Comparison of adaptive magnetorheological elastomer isolator and elastomeric isolator
in near-field and far-field earthquakes

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Abstract

Magnetorheological elastomer (MRE) materials are widely used in the development of smart isolators and absorbers due to their stiffness and damping adaptability. This study investigates the performance of MRE isolators and elastomeric isolators from near-field and far-field earthquakes in benchmark base isolation buildings. All earthquakes are simultaneously applied in two horizontal directions to the horizontal plan. Vertical earthquakes are not attended in the dynamical analysis of benchmark base isolation buildings. For making an isolator model, the effect of bilateral interaction has been considered. The behaviors of MRE isolators and MR dampers are compared. To this end, three control systems including adaptive isolator, passive isolator and semi-active MR damper are considered. The results show that the MRE isolator has a better performance in near-field earthquakes due to its variable stiffness and damping, as compared to the elastomeric isolator. The semi-active MR damper for both far-field and near-field earthquakes has a better control to reduce base displacement, but causes to increase floor accelerations, story drifts and story shear. According to the results of this study, it can be observed that MRE isolator can be used instead of MR damper. The MRE isolator can reduce the base displacement without increasing other responses.

Keywords: Magnetorheological elastomer isolator (MRE isolator), benchmark base isolated building, near-field earthquake, far-field earthquake, magnetorheological damper (MR damper)
A seismic isolator is one of the best methods for protecting structures against severe earthquakes [1-3]. In this method, the effects of earthquakes, especially in frequencies that the structure suffers from severe damage, reduce damages to the structure by separation of the structure from ground vibration. The seismic isolator system has been widely considered in many countries over the past three decades [4-7].

The design of traditional seismic isolators depends on the magnitude and frequency of the design earthquake. The results demonstrate that the traditional seismic isolation system may not perform well in all earthquakes. In other words, it may have successful performance in one earthquake but poor performance in another. Therefore, the adaptability of a seismic isolator system is a major concern in seismic applications of this system [8-9]. Recent research has shown that seismic isolators suffer from near-field earthquakes [10-13] and far-field earthquakes [13-14]. In near-field earthquakes, such as the 1994 Northridge earthquake, large displacements and long-period pulses cause the seismic isolator to be overstretched and this system to be damaged [11-15]. Far-field earthquakes with low frequency contents may cause a resonance phenomenon in the seismic isolator structure; thus, the seismic isolator aggravates the responses and causes the structural failure instead of reducing the dynamic responses [14]. Yaghmaei-Sabegh et al. [16] investigated the inelastic displacement ratio of base-isolated structures. To this end, a two-degree of freedom model was employed. The behavior of isolators and superstructure take inelastic. Moreover, influence of isolators and superstructure properties was considered on the inelastic displacement ratio according to two sets of near-fault and far-fault ground motions. The straightforward approximate method to estimate the inelastic displacement ratio for base-isolated structures subjected to near-fault and far-fault ground motions was developed by Yaghmaei-Sabegh et al. [17]. Vertical distribution of the lateral seismic force for base-isolated structures was investigated by Rofouei et al. [18]. In another study, 3-D base-isolated structural models with LRB isolators considering variety of effective damping and periods ratios were investigated. The results showed that the base shear force recommended by UBC97 was reasonably accurate.

The most common isolators that are currently in use are laminated rubber bearing [19-20], lead-core rubber bearing [20] and high-damping rubber bearing [21]. In designing these isolators, geological conditions and performance of the structure are required [3]. Because of the passive nature of the traditional rubber, the rubber properties (stiffness and damping) do not change, and when the structure is placed against various earthquakes, the problems described above are created. In order to increase the adaptability of passive base isolation systems, researchers [22-24] have proposed several techniques including adding supplementary energy
dissipation devices such as magnetorheological dampers, friction dampers or hydraulic fluid dampers to reduce structural responses. These methods are classified into hybrid base isolation systems which are one of the possible solutions to solve the problem of base isolation systems. Adding supplemental energy dissipation devices to the base isolation system can lead to some problems [11-15]. Reducing base displacement greatly increases story drifts and floor accelerations. In addition, hybrid base isolation systems increase the complexity of design and implementation of base isolation systems as well as the reliability of the systems. Moreover, the proposed hybrid base isolation systems may not be able to perform well in far-field earthquakes because their design is based on a fixed natural frequency and the frequency compatibility is not tuned in real conditions.

