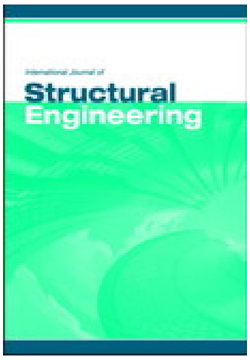

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Seismic response control of base-isolated structures with fluid inerter damper

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Seismic response control of base-isolated structures with fluid inerter damper

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Abstract: This study investigates the response of a multi-story base-isolated building with traditional bearings supplemented by fluid inerter dampers (FID). The structure is modelled as a multi-storey shear structure. The governing equations of motion of the multi-story isolated buildings with FID are derived and numerically integrated to obtain the seismic response. Following that, four recorded earthquake ground motions are applied, and various response quantities are evaluated. The response quantities of interest are base displacement and top floor acceleration. In this work, the effect of the ratio of FID inertance to total mass of isolated structures and the effect of the number of stories on the acceleration and displacement response of the structure are evaluated. The FID has indeed been found to be an effective supplemental device for traditional base isolated buildings in reducing their response during seismic excitations.

Keywords: fluid inerter dampers; FID; inertance; inertance ratio; shear building; seismic control; top floor acceleration; base displacements; bearings displacement; supplemental devices for base isolation.

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Biographical notes: Ashish R. Akhare is currently working as an Assistant Professor, Applied Mechanics, in the Department of Civil Engineering, College of Engineering Pune, India, with 17 years of experience. He was on deputation to the Indian Institute of Technology Bombay, India, to complete his PhD in Structural Engineering. He has authored many research papers in well-reputed national and international journals and conferences. He has taught many courses in structural engineering at the graduate and post-graduate levels and guided several BTech and MTech projects. His areas of interest include seismic control, vibration control, earthquake engineering, and structural engineering.

1 Introduction

Every year earthquake causes loss of human lives and property in and around the parts of the world. Basically, it's the ground acceleration which damages the structures and property causing devastating effects. To stop these seismic excitations, it can be possible to decouple the complete structure or part of it, or even some costly sensitive equipment's placed in the buildings. This concept is known as base isolation which is in practice since ancient time. The fixed base structure's fundamental frequency and the predominant frequencies of seismic excitations cause most of the damage to the structure. The base isolation of building shifts this fundamental frequency away from their damaging effects. An isolation system's other objective is to have an alternative means of energy dissipation, thereby lowering the transmission of ground acceleration into the superstructure. Many types of isolation systems are established and tested in laboratories in the recent times. The strategic buildings such as emergency management headquarters, pandemic control stations, fire control buildings, police stations, hospitals, barracks etc., shall be functional even after the event of earthquake. Hence, these tested isolation systems are widely used in such buildings. It is thus proved that isolation systems help in protecting the structures from the damaging effects of earthquake (Naiem and Kelly, 1999). Two types of the base isolation systems like rubber bearings (Derham et al., 1985; Jangid, 2008; Rahnavard and Thomos, 2019) and sliding bearings (Zayas et al., 1990; Soni et al., 2011) have been studied by various researchers. The seismic isolation is found to be much effective and efficient for the liquid storage tanks (Jadhav and Jangid, 2004, 2006; Panchal and Jangid, 2011, 2012).

Generally, it is the not necessary to completely provide 'full' isolation. In fact, in recent times, the most of buildings adopt only 'partial' isolation. The 'partial' in the sense denotes that the large portion of the force is transmitted to the superstructure, but the resultant responses of the building are reduced by adding the layer of the flexibility and a mechanism for the energy dissipation of the structure. The use of supplemental devices for base isolation can improve this partial method of seismic force mitigation. Inerters are one type of supplemental energy-dissipating device that is used to resist lateral forces in structures. Inerters aid in the reduction of column buckling, beam deflection, and structural rigidity. Inerters are used to reduce building vibration and deformation during earthquakes. As a result, inerter devices have recently been used as a supplemental device for earthquake response mitigation. Until recently, inerters were used to reduce vibrations in automobiles. However, according to a recent study, it can also be used to mitigate earthquake response. An inerter is essentially two terminal devices with a force across them proportional to their relative acceleration. According to a review of the literature, inerters have a wide range of applications in vibration suppression. It demonstrates the use of inerters with traditional bearings. On the other hand, the use of inerters as supplemental devices for seismic control of structures is urgently required.

The passive protection of the structures was done using base isolation only until recently, when an alternative to it was devised. As in modern motorcycles, car suspension work is modified with the help of a device called an inerter. Ideally, an inerter is a mechanical model component in which the force applied at the terminals is proportional to the difference in relative acceleration between them (Smith, 2002). Such devices are in use in automobiles, such as formula 1 racing cars, for vibration suppression. However, a recent study indicates that it can also be used for mitigating response during an earthquake. Basically, an inerter consists of the two-terminals across which the force is proportional to their relative acceleration.

An inerter helps in reducing the effects of vibration. Shen et al. (2016) correlated the two terminals of the inerter as spring and damper in base-isolated structures. In the models studied by Chen et al. (2009), it is discovered that the force applied on an inerter device is directly proportional to the relative acceleration of the two terminals. Hence it was then called as a two-terminal element. The spring, damper along with an inerter is studied by Chen et al. (2009) and Jiang et al. (2012). They did replacement of the mass element by the inerter in the 'force-current' analogy. There were experiments conducted to show that introducing the inerter into the tuned mass dampers, which were then known as tuned mass damper inerter (TMDI), can supplement the work of tuned mass dampers (TMD), and by doing so, lightweight passive vibration control is achieved. It is also proved that the inerter reduces the natural frequencies of the vibration system. In the recent past, base-isolated structures are supplemented with TMDI to prove the effectiveness and efficiency of the resulting system in controlling the seismic response of the base-isolated structures (De Domenico and Ricciardi, 2018a, 2018b; Di Matteo et al., 2019; Masnata et al., 2021). The ideal grounded linear inerter supplemented with TMDI is checked for assessing the control of displacement demands of the base-isolated structures in reference (De Angelis et al., 2019) and suggested the efficiency of TMDI in control of vibration. The TMDI if placed on the upper floors of the isolated structure, improves the performance in control of seismic response of base-isolated structure (Li et al., 2021).

