Experimental Study on Mechanical Properties of Small Size Viscoelastic Damper

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Abstract: Long span roofs are very likely to oscillate when subjected to wind load that can lead to structure fatigue and endanger structures safety. Dampers have been used for long time to dissipate wind and earthquake induced energy in structures. This research work aims to present experimental study of small size viscoelastic damper that can be installed in truss of long span roof. Small size viscoelastic dampers that can be used to dissipate wind induced energy in large span roof structure need to be tested to know their performance behavior and mechanical properties at different loading amplitudes and frequencies. A kind of viscoelastic dampers were manufactured and tested under horizontal cyclic loads. Resistance and deformation of the damper were measured to study the viscoelastic damper properties dependence on frequency and amplitude. Mechanical properties including shear storage modulus, shear loss modulus, loss factor and energy dissipation are studied. Experimental results show that the small size damper's mechanical properties are significantly related to its loading frequency and amplitude. The energy dissipation capacity of the damper was stable under different loading frequency and amplitude.

1 Introduction

Earthquakes and heavy winds have occurred in different parts of the world, resulting in serious damages and destruction of buildings and infrastructures, which inflicted serious injuries, human lives loss, and properties loss [1]. Researchers have discovered that seismic and wind-induced energy in structures can be dissipated by the addition of dampers. Dampers are usually used to retrofit and strengthen new structures by dissipating induced energy hence reduce structural damages [2,16].

Dampers can be classified as passive, active, and semi-active damper. where viscoelastic dampers are classified as a passive energy dissipation device as they do not need an external source of energy [3,15]. Viscoelastic damper has a viscoelastic material which is used as the medium transaction where mechanical energy transfers to heat energy [4]. Viscoelastic dampers have a special characteristic of functioning at a very small displacement, hence are very effective to be used against winds-induced oscillation.

Viscoelastic dampers started to be used in civil engineering since 1960. Viscoelastic dampers are widely used in the wind-resistant design of high-rise structures due to its effectively energy dissipation at any displacement, simple structure and low cost [5]. Reduction of wind vibration was achieved by installing more than 10,000 viscoelastic dampers in each tower of World Trade Center in New York [2]

The viscoelastic damper has received much popularity for its special characteristic to dissipate energy from lower to high displacement or amplitude [6]. Hence, resistance against winds, earthquakes, and assurance of structure habitability during wind and earthquake can be achieved by using the devices. Researchers have discovered that the mechanical properties of viscoelastic material are heavily dependent on loading frequency, amplitude, and temperature [7,14]. To ensure the successful application of viscoelastic damper, appropriate evaluation of their mechanical properties is needed. However, the mechanical model used for property analysis are relatively complex [8].

Long-span roof structures like stadium, airport lobby and exhibition hall are widely used worldwide. Lightweight, flexibility, low damping ratio and close natural frequencies are the main characteristic of long-span roofs, hence make them more likely to oscillate when they are under wind load, which may lead to structure fatigue or endanger structure safety [9]. Control of wind-induced vibration in long span roof is of urgent need. Although, many researchers have been studying mechanical properties of viscoelastic damper which are mainly used in framing structures as braces, aim of this research is experimental investigation of mechanical properties of small size damper which can used in long roof truss structure.

To investigate the mechanical properties of small size damper, a kind of viscoelastic dampers with same parameters were manufactured and tested under

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horizontal cyclic loads. Mechanical properties, dependency on frequency and amplitude, including shear storage modulus, shear loss modulus, loss factor and energy dissipation are studied in this paper.

2 Properties of Viscoelastic Materials

Viscoelastic materials, as their name suggests, have to main properties which are viscous and elastic properties [10]. The term “viscous” means that they deform slowly when they are subjected to an external force. The term “elastic” means that once the force has been removed, the material will return to its original configuration (For purely elastic materials, loading and unloading “stress versus strain” curves (lines) are superimposed). For viscoelastic material, they form a “hysteresis” loop [11]. Viscoelastic material total resistance to deformation is studied in term of complex modulus. The contribution of elastic component to deformation is studies as shear storage modulus (S_s) while contribution from Viscous component is studies as shear loss modulus(S_L). Simply, shear storage and shear loss modulus significantly affect the damping performance of viscoelastic dampers [12]. For clinical application, it is very important to know the response behavior of viscoelastic material (specifically shear storage, shear loss and loss factor) at a corresponding loading rate and temperature [13]

The strain of a viscoelastic body is out of phase with the stress applied, by the phase angle, δ [18]. This phase lag is caused by the excess time necessary for molecular motions and relaxations to occur.