Malekzadeh et al. [25] investigated two isolated structures with FPS and double concave friction pendulum (DCFP) at three different hazard levels (SLE, DBE and MCE). The results indicated that the DCFP was able to significantly reduce the peak floor acceleration and peak inter-story drift of the super-structure in comparison to isolated buildings with the FPS bearing at SLE and DBE levels. Since stiffness and damping varied during ground motion, the DCFP acted as an adaptive isolation system and was able to control peak floor acceleration and inter story drift together.

The development of a kind of smart material, namely magnetorheological elastomer (MRE), overcomes the major shortcomings in traditional base isolation systems and creates a new type of seismic isolators whose stiffness and damping can be controlled in real conditions. MRE is the new generation of MR materials in which stiffness and damping are changed by the magnetic field in real-time [26-27]. MRE is like a soft rubber in the absence of a magnetic field. Due to the effect of the magnetic field, the MRE material modulus can greatly increase with respect to the magnetic field strength. The maximum variation of the MRE modulus varies from about 50% (stiffer rubber carrier) to beyond 300% (soft rubber carrier like silicone gel) [28-29]. The maximum variation of the MRE damping varies from about 10% to about 32%, depending on the type of rubber matrix and percentage of iron particles, and mostly on the magnetic field [30] (Chen et al.). MRE materials are offered in various engineering applications and new tools for mitigation and vibration control.

Although research and development in MRE materials have progressed in recent years, research into the applications of MRE materials, especially the development of MRE devices and their implementation, is very limited. Behrooz et al. [31] proposed a semi-active/passive isolator, i.e. the variable stiffness and damping isolator (VSDI), which was capable of reducing the vibration of the structure. The experimental results indicated that stiffness increased by about 30%. Opie and Yim [32] proposed a variable stiffness vibration isolator (VSVI) and the experimental results showed that the MRE isolator reduced payload velocity by 16-30%. To challenge
the problem of traditional isolators against earthquakes in far-field and near-field, an adaptive seismic isolator was proposed by Li et al. [33]. MRE materials are used in new isolators. Experimental tests to consider the MRE isolator behavior were conducted on a shake table under harmonic cycling loading. Experimental results indicated that the damping force and lateral stiffness can change in real time up to %45 and %37, respectively. Li et al. [34] developed a novel adaptive seismic isolation system. Experimental results indicated that lateral stiffness increased up to 1630%. Li et al. [35] developed a highly adjustable MRE base isolator. Shear modulus can be highly adjusted by a medium level of magnetic field. To consider the characteristics and performance of this new adaptive MRE isolator, comprehensive static and dynamic testing was conducted. The experimental results indicated that lateral stiffness of the isolator up to 1630% could be changed by the medium level of magnetic field. Zhao et al. [36] investigated the characteristics of the MRE isolator under various loading conditions. The experimental results indicated that effective stiffness increased up to 114.12% with the current increasing from 0 A to 3 A. Xiaoyu et al. [37] evaluated the performance of the MRE isolator numerically on a 5-story building model. To this end, three different building systems, a bare building, a building with passive base isolation, and a building with adaptive base isolation system, were evaluated. A linear quadratic regulation (LQR) control law was applied to the adaptive base isolation system. Simulation results indicated that the adaptive base isolation system was superior to the other two systems in different earthquakes. The passive base isolation system works well in reducing floor accelerations although it cannot reduce inter story drifts. In addition, the performance of the passive base isolated model is highly dependent on the nature of earthquakes. On the other hand, the adaptive base isolation system performs well in reducing floor accelerations, inter story drifts and base shear. Xiaoyu et al. [38] proposed a smart base isolation system employing MRE isolators and a frequency control algorithm, which shifted the fundamental frequency of the structure away from the dominant frequency of earthquakes. This design avoids the building from resonance state. Simulation was conducted on a 5-story building model. The simulation results indicated that the proposed control system could reduce floor accelerations, inter story drifts and base shear under different types of earthquake attacks. Xiaoyu et al. [39] proposed a semi-active story isolation system. MRE isolators were utilized in the proposed system. The MRE isolators were installed under each story of the structure instead of being only installed beneath the entire structure. Simulation was conducted on a 5-story building model. The simulation results indicated that the proposed control system could reduce floor accelerations, inter story drifts and base shear under different types of earthquake. In addition, the structural stiffness of each floor in this system can be easily controlled by the applied current to each isolator. Gu et al. [40] investigated the inherent
response time of the MRE isolator and developed two practical approaches to minimize the response time delay. The proposed approaches on minimizing time delay were (i) the transient response of shear force from the MRE isolator and (ii) the transient response of current of a large coil that generated magnetic field. The results indicated that the proposed approaches were promising and impressive. Yang et al. [41] investigated the performance of a stiffness softening MRE isolator in a scaled 3-story building. The current signals to the isolators based on the real-time responses of the building floors were calculated by a fuzzy controller. Before carrying out an experimental test, the feasibility of the closed loop control system was evaluated by simulation. The experimental results and simulation indicated that the stiffness softening MRE isolator could suppress structural vibration well.

