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Performance of low-cost viscoelastic damper for coupling adjacent structures subjected dynamic loads

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ABSTRACT

The application of viscoelastic material to reduce the vibrations of various structures has been interest of many researchers from past three decades. The viscoelastic material as a damper has gained popularity for mitigating the vibrations induced on buildings due to wind or earthquake forces. Despite many viscoelastic damper models are proposed for seismic protection of buildings, still its application is not widely spread in developing countries. Hence, this study focuses on modelling and fabrication of viscoelastic damper using locally available natural rubber. A systematic and detailed analysis on the performance of fabricated damper to reduce the vibrations in buildings is carried out. For this purpose, fifteen story adjacent similar buildings are connected with viscoelastic dampers. The performance of natural rubber based viscoelastic damper to improve the seismic performance of buildings is compared with that of 3 M Viscoelastic damper. Time history analysis of buildings with and without dampers is carried out under strong ground motion record. The top story time history response of displacements values indicates that, these natural rubbers based viscoelastic dampers when coupled with adjacent similar buildings reduces the seismic response significantly.

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1. Introduction

In mechanical devices, two types of structural control systems are found i.e. passive and active control devices. Active control devices require a constant supply of power to actuate the dampers and therefore can be unreliable especially during events of earthquake where there are high chances of power disruption. On the other hand, passive control devices have gained popularity as special systems that can be assimilated within the structure to dissipate induced vibration energy. Passive energy dissipating devices does not require an input power supply. Today, there are different types of passive damper devices are manufactured to achieve various levels of damping and stiffness by using variety of materials. Some of these include viscoelastic, viscous fluid, friction and metallic yield dampers. The viscoelastic (VE) damper is one of the simple and effective passive control devices, which consists of a viscoelastic polymer sandwiched between metal plates attached by epoxy. Past research [1–3] has focused on characterization of VE material properties using a series of harmonic tests at different frequencies, strain amplitudes, and temperatures. The application of VE materials for vibration control has started from past two decades. The study on scaled steel structure shows that, the added VE dampers are very efficient in decreasing the undue vibration of the system due to earthquake excitation [4]. Further study [5] showed that the effectiveness of a viscoelastic damper is more than viscous damper under strong ground motion. The advantage of viscoelastic dampers over fluid dampers is that its added stiffness helps the structure to behave elastically under seismic loads [6]. The fatigue analyses of VE dampers subjected to dynamic loading has been carried out [7,8]. Also, VE dampers were added in the structures to effectively reduce the dynamic response. The effectiveness of VE damper device is experimentally studied on the performance of a steel frame with under earthquake excitation [9]. Coupling of two dissimilar adjacent buildings with viscoelastic dampers has been proposed to decrease earthquake vibration of both the buildings [10]. The performance of VE damper as a connecting link between fixed-base and base-isolated buildings is found to be more significant in comparison to connection between both base-isolated buildings. Also, the torsional vibration of plan

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asymmetric structures with added viscoelastic dampers are carried out through experimental and analytical studies [11]. The optimal placement of VE dampers are capable of achieving control of the torsional response of asymmetric structures. The coupled technique for adjacent dissimilar buildings, strengthening of existing buildings by d connecting different viscoelastic dampers are studied [12]. The performance of VE damper with varied ambient temperature and operating frequency can be properly simulated using higher order fractional derivative model [13], with different VE materials. Similarly, circular type of viscoelastic damper has been used in a structural application to improve the seismic performance [14]. Recently, VE dampers were used in new buildings and to retrofit old buildings for reducing structural response and dissipate seismic energy during an earthquake [15]. In spite of many VE damper models are proposed for seismic protection of buildings, still its application is not widely spread in developing countries. Hence, this study focuses on modelling and fabrication of viscoelastic damper using locally available natural rubber. A thorough and methodical examination on the performance of fabricated damper to reduce the vibrations in buildings is carried out. For this purpose, fifteen story adjacent similar buildings are connected with viscoelastic dampers. The performance of natural rubber based viscoelastic damper to improve the seismic performance of buildings is compared with that of 3 M Viscoelastic Damper. The mechanical properties of 3 M Viscoelastic Damper material are taken from previous study [16].

