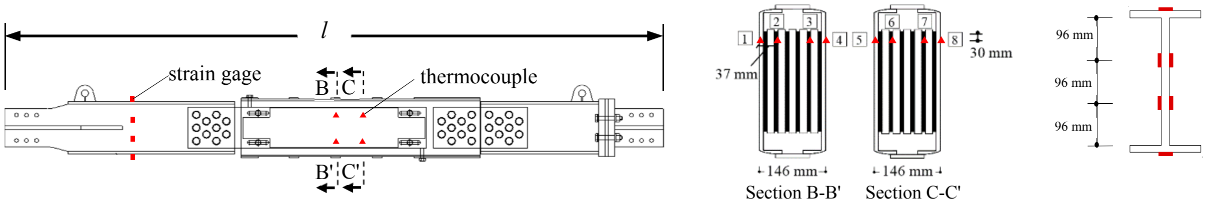


Figure 1. Viscoelastic (VE) damper test setup



(a) VE damper side view　(b) Thermocouple positions　(c) Strain gage positions

Figure 2. Measurement locations for the test setup [unit: mm]

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Locations of the strain gages and thermocouples are shown in Figure 2. Temperature was measured at 1-s interval, while damper strain was measured at 0.02-s interval. From the average of the measured strain, damper force F_d is calculated.

Ambient temperature was monitored at two locations (Figure 1), *Air Near* and *Air Far* were 8.0 cm and 86.0 cm from the VE damper, respectively. Temperature measurements were continued even after the loading.

3. RESULTS AND DISCUSSIONS

3.1 Temperature

Aside from thermocouples, a thermal imaging device was used to monitor the temperature of the VE damper. Figure 3 shows an example of infrared image of damper surface during excitation. It can be seen that the damper surface temperature had indeed increased from dissipating kinetic energy.

Figure 4 shows the time-history plots of the measured temperatures. From initial temperature of around 6.0°C, damper temperature increases drastically. However, after about 1 hour of loading, the temperature rise has noticeably becomes small and eventually the plots of the temperature plateaued. The inner portion of the VE damper manifests heat accumulation as the recorded temperatures (Points 2, 3, 6 & 7) are higher than those on the damper surface (Points 1, 4, 5 & 8). Peak recorded θ in the VE lamination (Point 2) was 59.63°C while on the damper surface (Point 8) was 37.21°C.

Also shown in Figure 4 are the recorded ambient temperatures. Due to its close proximity to the VE damper, the thermocouple near the VE damper *Air Near* had recorded a higher temperature than *Air Far*.

Immediately after the loading, damper temperature dropped significantly. This is attributed to the dispersion of heat to the surrounding air.

3.2 Damper Deformation

Figure 5 shows the shear deformation of the VE laminations or the damper deformation u_d. As mentioned above (Section 2), there are deformation losses such as shrinkage of the steel brace. At early loading cycles, the VE laminations were stiff causing the steel brace to compensate the deformation, thus, u_d is relatively low. As the damper temperature increased, the VE laminations softened, thus, u_d increased. Eventually, the VE damper behaved steadily.

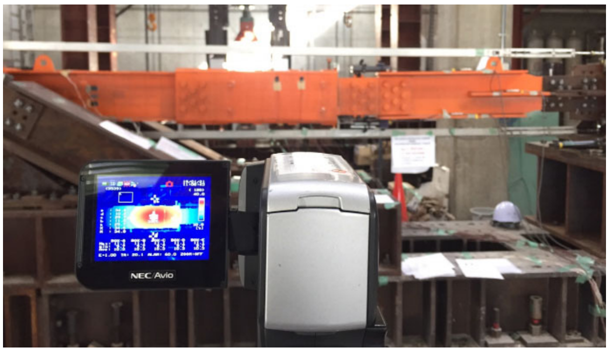

Figure 3. Thermal imaging device capturing the damper temperature during long-duration loading test.

