Comparison of energy dissipation devices in response reduction of blast-induced vibration of buildings

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Abstract

Vibration control of structures subjected to wind and seismic forces has been widely studied. However, the focus on vibration control of structures against underground blasts is restricted. The ground motion caused by the blast is modelled in this study by an exponentially decaying function illustrative of an ordinary rock impact. The impact of the different parameters on execution is analyzed in the time domain by considering a sensible five-story example building using FORTRAN, Origin, and MS-excel. Two devices considered in the current study are viscoelastic damper and viscous damper. The result shows that the viscous system is exceptionally powerful in lessening both the maximum structural acceleration and displacement due to the underground blast-induced ground motion.

1 Introduction

In recent years, development of structural control devices is at a fast pace, and we have many control devices installed in a wide variety of structures [3]. Among the suggested systems, energy dissipating devices, base isolators, and active and hybrid methods are some of them. These proposed devices are capable of reducing inter-story drifts and thus reduces the damages. A parametric study has been carried out of steel chevron braced frame system equipped with and without viscoelastic damper subjected to a seismic load [2]. Passive energy dissipation systems do not require any additional source to operate and are activated by seismic input motion as they dissipate energy through by yielding of metals, phase transformation in metals, friction sliding, deformation of viscoelastic solids or fluids and fluid orifice [1]. Devices such as viscoelastic damper consist of viscoelastic layers bonded with steel plates with viscous materials such as co-polymers or glassy substances. The energy is dissipated in the form of shear deformation when mounted on a structure, and they are highly dependent on ambient temperature and frequency excitation.

A viscous damper generally consists of a piston in the damper housing filled with a compound of silicone or similar type of oil and the piston may contain a number of small orifices through which the fluid may pass from one side of the piston to other. Hence, the dissipation of energy during ground motion occurs via conversion of mechanical energy to heat as the piston deforms the thick and highly viscous substance, i.e., silicone gel or similar type of oil, using the concept of fluid orificing. The total input energy for the above cases will be distributed in the form of kinetic energy, potential energy and dissipated energy (through heat) depending on the structural properties.

Ground vibrations induced by underground explosion might cause damage to nearby structures. The most important parameters for explosion ground motion that affect structural responses are its intensity and frequency content [4, 7]. Because of the complexity of blast design parameters and rock mass parameters, it is difficult to develop a general equation. The peak particle velocity (PPV) is accepted as a principal parameter for vibration measurement. Numerical studies reveal that the New Zealand type base isolation system is highly effective in reducing both the underground blast-induced structural acceleration as well as the displacement [8]. However, studies on vibration control of structures against underground blasts are limited. It is thereby important to study the usefulness of established vibration control technologies in the blast resistant design of structures. This paper reviews various energy dissipation systems and their application to building structures for response control.

The effectiveness of viscous damper to control response of a lateral load resisting frame subjected to blast-induced ground motion are discussed [11] in three different steps. These steps are (a) development of blast loading time history, (b) applications of fluid viscous dampers, and (c) performance comparisons of a conventional steel building frame with or without dampers. Simulation results indicate that fluid viscous damper provides a cost-effective way to improve the performance of building frames under blast loading greatly.

2 Modelling of blast-induced ground motion

In the present study, the Blast Induced Ground Motion (BIGM) generated typically from an underground explosion is modelled by an exponentially decaying function [12]. The blast loading on the structure, $F(t) = [M]\{1\}\ddot{y}_g(t)$is obtained from the blast-induced ground acceleration, $\ddot{y}_g(t)$, as expressed by

$$\ddot{y}_g(t)=(-1/t_d)y_g(t)e^{(t/td)} \tag{1}$$

Where $y_g(t)$ is the PPV and $t_d = 0.25(R/C_p)$ is the arrival time. R and C_p denote the distance to the charge centre and propagation velocity of the wave in soil or rock, respectively [6].