2. Viscoelastic damper (VE)

These damper devices comprise of VE material having both viscosity and elasticity characteristics. VE dampers are capable of dissipating energy even at small levels of vibration as well, as they are linear in their behavior under small displacements. Perhaps, one shortcoming of VE dampers is that the ambient temperature will affect their performance. The information on the mechanical properties of viscoelastic material is very much essential for the design of VE damper. The polymer materials class is massive with families of products namely natural rubbers, synthetic rubbers, the plastics and the adhesives. The composition and production process involved in manufacturing of these polymers will greatly affect the damping and stiffness properties of VE material. These properties depend on storage and loss modulus of VE material, which are obtained though dynamic mechanical analysis.

2.1. Dynamic mechanical analysis

The dynamic mechanical analysis of test piece was carried out using TA instrument (DMA Q800). Natural rubber samples were molded to specimen dimension of 20 mm × 8 mm × 5 mm. The samples were tested using shear mode to obtain the shear and loss modulus. On commencement of the test, the temperature was increased at the rate of 3 °C/min. Samples were subjected to sinusoidal load at a frequency of 0.1 to 4 Hz with an amplitude corresponding to a strain of 2% and 5% using temperature sweep mode from room temperature to +43 °C. During the test the viscoelastic spectrum of natural rubber is captured through measurement of storage modulus G_1, loss modulus (G_2) as a function of temperature as shown in Fig. 1. From the figure it is observed that, the loss modulus is not varied much with different strain levels but the storage modulus is varied slightly. However, the considerable variation in storage modulus and slight variation in loss modulus is observed with respect to forcing frequency. Hence, operating range of frequencies is very important for getting the average value of storage and loss modulus.

In present study, the efficiency of proposed viscoelastic damper is evaluated with buildings subjected to El Centro ground motion. For an El Centro ground motion the predominant frequencies are in the range 0.4–6 Hz. By considering the operating range of temperature to be 24 °C to 34 °C, the storage and loss modulus values between operating frequency range of 1–4 Hz are listed in Table 1. The corresponding average values of storage and loss modulus of natural rubber is given in Table 2. This table also presents the comparison of storage and loss modulus of 3 M Viscoelastic Damper [16] within the same frequency and temperature range. Also, the loss factor for both the materials are indicated in the Table 2. Higher the loss factor, higher will be the energy dissipation.

2.2. Properties of VE dampers

A typical VE damper configuration with two layers of VE material bonded between three steel plates is shown in Fig. 2. Based on the physical and geometric properties of VE material, the damping and stiffness values of damper can be obtained as follows:

$$\text{The VE stiffness is,}\ k_d = \frac{n_v G_1 A_v}{h_v} \tag{1}$$

$$\text{The VE damping is,}\ c_d = \frac{n_v G_2 A_v}{\omega h_v} \tag{2}$$

where G_1 is the storage modulus, G_2 is the loss modulus, n_v is the number of VE layer, ω is the excitation frequency, h_v and A_v are the thickness and the area of VE layer respectively. For example (Fig. 2), by considering each layer of natural rubber material with 10 mm thickness and 150 cm^2 in area, the stiffnessk_d = 3900 kN/m and the damping c_d = 92.5 kN-sec/m values are obtained under excitation frequency of 1.23 Hz using Eqs. (1) and (2).

3. Application of dampers and numerical investigations

Two dynamically similar fifteen storey RC buildings are considered in this study as shown in Fig. 3. The earthquake (El Centro, 1940) ground motion is applied along the lateral direction. Both the buildings are assumed to be on the same floor level. The spatial variation of the ground motion is neglected in the study, assuming that the buildings are close to each other and at the same time sufficient distance is available between the buildings for the damper installation. Both the buildings are assumed to be built on a rigid foundation and hence the soil structure interaction effect is neglected. As the buildings are dynamically similar to the effect of pounding during the earthquake is not considered. The time history analysis is done using the numerical technique (Newmark-beta method) to find out the response for the building with connected VE dampers.