Now-a-days, in many structural vibration control systems the inerter-based dampers are seen due to its effectiveness in seismic response control (Ma et al., 2021). The device having large mass enhancement effect with two-terminal inertial element is called as inerter. The property of the inerter is that its resisting force is directly proportional to the relative acceleration between the two terminals. The different researchers have studied these devices as dampers for its application in building structures (Hwang et al., 2007; Makris and Kampas, 2016; Wen et al., 2017; Makris and Moghimi, 2019). The building shows improvement in its performance. The single inerter is not so effective as that of the two parallel inerter devices with ratchet/clutching effects (Makris and Kampas, 2016; Wen et al., 2017; Makris and Moghimi, 2019). Applications of clutching inerter dampers in effective seismic control of the structures were demonstrated by Wang and Sun (2018), Málaga-Chuquitaype et al. (2019) and Li and Liang (2020). The inertial devices were used in base-isolated structures and found to be more effective (Pradono et al., 2008; Saitoh, 2012; Ye et al., 2019; Li and Liang, 2019). The nonlinear stochastic response analysis method is used for the seismic response control in buildings with the friction pendulum inerter system (FPIS) (De Domenico et al., 2020). According to the findings, the FPIS helps reduce response of the structure under various types of earthquake ground motion. The performance of a tuned inerter damper and the optimum parameters for controlling the seismic response of isolated structures are also studied (Jangid, 2021). Recently, fluid-inerters have been introduced instead of fly-wheel-based inerters. Fluid inerters use hydraulic resistance and inertial effects to suppress the vibration effects. It also possesses the properties of inherent damping, improved durability and simplicity of design. According to the above review, inertial devices are effective in controlling the response of structures. The FID has been discovered to be the most promising inertial device for controlling structural seismic response. The performance of the FID and the optimal design for base-isolated structures, on the other hand, have yet to be studied. Fluid-inerters have recently been introduced as an alternative to flywheel-based inerters.

A literature review indicates enormous applications of FID in suppressing vibration. It shows the use of conventional bearings with FID. However, the use of FID as supplemental devices for seismic control of the structures is the need of the hour. Hence, the need for this study is to find an application of FID with traditional bearing to see how it acts as a supplemental device and observe its performance.

Therefore, in this study, an *N*-storey shear building is analysed using FID-based supplemental devices along with the traditional bearings. The precise objectives of this study are:

1. to examine the performance of FID in controlling the seismic response of the buildings
2. to find the effect of parameters of FID in controlling the top floor acceleration, base shear, displacement on the performance of the single storey and multi-storeyed buildings with and without FID
3. to find the effect of isolation time period, the total damping ration (consisting of isolation damping ration and FID damping ration), on the structures with and without FID
4. to explore the effect of number of storeys on the structures with and without FID.

2 Fluid inerter damper as supplemental device

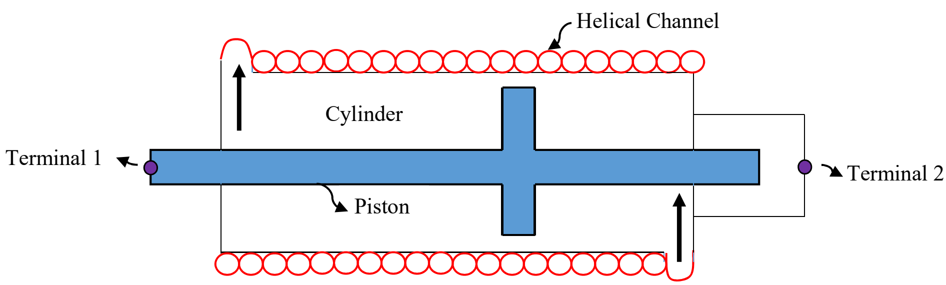
FID was used for mitigating vibrations in automobiles until recently. However, a recent study indicates that it can also be used for mitigating response during an earthquake. An FID is a supplemental device for base-isolated structures for mitigating responses during an earthquake.

It was Smith (2002) who introduced the term inerter to the engineering world for the first time, simulating the force-current between electrical and mechanical networks. As far as this is concerned, it was restricted to using it in place of a capacitor. As an equivalent capacitor, the force produced by this has the property of being proportional to the relative acceleration between its end points (or nodes). The constant of proportionality is known as inertance and is measured in kilograms (Wagg and Pei, 2020). In the late 1990, Japan became the first country to use the inertial components in damping devices to improve its performance in the event of an earthquake.

The different types of inerters are the rack and pinion inerter, the ball and screw inerter, the fluid inerter, and the electromagnetic inerter. All these can be effectively used in vehicles (for enhancing suspension), in train wagons (to improve suspension) and to some extent in civil engineering systems. Many researchers investigated the use of inerter-based isolation systems to suppress vibrations. The common belief of inertance being fixed is found to be incorrect when it comes to the application of fluid inerters as they give variable inertance.

Figure 1 depicts a schematic diagram of the FID installed in a rigid model of the base-isolated structure. An FID is made up of a piston and a cylinder that drives fluid through a helical tube that surrounds the cylinder. The FID's two terminals are the hydraulic cylinder and the piston rod. The fluid flow through an external helical channel produces rotational inertia to compensate for the pressure loss (Swift et al., 2013; Wagg and Pei, 2020). The FID's resisting force depends on the friction, oil density, and viscosity of the fluid. The FID is modelled as a linear inerter in parallel with a linear (Zhao et al., 2019a, 2019b; Sun et al., 2019) and a nonlinear (De Domenico et al., 2019; De Domenico et al., 2020) dashpot for studying the seismic response of the base-isolated structures.

Figure 1 The schematic diagram of the FID (see online version for colours)



Fluid inerters have the benefits of getting fewer moving parts because the inertia influence is produced by the flowing fluid. This inertial effect exists because of the hydraulic inerter in which the fluid is driving a mechanical fly wheel, or because of the mass of the fluid itself moving in the helical pipe, called the helical fluid inerter. The model identification method based on theoretical and experimental dynamic responses, for fluid-based inerters, is developed by Liu et al. (2018). Wagg and Pei (2020) devised an experimental setup in which the inerter system consists of a central fluid-filled cylinder connected to a helical coil on the cylinder's outside. If the helix radius is larger, it will generate higher inertance. The cylinder body and the piston rod are two device terminals, according to Swift et al. (2013), and their relative motion drives fluid through the helical channel. Inside the piston head and outside the piston cylinder, prototypes are made with tightly wound helical channels. A fluid inerter model consists of a piston and cylinder as shown in Figure 1.

The fluid flows through the helical tube surrounding the cylinder. If A_1 = area of the main cylinder, A_2 = cross-sectional area of the channel, l = length of the channel, ρ = density of the fluid, F = equal and opposite force applied to the terminals, x = relative displacement between the terminals, b = inertance in kg, then an ideal FID equation is given by,

$$F = c_f \dot{x}_b + b\ddot{x}_b \tag{1}$$

where c_f = viscous damping; x_b = displacement between two terminals of FID which is equal to the displacement of the base mass as shown in Figure 2; $\dot{x}_b$ = velocity between two terminals of FID; $\ddot{x}_b$ = relative acceleration between two terminals of FID.