To describe the behavior of MRE materials, different models have been proposed by researchers. The proposed models should be able to show the displacement-force curve and nonlinear relation between force-velocity and conform to the results of experimental tests. Jolly et al. [42] proposed a quasi-static model. In this model, the modulus increased due to increase in magnetic field and interaction between the adjacent particles. Davis [43] used finite element methods for analyzing the increase in the modulus under varied magnetic fields. The inverse model for the MRE base isolator was proposed by Gu et al. [44]. This model was based on an optimal general regression neural network (GRNN). Testing result indicated that the desired control force reproduced by the GRNN inverse model was accurate. Li et al. [45] proposed a four-parameter viscoelastic model for demonstrating the behavior of MRE materials. In this modeling, a spring element was added parallel to the solid standard three-parameter model for representing the dependence of modulus on magnetic field. Yang et al. [46] proposed a new model for the behavior of MRE isolators. This model included the Bouc-Wen component, which reproduces hysteresis loops, in parallel with the Viogt element, which describes the behaviors of solid materials.

In this study, the model proposed by Yang et al. is employed. [46]. Due to the reception of the base isolated benchmark building by the ASCE Control Committee, base isolated benchmark buildings are used to compare the MRE isolator behavior with that of other isolators. Due to the three dimensional structure of the base isolated benchmark building, the effects of bilateral interaction are considered in isolation modeling. This study examines the effects of near-field and far-field earthquakes on the passive isolation system, hybrid system, and adaptive isolator system.

2. Base isolated benchmark building
The base isolated benchmark building is an 8-story building with steel-braced frame. The length of the building is 84.8 meters, the width is 54.3 meters and the story height is 4.04 meters, which is similar to the hospital building in Los Angeles, California. The plan of the first floor to the sixth floor is L-shaped and it is rectangular for the seventh and eighth floors. Braces are located at the building perimeter. Metal decking and a grid of steel beams support all concrete floor slabs. The steel superstructure is supported on a reinforced concrete base slab, which is integral with concrete beams below, and drop panels below each column location. The isolators are connected between these drop panels and the footing below, as shown in Figure 1. The structure is composed of linear elements of beams, columns, braces, and rigid slabs. The superstructure is modeled as a shear structure with linear elastic behavior and in three dimensions. The floor slabs and the base mat are assumed to be rigid. The superstructure and base have three degrees of freedom at the center of the mass of per floor. The combined building model has a total of 27 degrees of freedom, which has 24 degrees of freedom for the superstructure and 3 degrees of freedom for the isolation system. All the 24 modes in the fixed base case are employed in modeling the superstructure. The damping ratio of the superstructure in all the fixed base modes is 5%. The superstructure is a linear elastic system with lateral torsional behavior in dynamic analysis. The period of the structure for its first three modes is shown in Table 1. The isolation system consists of 92 seismic isolators at the base of the structure. In addition, there are 16 MR dampers at the base of the structure, 8 in the direction of the X axis and 8 in the direction of the Y axis. In Figure 1, the three dimensional model of the benchmark building, elevation view of the control devices and location of the elastomeric isolators and MR dampers are illustrated [47-51].