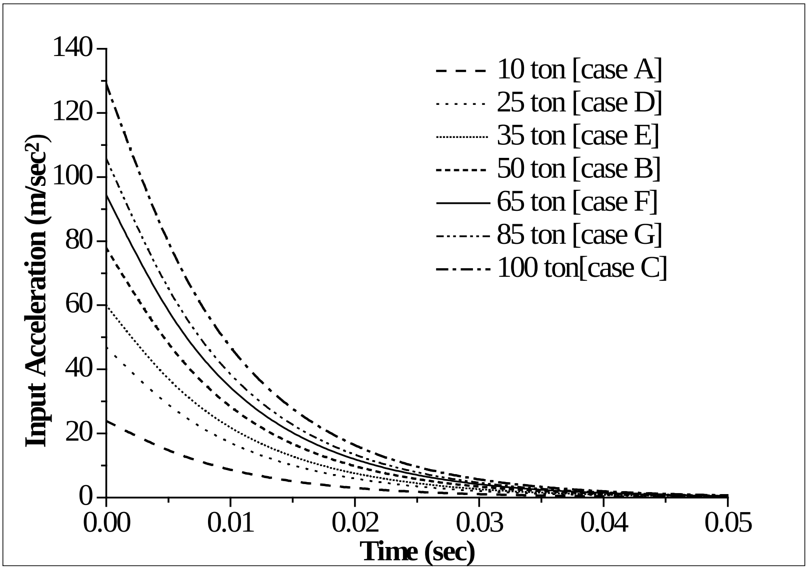

Fig. 1 Input acceleration time history.

The value of PPV is computed from the empirical attenuation relation available in the literature [9]. The resulting ground accelerations from other blast input are shown in Fig 1. The PPV of the three types of input motions (Cases A, B and C in Fig. 1) is calculated as 23.89 cm/s for 10 tons, 77.9 cm/s for 50 tons, and 128.96 cm/s for 100 tons respectively.

3 Description of Example Structure

The most crucial component in seismic design of structures with energy dissipation systems is realistic modelling of friction forces. The experimental model shown in Figure 7 of literature [13] is being used here for further analysis subjected to blast-induced ground motion, and all the dimensions are kept same. In Fig 2, a five-storey steel frame mounted on two heavy base floor girders that are supported by four rubber bearings resting on load cells. The load cells are anchored to the shaking table with high-tension stress rods. The model can be considered as a section through the weak direction of a typical frame structure at a scale factor of approximately one third. The dead load provided by concrete blocks, which are tied down to the frame at various floor levels, is kept constant at each level [13]. The mathematical formulation of multi-degree-of-freedom (MDOF) frame structure with supplemental damping system mounted on Chevron brace has been used in this study. Each floor of the building has two degree-of-freedoms: horizontal displacement of the storey and the brace with damper relative to the ground. The mass, stiffness, and damping coefficient of each floor are kept constant in this study, and the associated values are adopted from literature [11].

Fig. 2 Experimental model of five-storey steel frame adopted from literature [13].

Table 1 Structural Parameters.

Floor no	Floor mass [Kg]	Stiffness coefficients [kN/m]	Damping coefficients [kN s/m]
1	5897	33732	67
2	5897	29093	58
3	5897	28621	57
4	5897	24954	50
5	5897	19059	38

4 Solution procedure

For obtaining the numerical solution, an appropriate non-linear solution technique can be adopted. Among the many methods, one of the most effective is the step-by-step direct integration method. This problem is solved by modification of step-by-step linear acceleration method. For obtaining accuracy in the solution process, the selected time interval is subdivided, whenever a change in phase of motion is anticipated. These can be possible for single point sliding system. But for multi-point sliding system this will be very complex. In this solution process, the response is evaluated at successive increment Δt (10^{-4}second) of time for computational convenience. The condition of dynamic equilibrium is established at the commencement of each interval.

The generalized governing equations of motion for a structure with viscoelastic or viscous damper, in matrix form, can be given as:

$$M\ddot{u} + C\dot{u} + Ku = -Mr\ddot{u}_g \qquad (2)$$

Where M, C, and K are the mass, damping and stiffness matrices, respectively, r is the force-influence vector, u represents the displacement degrees of freedom relative to the base of the structure and $\ddot{u}_g$ is the ground displacement. The over dot represents derivatives with respect to time.

5 Performance indices

Three dimensionless performance indices have been considered to characterize the efficiency of dampers. All these indices are defined as the ratios between the peak values of a certain response quantity (displacements, acceleration, base shear) of the frame with dampers, and the peak value of the same responses of the free or braced frame structure without dampers. Consequently, these indices are dimensionless and always positive with their value range usually between zero and unity. Values close to zero indicate excellent performance of the dampers in reducing the response while higher values close to one indicate ineffectiveness of the dampers [5]. All the performance indices have been normalized with respect to both the free frame and the braced frame structures. This enables assessment of response reduction and performance enhancement of the structures with dampers including the influence of stiffness of the bracing system.

The response of the example structure with viscoelastic damper has been investigated for target equivalent damping ratio of 30%, *i.e*., 5% structural damping and 25% supplemental damping.