The equation for the inertance (b) is suggested by Swift et al. (2013), as,

$$b = \rho l \frac{A_1^2}{A_2} \quad (2)$$

In the above two equations, only the inertia of the fluid flowing in the channel is taken into account, thus neglecting the inertia of the piston itself. The mean fluid velocity can be enhanced by the ration $\left(\frac{A_1}{A_2}\right)$, thus giving large inertance ratios. The reason for the pressure drop (Δp) across the piston is due to the viscous effects in the channel, energy losses at the ends of the channel where the flow transitions between the main cylinder and the narrow channel (Swift et al., 2013). In this device, an inerter is modelled in parallel with a nonlinear parasitic damping component. The device geometry and fluid properties are sufficient to know the components of parasitic damping. The experimental verification and numerical simulation are validated with respect to the prototype models studied.

3 Modelling of base-isolated building and FID

In the present study, the 2D shear building with N-storey is considered and superstructure flexibility is duly taken in account (Jangid, 2000; Kulkarni and Jangid, 2003; Panchal and Jangid, 2009). It is a base-isolated building with traditional bearings and supplemental FID. For checking the performance of FID, an identical building with and without FID is taken for the study. Figure 2 shows the mathematical model of the building. The following are the assumptions made for the present study:

1 since shear building model of superstructure is considered, diaphragm action is ensured

2 the superstructure is assumed to remain elastic throughout the seismic excitation

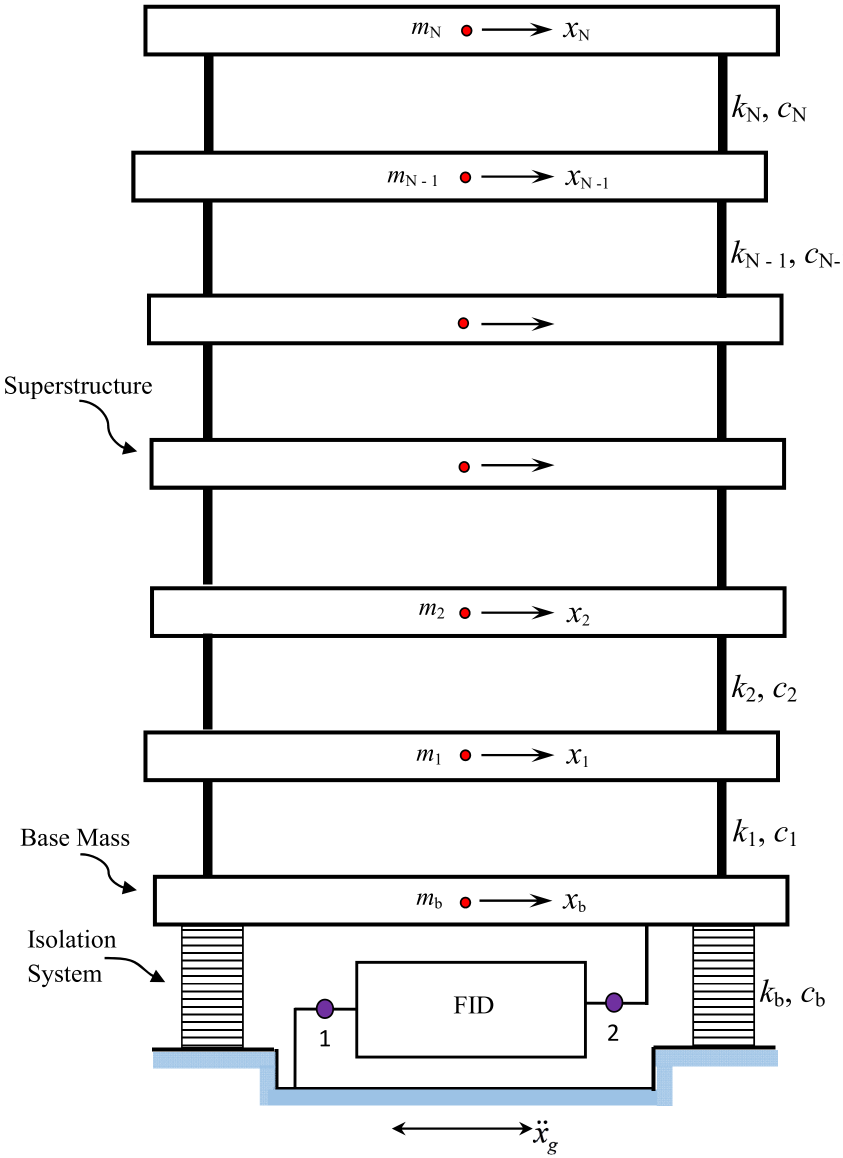
3 unidirectional component of excitation is considered

4 the interaction between the soil and the structure is not considered

5 the linear force deformation behaviour of isolation system with viscous damping is considered.

In this study, it is proposed to use FID as supplemental devices to traditional isolation bearings. For checking the performance of this, the two-dimensional shear building is taken for study. The proposed building model is a two-dimensional shear building model, having six storeys provided with isolation systems in the form of traditional bearings. A fluid inerter damper is used to supplement the traditional bearing systems. The important parameters for checking the response of the buildings are top floor acceleration and base displacement under the four earthquake response time-histories (refer Table 1). The influence of these parameters is mapped with the number of storeys, and with and without fluid inerter dampers. It is noteworthy to note the positive effects of the use of FID as an additional passive protective device for the structure.

Figure 2 Structural model of flexible base – isolated building with supplemental FID (see online version for colours)



4 Governing equations of motion

The 2D shear building of an *N*-storey is considered in this study, as shown in Figure 2. It's a base-isolated structure with traditional bearings and supplemental FID. The governing equations of motion can be written as:

$$[M_s]\{\ddot{x}_s\}+[C_s]\{\dot{x}_s\}+[K_s]\{x_s\}=-[M_s]\{r\}\left(\ddot{x}_g+\ddot{x}_b\right) \tag{3}$$

where $[C_s]$, $[K_s]$ and $[M_s]$ are the damping, stiffness and lumped mass matrices for the fixed base structure, respectively; $\{\ddot{x}_s\}$, $\{\dot{x}_s\}$ and $\{x_s\} = \{x_1, x_2, \ldots, x_N\}^T$, are the unknown acceleration, velocity, and relative floor displacement vectors, respectively; the subscript numbers 1 to N represents the floor numbers; x_i represent the displacement of i^{th} floor; $\{\ddot{x}_b\}$ and $\{\ddot{x}_g\}$ are the acceleration of base mass and ground, respectively; and $\{r\}$ is the influence coefficient vector.