3.1. Mathematical model

The analysis is carried out by considering the lumped mass system. Both the buildings are dynamically similar. The number of the story in each building 'n' represents the number of the DOF in the analysis as shown in Fig. 3. The installation of the dampers in an unsymmetrical way introduces the changes in the response of both the buildings. Hence. the horizontal displacement at the top floor of both the buildings is considered for response reduction. The total degree of freedom is '2n' for the dynamically similar coupled buildings. The floor of the building is assumed to be rigid and hence the mass of the slab alone is being considered in the shear building concept. The mass of the columns is considered to be negligible as compared to the floor mass and hence, the mass of

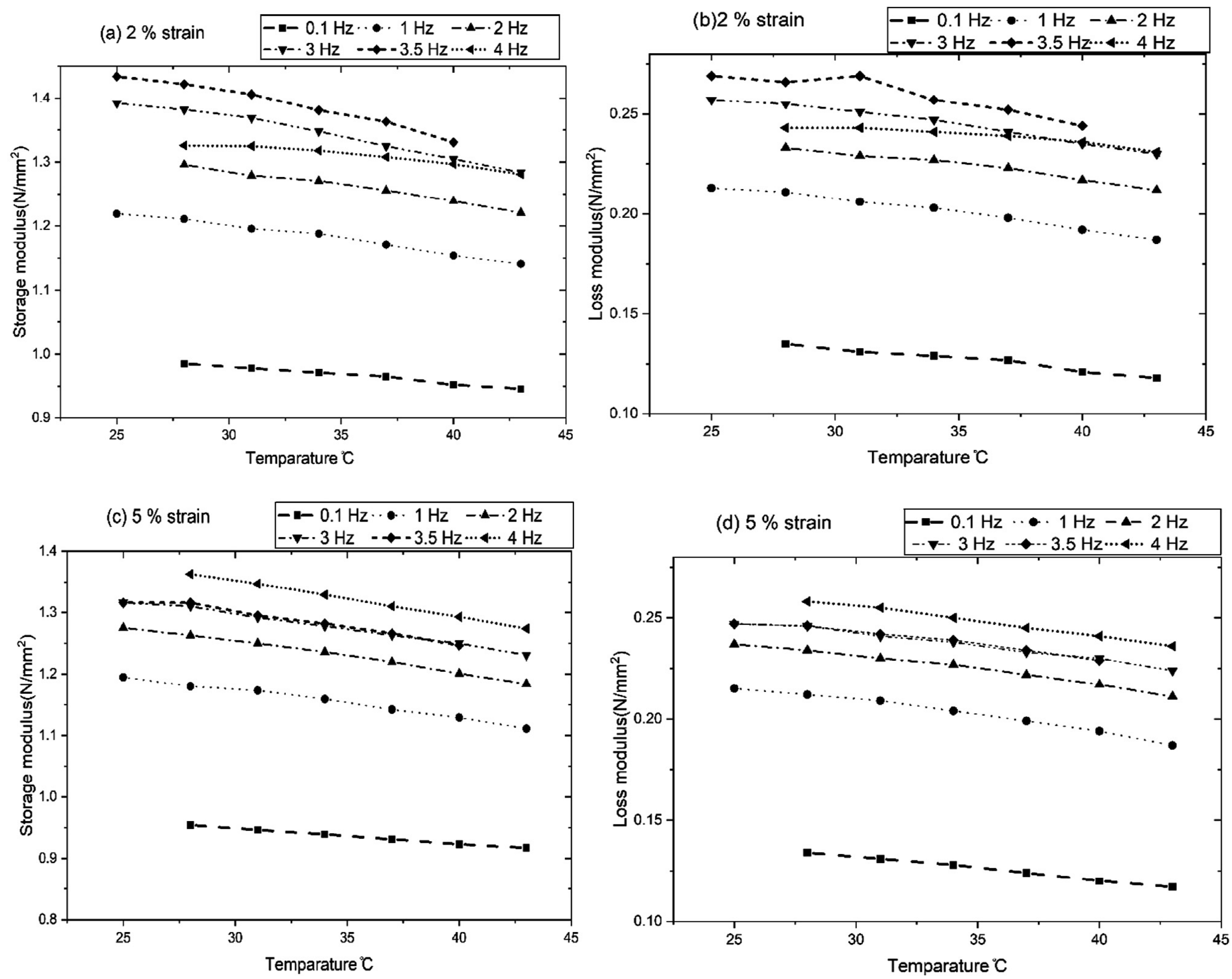

Fig. 1. DMA test data for natural rubber.

Table 1
DMA test data at working temperature.

Strain (%)	Freq Hz	1		2		3		3.5		4	
	Temp	G_1	G_2	G_1	G_2	G_1	G_2	G_1	G_2	G_1	G_2
2%	25	1.22	0.21	–	–	1.39	0.26	1.43	0.27	–	–