**Table 1. Periods of the benchmark building [47]**

**Figure 1.** (a) The three dimensional model of the benchmark building; (b) the elevation view of the control devices; (c) the plan of the base of the benchmark building which illustrates the location of the isolators and MR dampers [47]

The Equation of motion for the elastic superstructure is expressed in the following matrix form:

\[ M\ddot{U} + C\dot{U} + KU = -MR \left( \ddot{U}_g + \dot{U}_h \right) \]  

where \( M \) is the superstructure lumped mass matrix with a size of 24 * 24; \( C \) is the superstructure damping matrix with a size of 24 * 24 in the fixed base case; \( K \) is the superstructure stiffness matrix with a size of 24 * 24 in the fixed base case; \( R \) is the matrix of earthquake influence coefficients with a size of 24×3. Furthermore, \( \ddot{U} \),
\( \ddot{U}, \) and \( U \) are the floor acceleration, velocity, and displacement vectors relative to the base, respectively. These vectors have 24 entries. \( \dot{U}_b \) and \( \ddot{U}_g \) with the size \( 3 \times 1 \) represent the vector of base accelerations relative to the ground and the vector of ground accelerations, respectively. The Equation of motion of base mass can be written as follows:

\[
R^T M \left[ \ddot{U} + R \left( \dot{U}_g + \dot{U}_b \right) \right] + M_b \left( \dot{U}_g + \dot{U}_b \right) + f_B = 0
\]

where the diagonal mass matrix of the rigid base slab is shown by \( M_b \) which is a \( 3 \times 3 \) matrix. Moreover, \( f_B \) denotes the \( 3 \times 1 \) nonlinear force vector corresponding to the isolators. These forces are applied to the center of mass of the base slab. The above-cited Equations can be expressed as the subsequent form:

\[
\begin{bmatrix}
M & M & M & R \\
R^T M & R^T M & R^T M & R^T M + M_b
\end{bmatrix}
\begin{bmatrix}
\ddot{U} \\
\dot{U}_b
\end{bmatrix}
+ \begin{bmatrix}
C & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
\dot{U} \\
\dot{U}_b
\end{bmatrix}
+ \begin{bmatrix}
K & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
U \\
U_b
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0
\end{bmatrix}
\begin{bmatrix}
f_B
\end{bmatrix}
= \begin{bmatrix}
M & M & M & R \\
R^T M & R^T M & R^T M & R^T M + M_b
\end{bmatrix}
\begin{bmatrix}
\ddot{U}_g
\end{bmatrix}
\]

Equation 3 is solved using the Newmark Beta unconditionally stable constant average acceleration method.

Refer to References 47 to 51 for more information (The matrices of the \( M, C \) and \( K \) of the benchmark building).

3. Different parts of the MRE seismic isolator

Different parts of the MRE isolator are shown in Figure 2.