The governing equation of motion for the base mass is written as

$$m_b\ddot{x}_b + c_b\dot{x}_b + k_b x_b + F - c_1\dot{x}_1 - k_1 x_1 = -m_b\ddot{x}_g \tag{4}$$

where F = restoring force of the FID; c_1 = first storey damping; $\dot{x}_1$ = first storey velocity; k_1 = stiffness of first storey; x_1 = displacement of first storey relative to base mass; m_b = base mass; and c_b = viscous damping of the isolation system.

The equations of motion of the base-isolated structure are numerically solved using Newmark's step-by-step integration method. The linear variation of acceleration over a short time interval, 0.001 s, is taken into account.

The three parameters can be used to characterise the isolation system and FID in question, namely: T_b; ξ_b; β; and ξ_f defined as:

$$T_b = 2\pi\sqrt{\frac{M}{k_b}};\ 2\xi_b\omega_b = \frac{c_b}{M};\ \beta = \frac{b}{M};\ 2\xi_f\omega_b = \frac{c_f}{M} \tag{5}$$

where $M = \left(m_b + \sum_{j=1}^{N} m_j\right)$ is the total mass of the isolated building; and m_j is the mass of the j^{th} floor; b = inertance ration; and $\omega_b = 2\pi/T_b$ is the base isolation frequency.

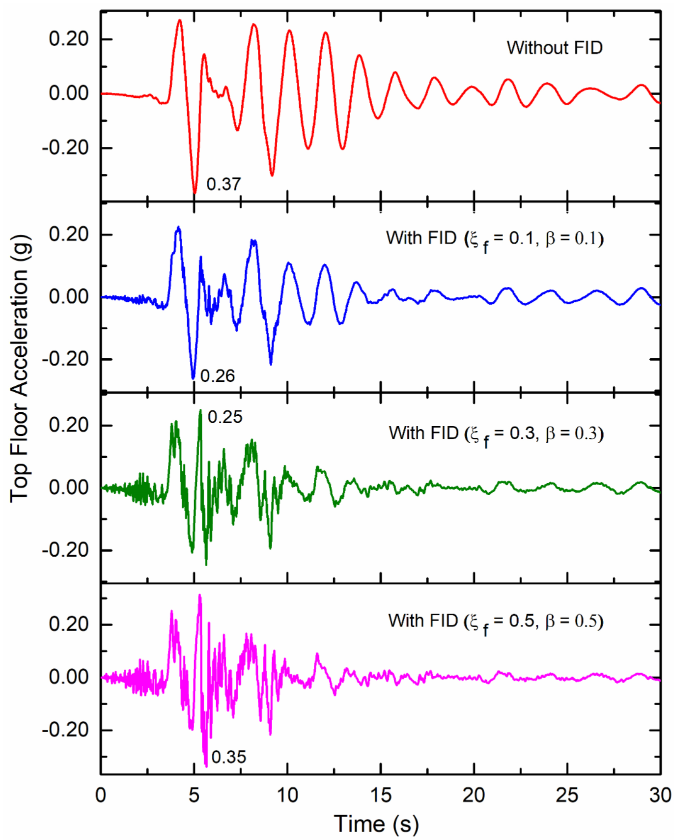
5 Numerical study

The 2D shear building of N storey is explored in this study (Figure 2). It is a base-isolated structure with traditional bearings and an additional FID. For both the with and without FID cases, the response parameters studied are base displacement and top floor acceleration. The total damping ratio of the structure is made up of the fluid inerter damping ratio (ξ_f) and the damping ratio of the isolated structure (ξ_b). The effect of the ratio of FID inertance to total mass of isolated structures (β) on the structure's acceleration and displacement response is investigated in this paper. The β values are taken as = 0.0, 0.025, 0.05, 0.075, 0.10, 0.125, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45 and 0.50. For each of these incremental β values, damping ratio of isolated structure (ξ_b) is taken as 0.1. The FID damping ration for each incremental (ξ_f) values is taken as = 0.0, 0.025, 0.05, 0.075, 0.10, 0.125, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45 and 0.50. For evaluating the performance of base-isolated building without FID, the total damping ration will constitute only of damping ratio of isolated structure (ξ_b). The fundamental time period of equivalence fixed base structure is assumed as 0.1 N. The isolation time period is taken in the sets of 2 s, 3 s and 4 s. As a result, the performance of a one-storey building and a six-storey base-isolated building with and without a supplemented fluid inerter device will be assessed.

Table 1 Details of earthquake ground acceleration records

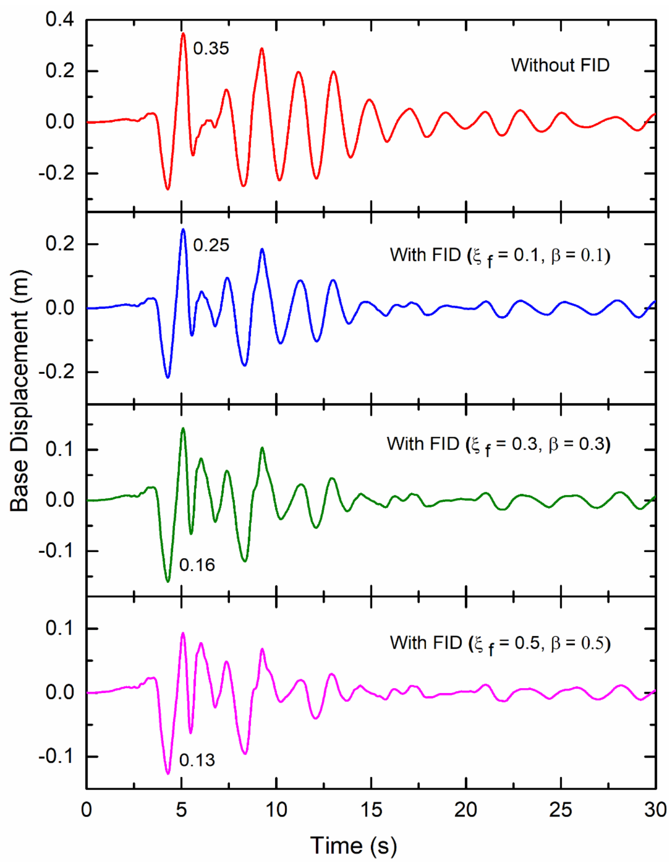
Serials	*Earthquake*	*Year*	*Station*
EQTH1	Imperial Valley	19.05.1940	El Centro
EQTH2	Kobe	16.01.1995	JMA
EQTH3	Northridge	17.01.1994	Sylmar
EQTH4	Northridge	17.01.1994	Newhall

Figure 3 Time variation of top floor acceleration for base-isolated one-storey building supplemented with and without FID subjected to Northridge (Newhall) 1994 Earthquake (T_b = 2 s, ξ_b = 0.1) (see online version for colours)