	28	1.21	0.21	1.30	0.23	1.38	0.26	1.42	0.27	1.33	0.24
	31	1.20	0.21	1.28	0.23	1.37	0.25	1.41	0.27	1.33	0.24
	34	1.19	0.20	1.27	0.23	1.35	0.25	1.38	0.26	1.32	0.24
5%	25	1.20	0.22	1.28	0.24	1.32	0.25	1.32	0.25	–	–
	28	1.18	0.21	1.26	0.23	1.31	0.25	1.32	0.25	1.36	0.26
	31	1.17	0.21	1.25	0.23	1.29	0.24	1.30	0.24	1.35	0.26
	34	1.16	0.20	1.24	0.23	1.28	0.24	1.28	0.24	1.33	0.25

Table 2
Damping and stiffness coefficients of VE material.

Type of VE Material	G_1, N/mm^2	G_2, N/mm^2	$\eta=\frac{G_2}{G_1}$, loss factor
Natural Rubber	1.2987	0.2385	0.183
3 M Viscoelastic [16]	0.883379	0.717087	0.811

columns is neglected. Then, the mass matrix will be a diagonal matrix with the mass of each floor as given below.

$$\text{Mass matrix is } [m] = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & m_n \end{bmatrix}$$

$$\text{and the Stiffness matrix is } [k] = \begin{bmatrix} k_1+k_2 & -k_2 & 0 & 0 \\ -k_2 & k_2+k_3 & -k_3 & 0 \\ 0 & -k_3 & \ddots & -k_n \\ 0 & 0 & -k_n & k_n \end{bmatrix}$$

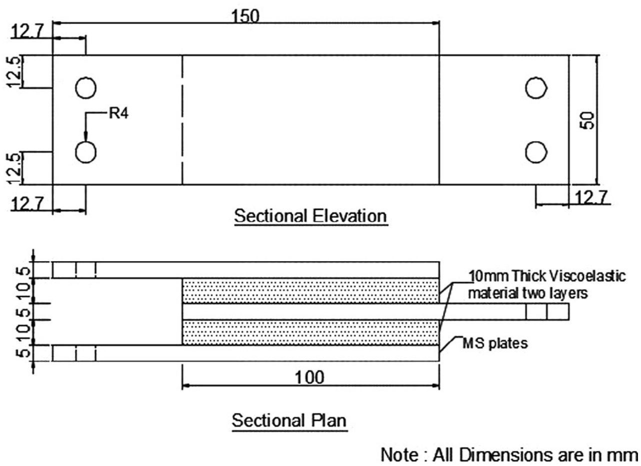

Fig. 2. Typical viscoelastic damper with geometric dimensions.