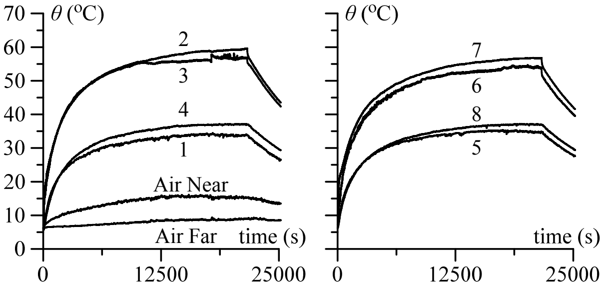

Figure 4. Temperature time-history.

3.3 Dynamic Properties

Figure 6 shows the hysteresis loops for cycles 1~10 (blue) and cycles 5391~5400 (red). The initial cycles manifest high damping (fat loop) and stiff VE laminations (steep slope). As such, large amount of energy was absorbed and large amount of heat was generated. This explains the drastic increase of damper temperature during the initial stage of loading (Figure 4). However, as the VE material softens, its dynamic properties decrease. Therefore, less amount of heat is generated.

Using Equation (1), storage stiffness K'_d per cycle is calculated.

$$K'_d = \frac{n\sum\left(u_d^{(i)} \cdot F_d^{(i)}\right) - \sum u_d^{(i)} \sum F_d^{(i)}}{n\sum\left(u_d^{(i)}\right)^2 - \left(\sum u_d^{(i)}\right)^2} \qquad (1)$$

Here, n refers to number of data per cycle. Figure 7 shows the storage stiffness K'_d. At low initial temperature, the VE damper was very stiff (31.28 kN/mm). It decreased and became almost constant at around 2.50 kN/mm due to the effect of heat transfer. In contrast, initial K'_d value of Test no. 15[4)] was lower than the current experiment due to higher initial damper temperature. With soft initial VE material, amounts of energy dissipated and heat generated are small. Hence, the decrease of K'_d is lower than the current experiment.

4. CONCLUSIONS

This study showed the real behavior of a full-scale VE damper under long-duration loading at low ambient temperature. With low initial damper temperature, the VE laminations were stiff and dissipated substantially large amount of energy during the initial cycles. Consequently, damper temperature increased drastically leading to abrupt softening of the VE laminations and the lowering of K'_d value. Despite the large increase of temperature and the long duration of loading, the damper behaved in steady-state due to the effect of heat transfer. This is the greatest advantage of VE dampers among other passive control devices under long-duration loadings.

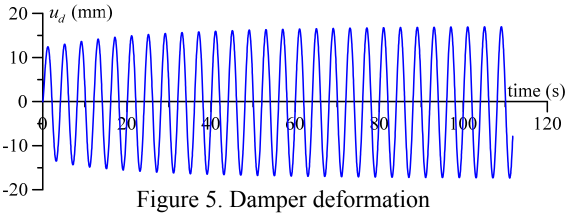

Figure 5. Damper deformation

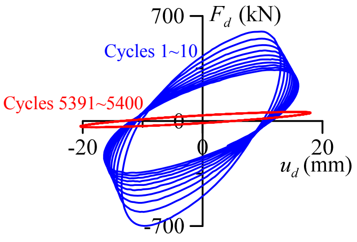

Figure 6. Hysteresis.

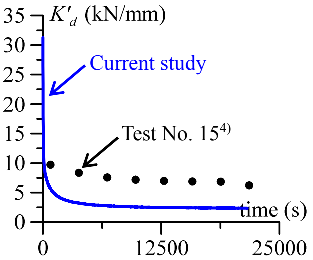

Figure 7. Storage stiffness.

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*1 東京工業大学 研究生
*2 東京工業大学 大学院生
*3 東京工業大学 准教授・博士（工学）
*4 東京工業大学 教授　Ph.D.

*1 Research Student, Tokyo Institute of Technology
*2 Graduate Student, Tokyo Institute of Technology
*3 Assoc. Prof., Tokyo Institute of Technology, Dr. Eng.
*4 Professor, Tokyo Institute of Technology, Ph.D.