The selection of ground motion for the modelling is an important task. The observed ground motions in the past indicate random behaviour. The earthquakes have different amplitudes, positive and negative sinusoidal peaks, which occur at various time intervals, but nothing is common between them. Near fault earthquakes have significant impact on the performance of the buildings. Hence, in this study, near-fault earthquakes are also considered. Four strong earthquake excitations are chosen to test the performance of the base-isolated building's seismic response with and without FID as shown in Table 1. Based on time history responses, the performance of various isolation systems is compared. Figures 3 and 4 show the results for a one-storey building and Figures 5 and 6 show the results for a six-storey building. Time history variations of top floor acceleration, base-displacement, are plotted for the base-isolated building with and without FID. The variation of top floor acceleration and base displacement for base-isolated one-storey building supplemented with FID against β (isolation time period T_b = 2 s, ξ_b = 0.1) is plotted in Figure 7. Similarly, it is plotted for isolation time period, T_b = 3 s and T_b = 4 s, in Figures 8 and 9 respectively. The variation of top floor acceleration and base displacement for base-isolated six-storey building supplemented with FID against β (isolation time period T_b = 2 s, ξ_b = 0.1) is plotted in Figure 10. Also, it is plotted for isolation time period, T_b = 3 s and T_b = 4 s, in Figures 11 and 12 respectively. Table 2 compares the effects of different earthquakes on a single-storey base-isolated building with and without FID. Similarly, Table 3 shows comparison of six-storey building with and without FID for different earthquakes.

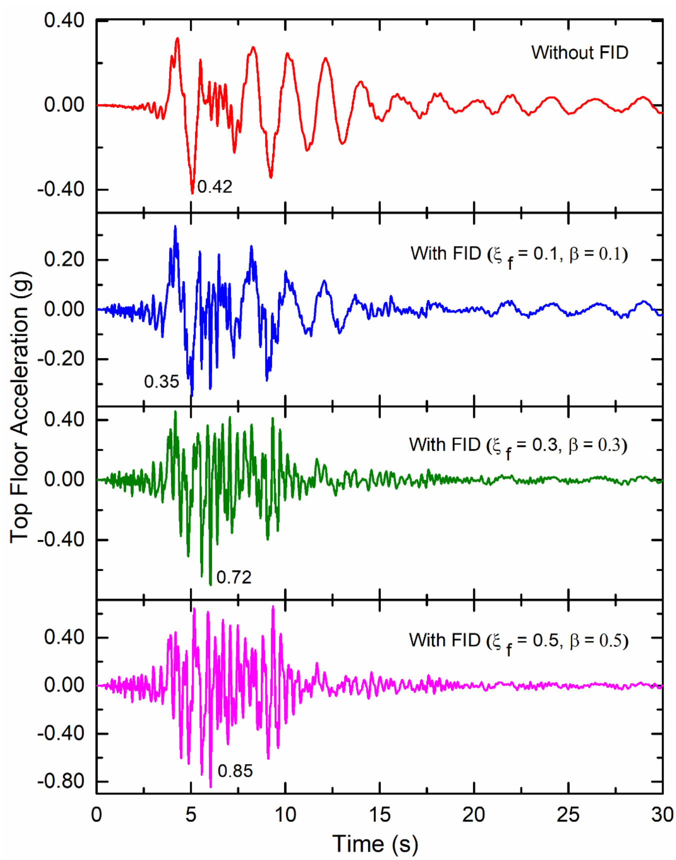
Figure 4 Time variation of base displacement for base-isolated one-storey building supplemented with and without FID subjected to Northridge (Newhall) 1994 Earthquake (T_b = 2 s, ξ_b = 0.1) (see online version for colours)



The effect of FID reduces top floor acceleration by 32.43% for a one-storey building with T_b = 2 s, ξ_b = 0.1, refer Figure 3. Given the limitations of traditional isolation devices, an FID has proven to be an effective vibration suppression supplemental device for the base-isolated structure. As the ratio of FID inertance to total mass of isolated structures

(β) increases, it is found that, up to $\beta = 0.25$ ($T_b = 2$ s, $\xi_b = 0.1$), FID reduces the top floor acceleration. However, beyond $\beta = 0.25$, it is found that top floor acceleration increases. When the base displacement values for cases with and without FID are compared, it is discovered that the FID reduces the base displacement by 54.28%, Figure 4. As a result, when compared to traditional isolation devices, nearly half of the base displacement is reduced. This results in less wear and tear on the components of the main isolation devices, extending their service life. However, with respect to the variation in the ratio of FID inertance to total mass of isolated structures (β), the base displacement values decrease and ceases to constant value at $\beta = 0.50$. Hence, the fluid inerter damping ration (ξ_f) and ratio of FID inertance to total mass of isolated structures (β) values suggested for the best performance of one-storey building, are 0.20 and 0.25, respectively.

Figure 5 Time variation of top floor acceleration for base-isolated six-storey building supplemented with and without FID subjected to Northridge (Newhall) 1994 Earthquake ($T_b = 2$ s, $\xi_b = 0.1$)



As shown in Figure 5, for the six-storey building with $T_b = 2$ s, $\xi_b = 0.1$, the FID application gives 17 % reduction in top floor acceleration. As a result, when compared to a single-storey building, the percent reduction is lower. As a result, it can be concluded that the application of FID is more suitable for low-rise structures of 1 to 5 storeys. In this case, from the variation of the ratio of FID inertance to total mass of isolated structures (β), up to $\beta = 0.1$, there is a reduction in top floor acceleration values, beyond which, the top floor acceleration values increase. Under same excitation, the reduction in base displacement values is found to be 60.00%, as shown in Figure 6 (T_b = 2 s, ξ_b = 0.1). Here, one interesting part with respect to (β) and (ξ_f) is observed. As the ratio of FID inertance to total mass of isolated structures (β) and fluid inerter damping ration (ξ_f) increases there is more reduction of the base displacement. So even though the acceleration values are increased, it is found that the base displacement values are reduced drastically. So, service life of the main base isolation devices increases.