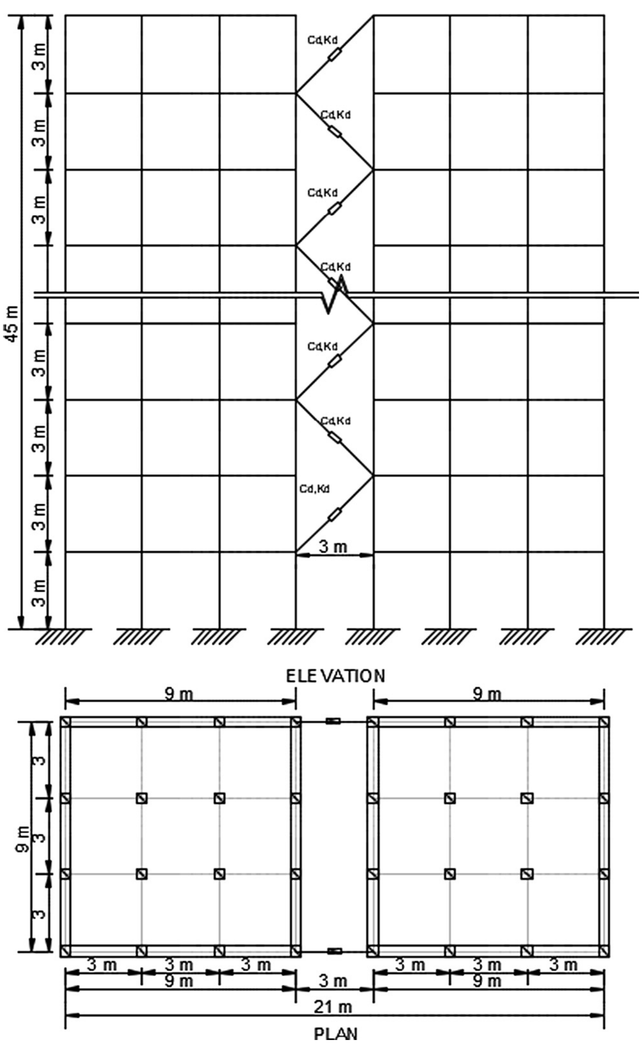

Fig. 3. Dynamically similar Fifteen storey RC buildings.

where, $k_1, k_2 \ldots, k_n$ are stiffness of each floor and $m_1, m_2 \ldots, m_n$ are mass of each floor. After obtaining the mass and stiffness matrices, through the characteristic equation the natural frequency and mode shapes are obtained. Internal damping matrix which indicates about the equivalent viscous damping of the building is obtained through the Rayleigh damping by considering damping ratio as 5%. As the building considered is symmetric, the internal damping matrix is a proportional damping matrix. The function of the proportional damping is energy dissipation only. Rayleigh damping matrix of the single uncoupled building is $[c] = \alpha[m] + \beta[k]$. Where, α and β are the mass proportional coefficient and stiffness proportional coefficient. External damping matrix for the coupled building is formed through the non-classical approach. For non-proportional damping both energy transfer as well as energy dissipation occurs.

3.2. The equation of motion for the coupled system

The equation of motion of the coupled system is given by

$$M\ddot{X} + (C + C_d)\dot{X} + (K + K_d)X = -MI\ddot{x_g} \tag{3}$$

where, $[M] = \begin{bmatrix} [m] & [0] \\ [0] & [m] \end{bmatrix}$ is the mass matrix, $[K] = \begin{bmatrix} [k] & [0] \\ [0] & [k] \end{bmatrix}$ is the stiffness matrix, $[C] = \begin{bmatrix} [c] & [0] \\ [0] & [c] \end{bmatrix}$ is the damping matrix of the coupled building. Here, K_d and C_d are the stiffness and damping matrix of VE dampers. Depending on the dampers configuration and connection provided between the two buildings, the C_d and K_d matrices has to be formulated. Further, I = unit vector, $\ddot{x_g}$ = earthquake ground acceleration. From the previous study [17] on various damper configurations using connected control technique for similar buildings subjected to earthquake, the alternate diagonal connection has proved to be best. Hence in this study, the alternate diagonal damper connection as shown in Fig. 4 is considered.