However, in case of the viscous damper, the damper stiffness is considered to be negligible. The damping coefficient of the viscous damper is assumed to be 4 kN.sec/m for calculation. The equivalent stiffness and damping coefficient of dampers is calculated for both the devices using the available expressions [10].

6 Behaviour of the example structure with dampers

The maximum inter-story drift, floor displacement and the maximum absolute acceleration for the example structure are evaluated at each story level subjected to the ensemble of different blast-induced ground motions with various damping devices. Since the prime objective of the frame buildings with energy dissipation system is to reduce the peak responses, the investigations of maximum responses enable one to evaluate the effectiveness of the dampers.

Fig. 3 shows that the inter-storey drift of structure with viscoelastic damper can be reduced by 50% to 70% of the peak inter-storey drift at first, second, third and fourth storey and up to 80% in the top storey with respect to free frame structure response for case A type of blast-induced ground motion. However, when compared to brace frame, it is seen that the maximum inter-story drift has been reduced for all the floors except first and second-floor level. This may be attributed to the high-frequency response of the viscoelastic model.

Fig. 4 shows that the inter-story drift of structure with viscous damper can be reduced by 55% to 85% with respect to free frame structure response for Case A types of BIGM. This reduction is in the range of 20% to 70% when compared with the braced frame. The maximum absolute acceleration of the structure with viscous damper can be reduced by over 20% to 35% of the absolute peak acceleration of free frame structure, and when compared with braced frame response overall 65% reduction was observed.

The steel flanges of the damper are connected to the roof beam, and the centre plate is connected to the chevron brace such that the displacement is allowed along the horizontal direction. Therefore, when the structural vibration induces relative motion between outer flange and centre plate, shear deformation in viscoelastic damper occurs and hence energy dissipation takes place. In Fig 5, a comparison of maximum inter-storey drift response of the example building frame with visco-elastic damper and the viscous damper is done when subjected to 10 ton and 100 ton of blast-induced ground motion. From this comparison, it can be concluded that viscous damper is more effective to reduce the drift response in all floor level of the example frame

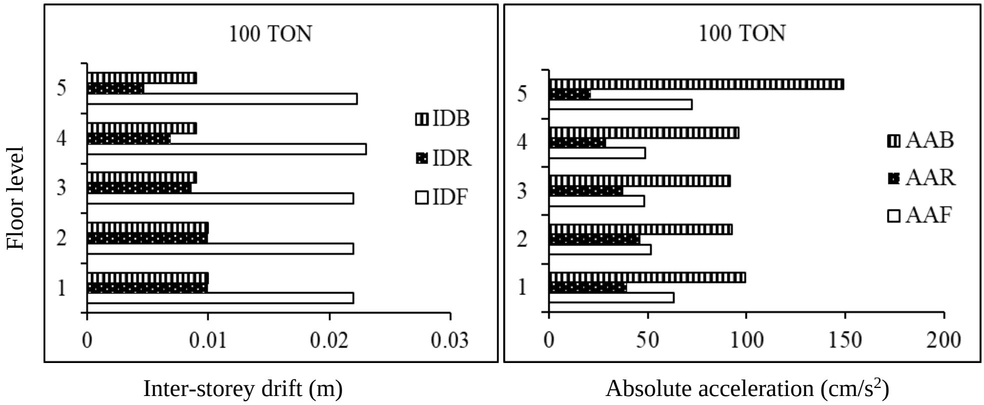

Fig. 3 Maximum inter-story drift (m) and Maximum absolute acceleration (cm/s^2) response of the example structure floor wise with Visco-elastic damper subjected to 100 tons of blast-induced ground motion. (B - Braced frame, R - viscous device and F - free frame)