Figure 6 Time variation of base displacement for base-isolated six-storey building supplemented with and without FID subjected to Northridge (Newhall) 1994 Earthquake (T_b = 2 s, ξ_b = 0.1)

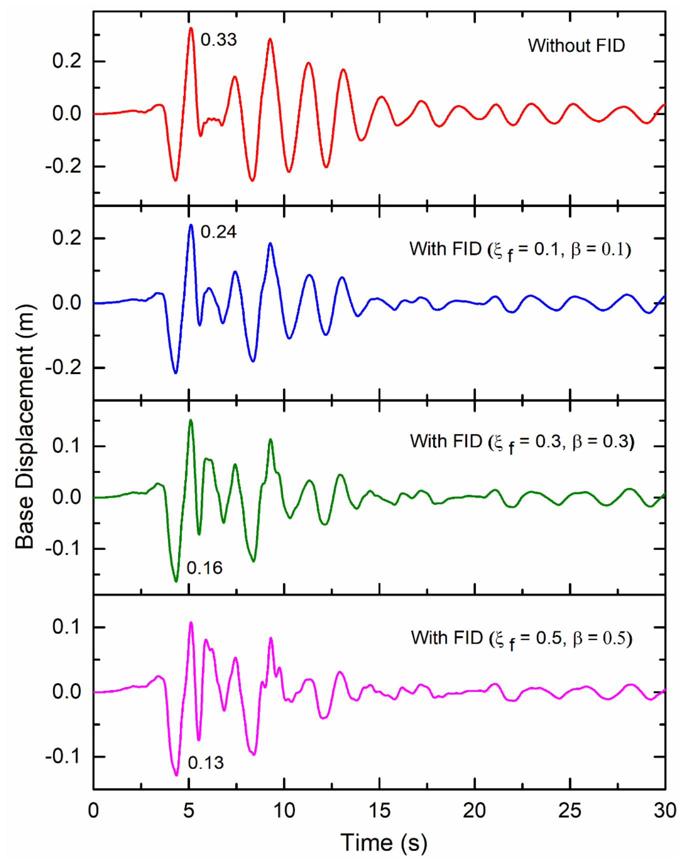
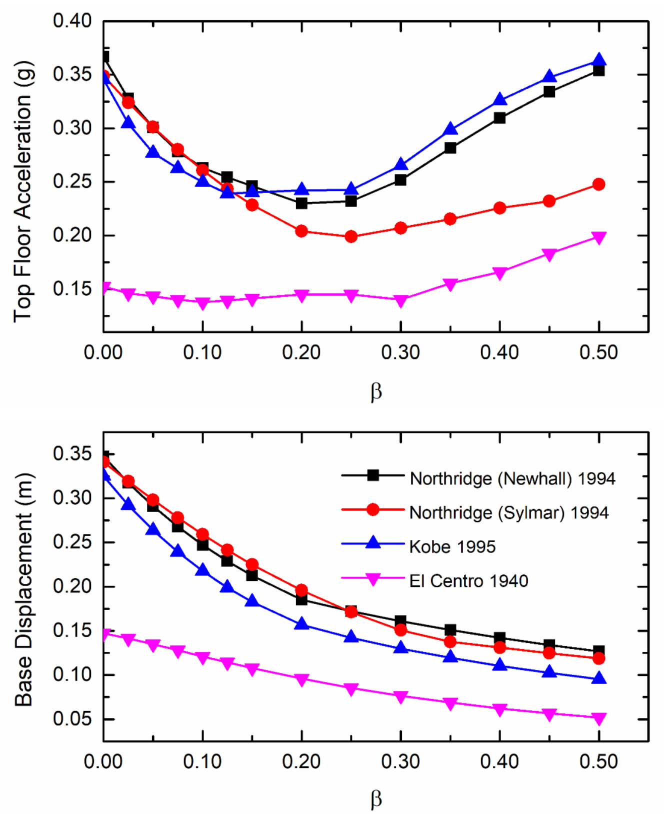


Figure 7 Variation of top floor acceleration and base displacement for base-isolated one-storey building supplemented with FID against β (T_b = 2 s, ξ_b = 0.1) (see online version for colours)



Finding the extent of variation of the ratio of FID inertance to total mass of isolated buildings (β) on the top floor acceleration and peak base displacement is also an important challenge. For the isolation time period = 2 s, as shown in Figure 7, as far as acceleration is concerned, all the earthquake tends to show the same results. As (β) increases, top floor acceleration decreases until it reaches (β) = 0.25, after which it increases. When it comes to base displacement, it can be seen in Figure 8 that as the (β) value increases, the base displacement decreases. It clearly demonstrates the use of an FID as a supplemental device, with the advantage of reducing base displacement at a low cost of increased top floor acceleration. As shown in Figure 8, for the isolation time period = 3 s, the reduction in top floor acceleration is achieved till (β) value increase up to 0.1, whereas the trend in reduction of base displacement is seen same as that for the isolation time period = 2 s. As seen in Figure 9, when isolation time period is = 4 s, the reduction in top floor acceleration is gained till (β) = 0.075. However, the reduction in base displacement follows the same pattern as that for the isolation time period of 2 s.

Figure 8 Variation of top floor acceleration and base displacement for base-isolated one-storey building supplemented with FID against β (T_b = 3 s, ξ_b = 0.1)

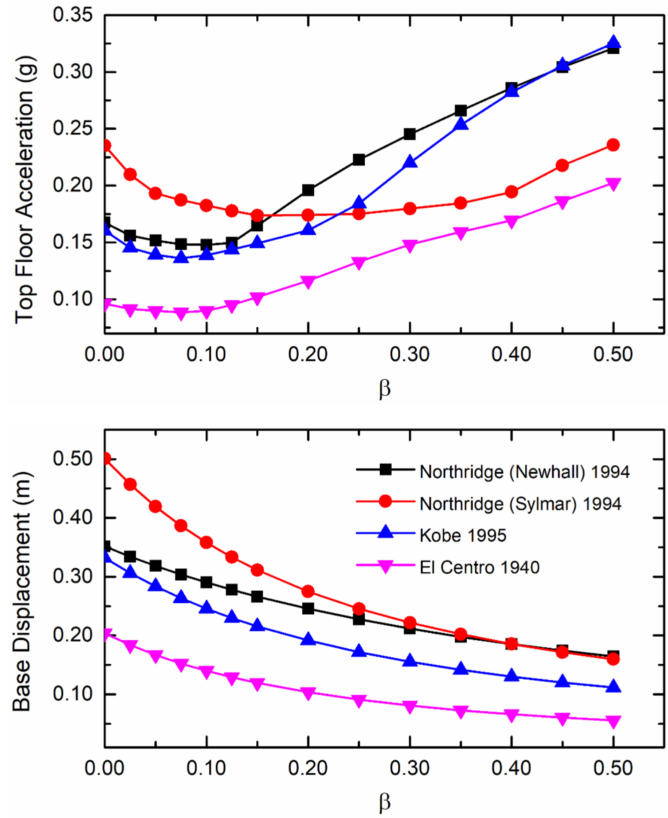


Figure 9 Variation of top floor acceleration and base displacement for base-isolated one-storey building supplemented with FID against β (T_b = 4 s, ξ_b = 0.1) (see online version for colours)