**Figure 2.** The cross section of a MRE base isolator [46]

The MRE isolator consists of some multilayer thin MRE sheets bonded onto multilayer thin steel plates. The layers of the MRE sheets and replacement of steel plates between the MRE sheets make it possible to avoid radial deformation of the isolator to the outside; thus, the axial pressure capacity increases and slight lateral stiffness is created in the isolator. MRE sheets and steel plates are inside the solenoid which produces magnetic field by applying electric current. Solenoid is made of an electromagnetic coil and thin non-magnetic supports. The non-magnetic thin plates in the top and bottom of the solenoid are made of epoxy material. The coil is attached to the support. The space between the MRE sheets and the coil is determined by the maximum allowable shear strain of the MRE isolator. Due to the very low conductivity of MRE materials, especially when used with thin MRE sheets, it is difficult to obtain MRE sheets into magnetic saturation. Replacing MRE sheets and steel plates can increase the conductivity of the isolator. Steel yoke is used to increase the magnetic field of the MRE isolator. To create the isolator movement capability, a small gap is placed between the top plate and the steel yoke. Refer to Reference [52] for more information.

4. Modelling of a novel adaptive MRE base isolator
The models used for MRE isolators should be able to capture the strain stiffening in force-displacement loops and the nonlinear relationship between force and velocity. As mentioned in the introduction, several non-parametric and parametric models have been developed to describe performances of MREs [42-46]. In this study, the model proposed by Yang et al. [46] is applied. This novel model is illustrated in Figure 3. Mathematical Equations are written in Equations 4 and 5 [46]. This model includes a Bouc-Wen component in parallel with a Viogt element. The former element is employed for reproducing hysteresis loops and the latter describes solid-material behaviors. The evolutionary variable $Z$ which represents a function of the time history displacement describes the Bouc-Wen component which is able to illustrate a large class of hysteretic behavior. Moreover, using this component is simple from the mathematical point of view. For these reasons, it is extensively applied in structural engineering and defining MR behavior.

$$F = \alpha K_0 U + (1-\alpha)K_0 Z + C_0 \dot{U}$$  \hspace{1cm} (4)$$

$$\dot{Z} = \alpha U - \beta |Z|^{n-1} Z - \gamma |Z|$$  \hspace{1cm} (5)$$

In these equations, the spring stiffness and viscosity coefficient of this model are denoted by $K_0$ and $C_0$, respectively. Note that $C_0$ represents the damping capacity of the system. It should be mentioned that $C_0 \dot{U}$ is a component of the total force. The rest part of the total force indicates the restoring force which is equal to the summation of a linear component $\alpha K_0 U$ and a purely hysteretic component $(1-\alpha)K_0 Z$. It should be added that $\alpha \in (0,1)$ is the linearity level of the hysteresis loops [46].

**Figure 3. The suggested model for the MRE isolator [46]**

In these relations, $A$, $n$, $\beta$ and $\gamma$ are non-dimensional parameters applied to introduce the shape and size of the hysteresis loops. The parameter $A$ has influence on the maximum force and the parameter $n$ controls the transition from linear to nonlinear range. In this work, the parameter $n$ is assumed to be equal to 1. Mainly, $\beta$ and $\gamma$ form the hysteresis loops. It is observed that the parameters $A$, $\alpha$, $K_0$ and $C_0$ seem to vary linearly with the current and the parameters $\beta$ and $\gamma$ are constant values for which the optimum values of parameters are proposed in Ref. 48. Therefore, the following Equations can be derived [46]:

$$A = A_a + A_b I$$

$$\alpha = \alpha_a + \alpha_b I$$

$$K_0 = K_{0a} + K_{0b} I$$

$$C_0 = C_{0a} + C_{0b} I$$  \hspace{1cm} (6)$$

In Table 2, the optimum values of the parameters $A_a, A_b, \alpha_a, \alpha_b, K_{0a}, K_{0b}, C_{0a}, C_{0b}, \beta, \gamma$ are listed [46].
Table 2. The optimum values of the parameters of the MRE isolator [46]

The maximum relative error corresponding to the introduced model and experimentally measured isolator force is less than 8% [46]. Figure 4 shows the isolator force time history, force displacement, and force velocity relationships under sinusoidal load with the frequency of 4 Hz and amplitude of 4 mm.