Dynamic stress, σ , and strain, γ , given as:

$$\sigma = \sigma_0 \sin(\omega t + \delta), \quad (1)$$

$$\gamma = \gamma_0 \sin(\omega t), \quad (2)$$

where ω is the angular frequency. Using this notation, stress can be divided into an “in phase” component ($\sigma_0 \cos \delta$) and an “out-of-phase” component ($\sigma_0 \sin \delta$) and rewritten as,

$$\sigma = \sigma_0 \sin(\omega t) \cos \delta + \sigma_0 \cos(\omega t) \sin \delta \quad (3)$$

Dividing stress by strain to yield a modulus and using the symbols S_s and S_L for the in phase (real) and out-of-phase (imaginary) moduli respectively:

$$\sigma = \gamma_0 S_s \sin(\omega t) + \gamma_0 S_L \cos(\omega t), \quad (4)$$

$$S_s = \frac{\sigma_0}{\gamma_0} \cos \delta. \quad \text{and} \quad S_L = \frac{\sigma_0}{\gamma_0} \sin \delta, \quad (5)$$

$$\gamma = \gamma_0 \exp(i\omega t). \quad \text{and} \quad \sigma = \sigma_0 \exp(i\omega t + \delta), \quad (6)$$

$$S = \frac{\sigma}{\gamma} = \frac{\sigma_0}{\gamma_0} e^{i\delta} = \frac{\sigma_0}{\gamma_0} (\cos \delta + i \sin \delta) = S_s + i S_L, \quad (7)$$

Equation (7) shows that the complex shear modulus(S) consists of “real” and “imaginary” parts. The real “shear storage modulus (S_s)” part describes the ability of the material to store energy and representing the elastic

portion. The imaginary “shear loss (S_L)” part is associated with energy dissipation in the form of heat upon deformation and representing the viscous portion.

The phase angle δ is given by

$$\tan \delta = \frac{S_L}{S_s} \quad (8)$$

The storage modulus is related with the stiffness of a material and is related to the Young’s modulus, the dynamic loss modulus is related to internal friction and is sensitive to molecular motions, relaxation processes, transitions, morphology and other structural heterogeneities. Understanding the dynamic properties gives information that help to understand polymer mechanical behavior [19].

3 Damper Configuration

Viscoelastic dampers are non-load-carrying structure elements, whereas they reduce the mechanical energy of structure motion and transfer them into heat energy [20]. This energy transfer achieves only through an energy transfer medium or a damping medium, i.e., viscoelastic material. Standard viscoelastic dampers are made of three-layer of rigid parts, and two-layer of viscoelastic materials (Figure 1~2). The damper should be installed so that the viscoelastic material undergoing pure shear deformation. In this research, the damper consists two viscoelastic materials of 100 mm × 50 mm × 10mm. The steel plate is 362 mm × 50 mm and 10 mm thick. The viscoelastic material is firmly bonded to the steel plate.

Figure 1. Sketch of standard viscoelastic damper

Figure 2. Photo of standard viscoelastic damper

4 Test Setup and Protocol

The two outer steel plates were fixed on the truss of the base, and the inner steel plate was connected to the MTS Hydraulic actuator by holes at the end of the specimen. The inner steel plate was relatively displaced by the MTS Hydraulic actuator, which causes the viscoelastic material

to shear and deform (Figure 3). The displacement gauge was placed on the damper between the steel plates connected to the base and the actuator to record accurately deformation of the specimen.

Figure 3. Test setup.