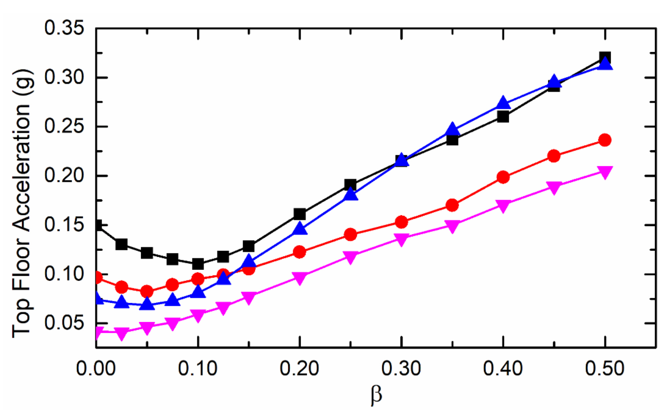


Figure 9 Variation of top floor acceleration and base displacement for base-isolated one-storey building supplemented with FID against β (T_b = 4 s, ξ_b = 0.1) (continued) (see online version for colours)

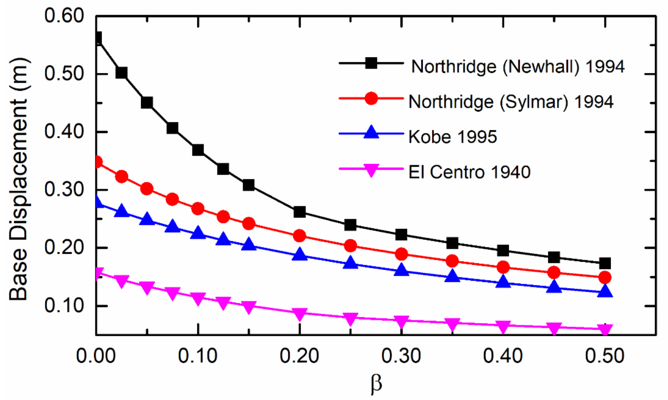
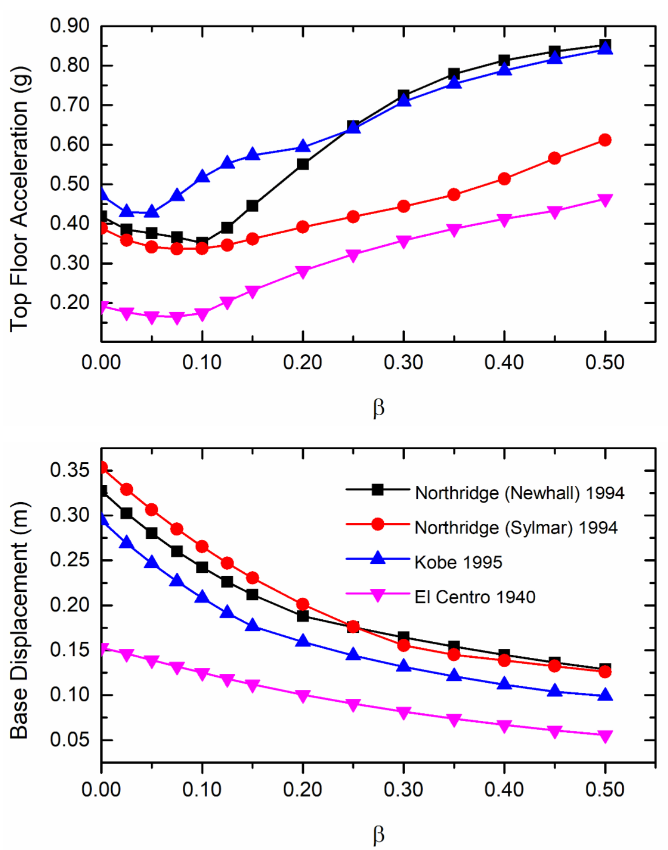


Figure 10 Variation of top floor acceleration and base displacement for base-isolated six-storey building supplemented with FID against β (T_b = 2 s, ξ_b = 0.1) (see online version for colours)



When the same study is extended to a six-storey building, the reduction in top-floor acceleration is seen only up to (β) value of 0.075, as shown in Figure 10. However, as the (β) value increases above 0.075, the top floor acceleration increases. So, as height of the building increases, there is no point of advantage in increasing the (β) value. But, there is reduction in base displacement values even if there is increase in (β) values. This is somewhat encouraging in terms of achieving a significant reduction in base displacement values at the cost of a small increase in top floor acceleration. As shown in Figures 11 and 12, for the isolation time period = 3 s, and = 4 s, respectively, it can be seen that there is no reduction in top floor acceleration values for any increase in (β) values. However, the common trend of reduction in base displacement values for increase in (β) values can also be observed here in Figures 11 and 12.

Figure 11 Variation of top floor acceleration and base displacement for base-isolated six-storey building supplemented with FID against β (T_b = 3 s, ξ_b = 0.1) (see online version for colours)

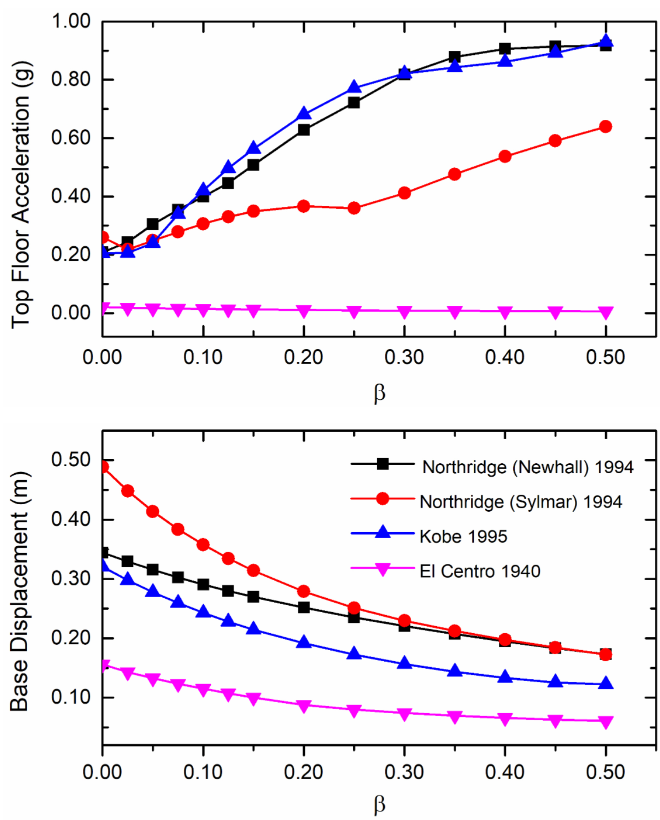
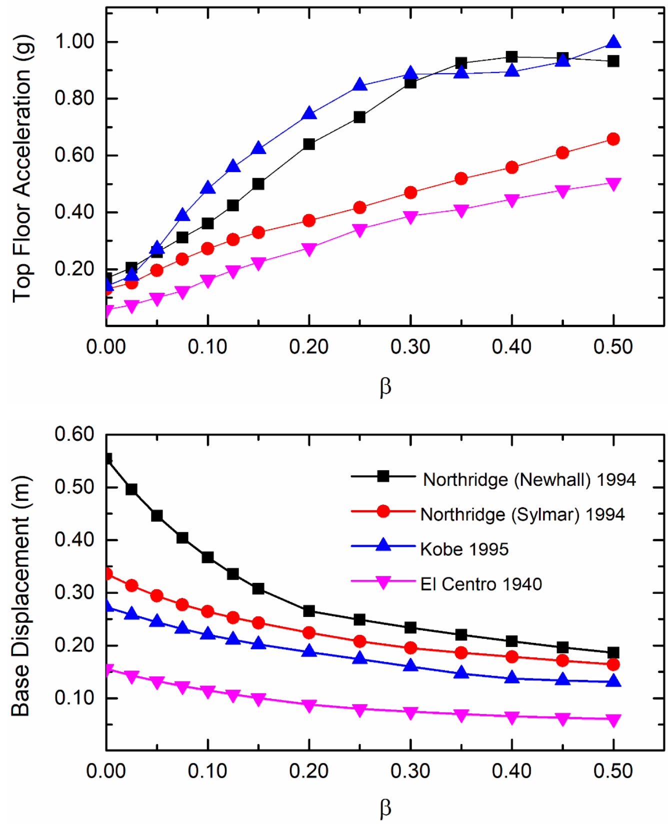