**Figure 4.** The responses of the model under sinusoidal load with the frequency of 4 Hz and amplitude of 4 mm

In this study, the MRE isolator is used in the benchmark base isolated building. Because the benchmark base isolated building is three-dimensional, bilateral interaction effects should be developed in the isolator behavior.

The isolator forces produced by the MRE isolator in \( x \) and \( y \) direction can be expressed as:

\[
F_x = \alpha K_a \dot{U}_x + (1-\alpha)K_oZ_x + C_o \dot{U}_x
\]
\[
F_y = \alpha K_a \dot{U}_y + (1-\alpha)K_oZ_y + C_o \dot{U}_y
\]

The evolutionary variable \( Z \) can be achieved with the help of following Equations [53]:

\[
\ddot{z}_x = A \dot{U}_x - z_x (\beta \dot{U}_x z_x + \eta \dot{U}_x z_x + \beta \dot{y}_y z_y + \eta \dot{y}_y z_y) \times (z_x^2 + z_y^2)^{n-2} \\
\ddot{z}_y = A \dot{U}_y - z_y (\beta \dot{U}_y z_x + \eta \dot{U}_y z_x + \beta \dot{y}_y z_y + \eta \dot{y}_y z_y) \times (z_x^2 + z_y^2)^{n-2}
\]

Figure 5 shows the three dimensional resultant force-displacement and Figure 6 shows the three dimensional resultant force-velocity under sinusoidal load with the frequency of 4 Hz and amplitude of 4 mm.

**Figure 5.** Three dimensional resultant force-displacement behavior

**Figure 6.** Three dimensional resultant force-velocity behavior

The MRE base isolator is used in the benchmark building. For this purpose, the damping and stiffness parameters of Table 2 should be adjusted in such a way that the isolator has the ability to control the benchmark building. Recall that the aforesaid parameters have influences on the isolator force. In this study, the values selected for these parameters cause the maximum isolator force to be equal to the maximum MR damper force in the benchmark base isolation building. In Figure 7, the force-displacement and force-velocity relationships corresponding to the seismic isolator are illustrated for the current of 1A, sinusoidal signal, and various values of damping and stiffness. Note that \( \frac{K_{ob}}{K_{oa}}, \frac{C_{ob}}{C_{oa}} \), the stiffness and damping ratios, are the same for the proposed model according to the selected values of stiffness and damping in Ref. [46].
Figure 7. Comparison of force-displacement and force-velocity relationships of the MRE isolator

In Figure 8, the force-displacement and force velocity relationships corresponding to the seismic isolator and MR damper are presented for the current of 1A, sinusoidal excitation with frequency of 1Hz and amplitude of 0.5m.

It is observed that the maximum isolator force is equal to the maximum MR damper force in the benchmark base isolation building. Table 3 shows the parameters utilized for the MRE isolator in this study.

Figure 8. Comparison of force-displacement and force-velocity relationships of the MRE isolator and MR damper

Table 3. The parameters of the MRE isolator utilized in this study

5. Comparison between the MR damper and MRE isolator

As previously mentioned, one of the purposes of this study is to investigate the MRE isolator behavior in the benchmark base isolation building. In addition, of interest is to compare the effects of the MRE isolator and MR damper on structural responses. This section compares the behavior of the MRE isolator and MR damper.

Several parametric mechanical models have been proposed to describe the non-linear behavior of MR dampers [54-55]. The most reputable model that suitably predicts MR damper behavior and has been used to simulate MR dampers for the semi-active control system is the smooth Bouc-Wen model [56-57]. Figure 9 illustrates the simple Bouc-Wen model for MR dampers. It includes a spring, dashpot, and hysteretic element in parallel, as shown in Figure 9.