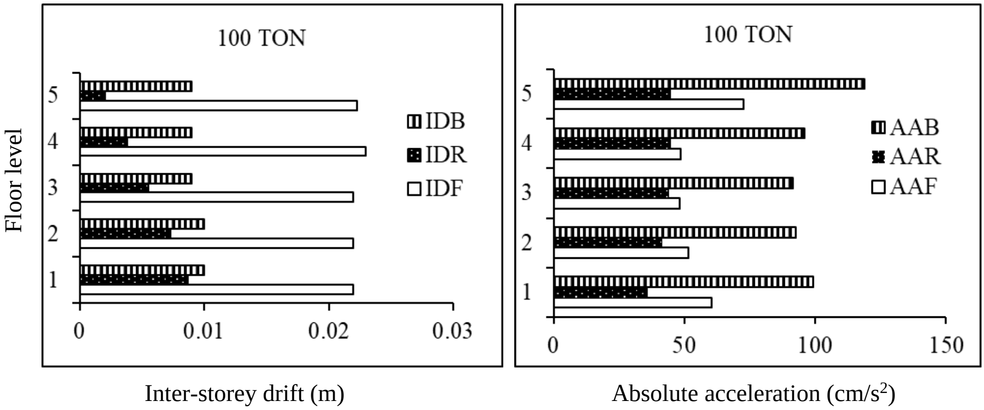

Fig. 4 Maximum inter-story drift response (m) and Maximum absolute acceleration response (cm/s^2) of the example structure floor wise with viscous damper subjected to 100 ton of blast-induced ground motions. (B - Braced frame, R - viscous device and F - free frame).

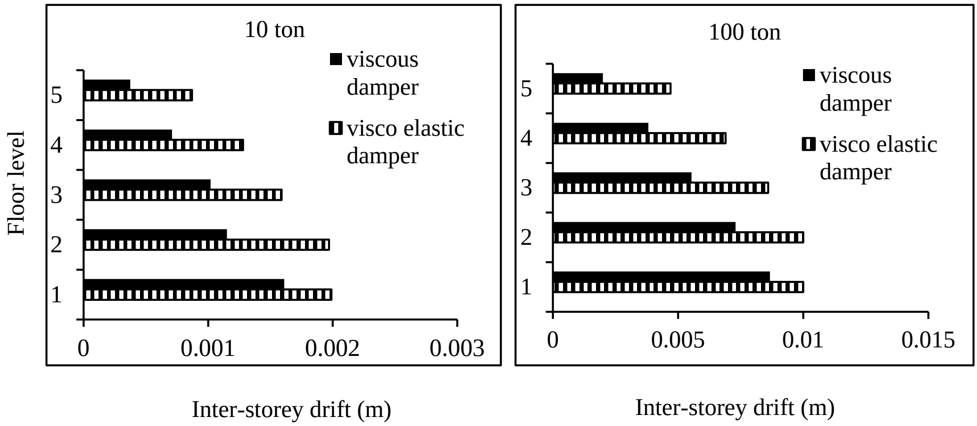

Fig. 5 Maximum floor wise displacement response of the example structure with various dampers subjected to 10 tons and 100 ton of blast-induced ground motions.

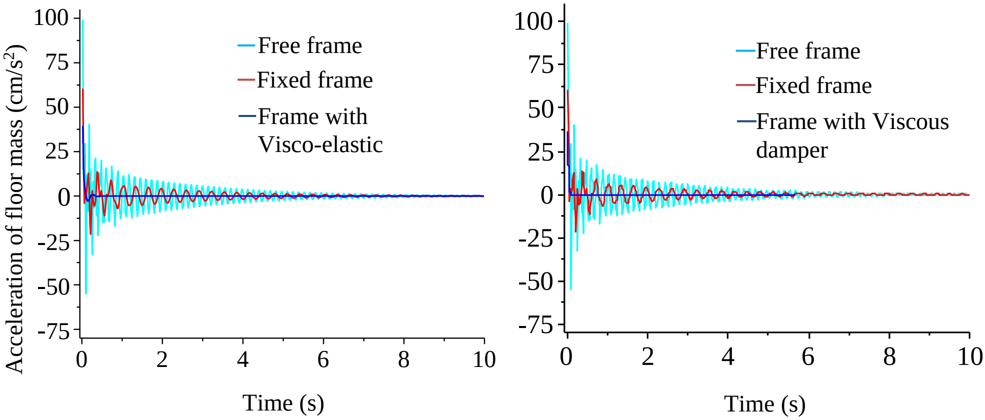

Fig. 6 Absolute acceleration at the first floor level of the example structure with various dampers subjected to 100 ton of blast-induced ground motion.