Figure 12 Variation of top floor acceleration and base displacement for base-isolated six-storey building supplemented with FID against β (T_b = 4 s, ξ_b = 0.1) (see online version for colours)



Finally, when comparing isolated buildings with and without FID for different earthquake excitations (Table 1) and different building heights (T_b = 2 s, ξ_b = 0.1), it is concluded that the FID reduces the top floor acceleration for the combinations of FID inertance to total mass of isolated structures (β) and the fluid inerter damping ration (ξ_f) from 0.1 to 0.25, respectively, in Tables 2 and 3. However, beyond this, there is increase in the values of peak acceleration. But reduction in base displacement is seen even when (β) and (ξ_f) values increases beyond 0.25. For one-storey height building, as compared to without FID case, the reduction in top floor acceleration is achieved only when (β) and (ξ_f) values are up to 0.25. This reduction is about 32.43%. However, even when (β) and (ξ_f) values are increased beyond 0.25, a reduction in the base displacement is achieved. This reduction in base displacement is more than 50%. When six-storey building is compared, it is seen that FID can reduce the top floor acceleration values only when (β) and (ξ_f) values are up to 0.075. However, even when (β) and (ξ_f) values are increased beyond 0.075, the base displacement is reduced. When compared to the non-FID case for a six-storey building, the top floor acceleration is reduced by 17%, while the base displacement is reduced by more than 60%.

Table 2 Comparison of peak acceleration and peak base displacement for one storey building

Sr. no.	*Earthquake*	ξ_f	β	*With FID*	*Without FID*	*With FID*	*Without FID*
				Peak acceleration (g)	*Peak acceleration (g)*	*Base displacement (m)*	*Base displacement (m)*
1	Northridge (Newhall) 1994	0.1	0.1	0.26	0.37	0.25	0.35
		0.3	0.3	0.25	-	0.16	-
		0.5	0.5	0.35	-	0.13	-
2	Northridge (Sylmar) 1994	0.1	0.1	0.26	0.35	0.26	0.34
		0.3	0.3	0.21	-	0.15	-
		0.5	0.5	0.25	-	0.12	-
3	Kobe 1995	0.1	0.1	0.25	0.34	0.22	0.32
		0.3	0.3	0.26	-	0.13	-
		0.5	0.5	0.36	-	0.09	-
4	El Centro 1940	0.1	0.1	0.14	0.15	0.12	0.15
		0.3	0.3	0.14	-	0.07	-
		0.5	0.5	0.20	-	0.05	-

Table 3 Comparison of peak acceleration and peak base displacement for six storey building

Sr. no.	*Earthquake*	ξ_f	β	*With FID*	*Without FID*	*With FID*	*Without FID*
				Peak acceleration (g)	*Peak acceleration (g)*	*Base displacement (m)*	*Base displacement (m)*
1	Northridge (Newhall) 1994	0.1	0.1	0.35	0.42	0.24	0.33
		0.3	0.3	0.72	-	0.16	-
		0.5	0.5	0.85	-	0.13	-
2	Northridge (Sylmar) 1994	0.1	0.1	0.34	0.39	0.26	0.35
		0.3	0.3	0.44	-	0.15	-
		0.5	0.5	0.61	-	0.13	-
3	Kobe 1995	0.1	0.1	0.52	0.47	0.21	0.29
		0.3	0.3	0.71	-	0.13	-
		0.5	0.5	0.84	-	0.10	-
4	El Centro 1940	0.1	0.1	0.17	0.19	0.12	0.15
		0.3	0.3	0.36	-	0.08	-
		0.5	0.5	0.46	-	0.05	-

6 Conclusions

Four earthquakes in horizontal directions have been used to test the performance of linear base isolation systems using FID for base-isolated buildings. This study emphasises the effectiveness of using FID as supplemental isolation devices for base isolation of the buildings. Nonlinear FID forces and their hysteretic behaviour are modelled using the linear model. The time history variation of top floor acceleration and bearing displacement of the base-isolated structure is obtained using Newmark's method of step-by-step integration. The following conclusions are drawn from the observed results in the form of time histories and peak responses.

1 The FID is found to be effective in controlling the seismic response of base-isolated structures. The bearing displacement is found to be decreased with the increase of the damping of the FID. Therefore, the main isolation device components are subjected to less wear and tear, extending their service life.

2 There is a reduction in top floor acceleration values, up to certain value of the damping of the FID beyond which the top floor acceleration values increases. The damping of the FID must be carefully chosen for the best performance of the base-isolated structure.

3 For a given base-isolated structure and excitation, there exists optimum value of damping of FID for which top floor acceleration attains a minimum value. This optimum value is found to be higher for single-storey building as compared to six-storey building.

4 The FID application reduces top floor acceleration in the six-storey building. However, when compared to a single-storey building, the percent reduction is lower. As a result, it can be concluded that the application of FID is more suitable for low-rise structures.

5 When a six-storey building is compared to a one-storey building under the same excitation, the reduction in base displacement values is found to be higher. The base displacement is reduced as the ratio of FID inertance to total mass of isolated structures and FID ration increases.

6 When isolation time period and ratio of FID inertance to total mass of isolated structures is increased, the base displacement values go on decreasing more rapidly than the top floor acceleration values. The FID is more effective for flexible base-isolated structures. The optimum damping of FID is found to decrease with the increase of the flexibility of the isolation system.

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