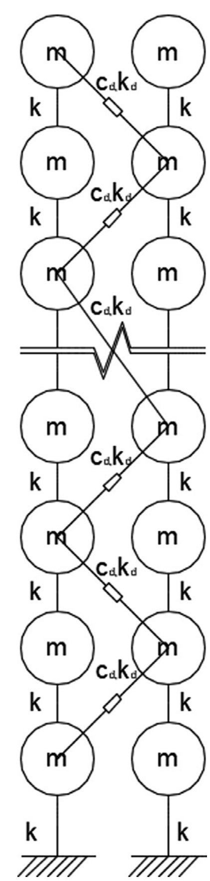

Fig. 4. Mathematical model of dynamically similar adjacent buildings.

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Table 3
Stiffness and damping values of dampers used.

Type of Damper	Area, cm^2	Thickness of each layer (mm)	K_d, kN/mm	C_d, kN-sec/mm
Natural Rubber	25,000	10	649	15.4
3 M Viscoelastic	25,000	10	442	46.4

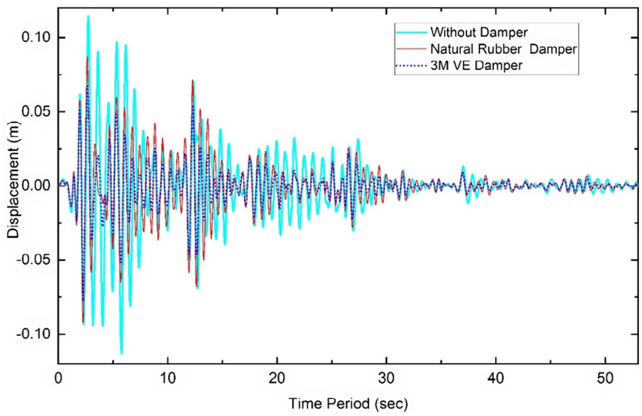

Fig. 5. Top story displacement of adjacent buildings.

4. Results and discussion

Viscoelastic dampers connected to the adjacent buildings in alternative diagonal manner is studied subjected to earthquake. The time history analysis of buildings without and with dampers is performed subjected to El centro ground motion record. The stiffness and damping values required at each floor level of the buildings are obtained by considering excitation frequency to be at fundamental frequency (1.23 Hz) of building as shown in Table 3. These values are obtained based on trial and error procedure [17] to get the effective response reduction in buildings. Considering the thickness of viscoelastic material as 10 mm, the area VE material for damper required is obtained using Eqs. (1) and (2). Area of VE damper can further be divided amongst the number of dampers at each floor level. Schematic representation of the position dampers between buildings in plan and elevation is shown Fig. 3 by considering two dampers between each floor level.

The time history analysis is carried out on buildings without and with dampers subjected to earthquake. The top floor displacement time response of buildings connected dampers compared to that of without dampers is shown in Fig. 5. The results clearly demonstrate that the integration of dampers to buildings reduces the peak displacement of the structure, under seismic loads. Further, it can be seen that 3 M viscoelastic material reduces the peak displacement by 30% while the natural rubber reduces by 20% approximately. The higher reduction in case of 3 M material is due to its high loss factor. However, the point should be noted that with naturally available rubber material as damper, considerable response reduction is archived for same shear area as 3 M damper. Further, the higher value for loss factor of natural rubber can be achieved by varying its composition.

Hence, the application of natural rubber as VE damper can become economical solution for seismic protection of buildings in developing countries.

5. Conclusions

The application of natural rubber as a viscoelastic material to reduce the vibrations of buildings has been studied with conclusions:

a. The 3 M viscoelastic damper out performs the natural rubber damper in reducing the vibration level of buildings due to its high loss factor.
b. The natural rubber based VE dampers will considerably reduce the seismic response of structures compared to the 3 M damper with same shear area leading to economical solution.
c. The use of locally available natural rubber as VE damper can be an economical solution for seismic protection of buildings in developing countries.

The efficiency of natural rubber to reduce the seismic response of building can further be increased by varying its composition to increase its loss factor. Therefore, further study can be continued with variation in composition of natural rubber at cheaper cost through local manufacturers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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