Figure 9. The simple Bouc-Wen model of the MR damper [54]

The force generated by the damper is given by [54]:

\[ F = \alpha Z_f (v) + C_0 \dot{U} + K_0 U \]  \hspace{1cm} (9)

where \( \alpha \) is the Bouc-Wen model parameter related to the MR material yield stress; \( K_0 \) and \( C_0 \) are spring stiffness and dashpot damping coefficient, respectively; \( U \) and \( \dot{U} \) are displacement and velocity, respectively;
\( f(v) \) is a function of voltage \( v \); and \( Z \) is hysteric deformation of the model which is defined by the following Equation:

\[
Y \dot{Z} = U - \beta |Z| \dot{Z} - \gamma U Z^2
\]  

(10)

where \( Y \) is the yield displacement of the hysteretic element and \( \gamma, \beta \) are the Bouc-Wen model parameters. For achieving the optimal performance of a control system equipped with MR dampers, the voltage applied to the current driver must be varied according to the measured feedback at any moment to change the damping force. Thus, for accounting this accordance, the coefficient \( \alpha \) and damping coefficient \( c_0 \) in Equation 9 are defined as a linear function of the efficient voltage, as given by the following Equations [56,57]:

\[
\alpha = \alpha_0 + \alpha_a I
\]

(11)

\[
c_0 = c_{0a} + c_{0b} I
\]

The linear viscoelastic region of the MR damper is too small so that the yield displacement of the MR damper is too small. In other words, the MR damper operates at the post-yield region. Table 4 shows the parameters utilized for the MR damper in the benchmark base isolation building.

**Table 4.** The parameters of the MR damper utilized in the benchmark base isolation building [47]

In Figures 10 and 11, the force-displacement and force-velocity relationships of the MRE isolator and MR damper are respectively presented for the current of 1A, sinusoidal excitation with various frequency and amplitude of 0.5m. It can be observed that the loading frequency has no effect on the maximum force of the MRE isolator and is more effective on the maximum force of the MR damper.

**Figure 10.** Force-displacement and force-velocity relationships of the MRE isolator for various frequencies

**Figure 11.** Force-displacement and force-velocity relationships of the MR damper for various frequencies

In Figures 12 and 13, the force-displacement and force-velocity relationships of the MRE isolator and MR damper are respectively shown for various currents and sinusoidal excitation with frequency of 1HZ and amplitude of 0.5m. Obviously, intensifying the current increases the slope of the force-displacement curve and
surrounded area of the force-displacement curve of the MRE isolator. Note that the slope and area of the curve are related directly to the stiffness and damping, respectively. Therefore, the MRE isolator exhibits variable stiffness and damping properties. Moreover, obviously, intensifying the current increases the surrounded area of the force-displacement curve of the MR damper but does not change the slope of the curve. In other words, by intensifying the current, damping of the MR damper increases but stiffness does not change.

**Figure 12.** The force-displacement and force-velocity relationships of the MRE isolator for various currents

**Figure 13.** The force-displacement and force-velocity relationships of the MR damper for various currents

In Figures 14 and 15, the force-displacement and force-velocity relationships of the seismic isolator and MR damper are respectively illustrated for the current of 1A, sinusoidal excitation with frequency of 1HZ and various amplitude. It is clear that the MRE isolator behavior is linear in small displacements but nonlinear in large displacements. It is also clear that the MR damper behavior is nonlinear in all displacements. It should be added that more energy can be absorbed when the system behavior is nonlinear.

**Figure 14.** Force-displacement and fore-velocity relationships of the MRE isolator for various amplitudes

**Figure 15.** Force-displacement and fore-velocity relationships of the MR damper for various amplitudes

Therefore, it is concluded that:

1- The MRE isolator stiffness is dependent on the field while the yield stress of the MR damper is dependent on the field. In other words, the strength of the MRE isolator is determined by dependence of stiffness on the field while the strength of the MR damper is determined by dependence of yield stress on the field.

2- The MRE isolator acts with linear viscoelastic properties when the displacement is small. Increasing displacement causes nonlinear behavior of the MRE isolator. The linear viscoelastic region of the MR damper is in too small displacement. Therefore, the MR damper always behaves nonlinearly. In other words, the MRE isolator generally operates at the pre-yield region and increases displacement operates at the post-yield region while the MR damper operates at the post-yield region.