Loading amplitude and frequency are control variables in the tests, and test protocol is shown in Table 1. The test specimen was subjected to 4 cycles of different amplitudes at a frequency of 1.0 Hz to study the correlation of the deformation amplitude (strain) and the damper performance. The loading amplitudes were: 3mm, 5mm, 7mm, 9mm, 11mm, 13mm, and 15mm. The test specimen was loaded at 3mm strain amplitude at different loading frequencies to study damper performance dependency on the loading frequency. The test specimen was tested at 0.5 Hz, 1.0 Hz, 1.5 Hz, and 2.0 Hz.

Table 1. Test Protocol

Condition	Amplitude(mm)	frequency(Hz)	Temperature	cycle
Amplitude	3,5,7,9,11,13,15	1.0	20°C	4
Frequency	3	0.5, 1, 1.5, 2	20°C	4

5 Test Results and Analysis

There was no obvious change in the test specimen, and the viscoelastic body and the steel plate were intact after loaded in various test conditions.

5.1 Damper property related to amplitude.

The shear storage modulus (S_s) is defined as the ratio of stress at the peak strain to peak strain of the damper, which reflects the elastic performance of the damper in a shear deformation, and used to measure the energy stored during each cycle loading. The shear loss modulus (S_L) is defined as the ratio of the stress corresponding to zero displacement to the peak strain in the hysteresis loop. Shear loss modulus (S_L) reflects the viscous characteristics of the damper and is used to characterize the energy dissipation during loading cycle. The loss factor is defined as the ration of shear loss Modulus to shear storage modulus. The loss factor is the main indicator to measure the energy dissipation capacity of viscoelastic dampers.

The viscoelastic damper was subjected to the amplitude of 3, 5, 7, 9, and 11 mm at 20 degrees centigrade to analyze the correlation between damper properties and loading amplitudes. The relationship curves of shear storage modulus, shear loss modulus, loss factor, energy dissipation and loading amplitudes are shown in Figure 4a~4e.

Test result as shown in Figure 4e, the load-deformation hysteresis curve of the damper is stable and full, and the curve area increased as amplitude increases. The increase in the area of the curve show the increase in energy dissipated. Throughout the amplitude loading condition, the damper showed a stable performance. Figure 4a-4d, is obvious that damper properties are related to loading amplitude. As loading amplitude increases, there is a decrease of shear storage modulus, shear loss modulus and loss factor.

4.a. Shear storage modulus

4.b. shear loss modulus

4.c. Loss factor

4.d. Dissipated energy

5.a. Shear storage modulus

4.e. hysteresis curve

5.b. shear loss modulus

5.c. Loss factor

5.2 Damper property related to frequency

The damper was loaded with a sine wave of 0.5Hz, 1.0Hz, 1.5Hz, and 2.0Hz at a loading amplitude of 3mm at 20 degrees centigrade. Figure 5.e shows the load-deformation hysteresis curve at the different loading frequencies. Figures 5a~c respectively presents the shear storage modulus (S_s), the shear loss modulus (S_L) and the loss factor D . Figure 5.d shows energy dissipated. Test results show that shear storage, shear loss modulus, loss factor and dissipated energy increases as frequency increases. However, Shear storage and loss moduli increase very fast at frequency less than 1Hz after that start to increase slowly.

5.d. dissipated energy

5.e. hysteresis curve

6 CONCLUSION

The experimental research of small size viscoelastic damper demonstrates that hysteresis curve under different loading amplitude and frequency are stable, good energy dissipation capability. Test result showed that small size damper subjected to an increasing amplitude will experience relatively a constant shear storage and shear loss modulus and loss factor decreases as amplitude decrease.

The experimental research demonstrates that small size viscoelastic damper subject to a changing frequency have a stable performance. Mechanical property such as Shear storage, Shear loss moduli and loss factor increase as frequency increases. The increase in shear and loss modulus increase from 1.54GPa at 0.5Hz to 2.24GPa at 1.5 Hz and 0.82GPa at 0.5 Hz to 1.45GPa at 1.5Hz respectively but when reaches 1.5Hz, the increase is too small, where there is an increase up to 2.26 at 2Hz for shear storage and increase up to 1.51GPa at 2.0Hz for shear loss modulus, Loss factor shows a fast increase between 0.5Hz to 1Hz and then show a very slow increase up to 2Hz. Generally, the test results showed a stable

hysteresis curve which justify good energy dissipation capacity.

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