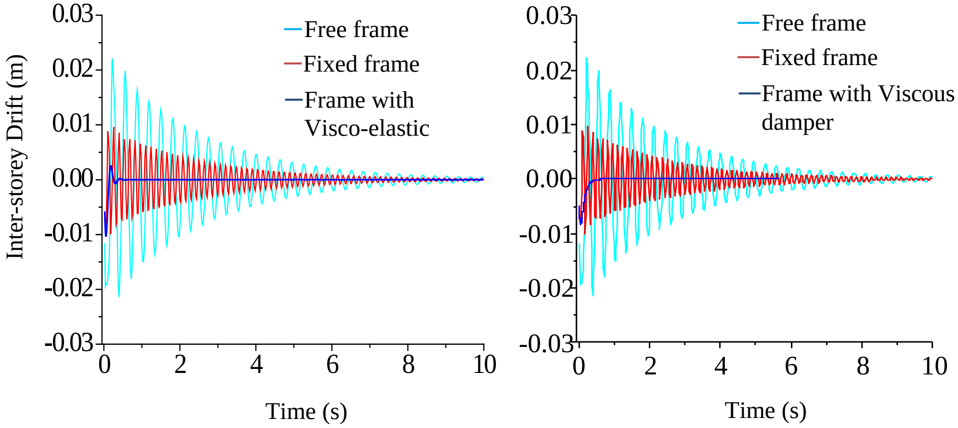

Fig. 7 Inter-storey drift response at the first floor level of the example structure with various dampers subjected to 100 ton of blast-induced ground motion.

Typical time-history response, i.e. absolute acceleration, inter-storey drift of example structure subjected to case C (100 ton) blast-induced ground motion are plotted for the free frame, fixed frame and frame with considered dampers as shown in fig 6 and 7 at first floor level of the example frame. The viscous damper is observed to be more effective in controlling the peak inter-storey drift and maximum absolute acceleration when compared to a visco-elastic damper for the Case C type of blast-induced ground motion at first floor level of the taken structure.

7 Comparison of results

In case of the viscoelastic damper, the floor displacement can be reduced by 35% to 55% whereas in case of viscous damper reduction is found to be 55% to 75% of the peak floor displacement of the free and braced frame structure (Fig. 5). It is observed that the base shear increases when bracings are added to the free frame structure. Addition of damper results in a decrease of base shear for all ground motions in comparison to both free fame and braced frame. Among the dampers, viscous dampers are found to be most effective in reducing the base shear of the structure in comparison to both.

A comparison of base shear, inter-story drift (first-floor level) response and absolute acceleration (first-floor level) response of the example structure is presented in Tables 2-4.

Table 2 Base shear of example building when subjected to an ensemble of BIGM.

Ground Motions	10 TON	50 TON	100 TON
Free Frame	140.59	458.94	758.98
Braced Frame	314.17	1024.54	1695.99
Frame with Viscoelastic damper	180.25	611.25	1000.12
Frame with Viscous damper	121.55	396.40	656.19

Table 3 Inter story drift (first-floor level) of example building subjected to an ensemble of BIGM.

Ground Motions	10 TON	50 TON	100 TON
Free Frame	0.00415	0.0135	0.0224
Braced Frame	0.00186	0.0062	0.010
Frame with Viscoelastic damper	0.00199	0.0065	0.010
Frame with Viscous damper	0.00161	0.00524	0.00867

Table 4 Absolute acceleration (first-floor) of example building subjected to an ensemble of BIGM.

Ground Motions	10 TON	50 TON	100 TON
Free Frame	11.18	36.54	60.40
Braced Frame	18.41	59.99	99.34
Frame with Viscoelastic damper	6.8	23.8	39.51
Frame with Viscous damper	5.912	21.97	36.17

The base shear is decreased in the structure with a viscous damper by up to 30% in comparison to structure with viscoelastic damper. The inter-story drift at first floor level in the structure with viscous damping is reduced by 20% to 35% in comparison to structure with viscoelastic damper. The absolute acceleration response at first floor of the example building with viscous dampers has been reduced by 15% to 25% when compared to the viscoelastic damper. While the dampers are found to be effective in reducing the responses of the structure, the viscous damper is found to be superior to the viscoelastic damper in controlling the responses.

8 Conclusion

The effectiveness of energy dissipation systems in controlling the response parameters when compared to free frame and braced frame structure has been investigated in this paper for a 5-storey example frame structure. Based on the investigations presented in this paper, the following main conclusions can be drawn:

Adding stiffness to the frames by mean of bracings does not always solve the purpose of strengthening of stories. Although the introduction of bracings in the frames can control the drift response parameters, it increases the absolute acceleration and base shear responses of the frame.

The viscoelastic damper can reduce 25% to 60% of the inter-story drift and 20% to 48% of the absolute acceleration of example multi-story frame with respect to free and braced frame without damper under different blast-induced ground motions. The reduction of base shear, inter-storey drift, and absolute acceleration is found to be in the range of 33-70%, 35-75%, and 30-60 % respectively for the example frame with viscous damper. The viscous damper is found to be the most effective damper among the two dampers considered in this study for response reduction for all blast-induced ground motions. The effectiveness of these devices is found to be minimal in case of hard soil in comparison to soft and alluvium soil.

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