3- The MRE isolator has controllable mechanical properties. In other words, the MRE damper exhibits variable stiffness and damping properties while the MR damper exhibits damping controllable properties.

6. **Numerical result**
In this study, the base isolated benchmark building is used to study an MRE isolator behavior. A three-dimensional model of the base isolated benchmark building was developed by Narasimhan and Nagarajah in 2004. In order to investigate the effect of far-field and near-field earthquakes, according to the Iranian code of practice for seismic resistant design of buildings (Standard No 2800), three far-field and three near-field earthquakes are investigated. Earthquakes are scaled to the acceleration 0.5g. Far-field and near-field earthquakes are selected based on the distance to rupture surface and ground velocity amplitude. According to the research by Jangid and Kelly [58], near-fault, pulse-like motion can be associated with ground velocity amplitudes of approximately 50cm/s or greater. Thus, it can be assumed that ground velocities below approximately 30cm/s would not be associated with near-field motion [58-60]. The earthquakes used in this study are the Bam, Manjil and Tabas earthquakes (near-field earthquakes) and the Loma Perita, San Ferando and Boshruyeh earthquakes (far-field earthquakes). These earthquakes are applied simultaneously in two horizontal directions. Each of these earthquakes has two components, fault parallel (FP) and fault normal (FN). The components are in the north-south and east-west directions. Vertical earthquakes are not considered in the dynamic analysis of the base isolated benchmark building. The specifications of the earthquakes are shown in Table 5. Here, TP is the period pulse of the earthquakes and Rrup is the distance to rupture surface.

**Table 5. Specifications of the earthquakes used in this study**

| J1 | Peak base shear of the base isolated benchmark building (KN) |
| J2 | Peak story shear of the base isolated benchmark building (KN) |
| J3 | Peak base displacement of the base isolated benchmark building (m) |
| J4 | Peak story drift of the base isolated benchmark building (m) |
| J5 | Peak absolute acceleration of the base isolated benchmark building (m/s²) |
| J6 | Root mean square (RMS) base displacement of the base isolated benchmark building (m) |
| J7 | Root mean square (RMS) absolute acceleration of the base isolated benchmark building (m/s²) |

Figure 16 shows the earthquakes applied in the two directions of fault normal (FN) and fault parallel (FP). Figure 17 shows the acceleration spectrum of the earthquake records, and Figure 18 shows the Fourier spectrum of the earthquake records.

**Figure 16.** Earthquakes applied in the two directions of normal fault and parallel fault
Figure 17. The acceleration spectrum of the earthquake records

Figure 18. The Fourier spectrum of the earthquake records

Equipping the structure with the seismic isolation system increases the period of structure but reduces the acceleration entered into the structure. In earthquakes such as in Bam and Manjil, long period pulses are observed. Long period pulses increase the acceleration of the structure with the seismic isolation system. The seismic isolation system in such situations will have poor performance and may even cause serious damage to the structure. Such conditions are also observed in the Boshruyeh far-field earthquake. Traditional isolation systems usually design for 2 or 3 times the fundamental period of the structure. Therefore, they may encounter the problem described above. In other words, the structure may have a successful performance in an earthquake but poor performance in another. This problem is resolved in adaptive isolators. In adaptive isolators, isolation stiffness and damping change during the earthquake.

In this study, two fuzzy controllers are applied for specifying the MRE isolator current. The schematic control system is shown in Figure 19.

Figure 19. The schematic of the control system

Earthquakes for the directions $x$ and $y$ are simultaneously applied to the structure. Sensors measure the inputs of the controllers. Each controller has two inputs, namely base displacement and roof acceleration, in the $x$ and $y$ directions. The current applied to the isolator is the average of the current of the $x$ and $y$ directions. Finally, the isolator force is calculated and applied to the structure. Each input includes three Gaussian membership functions. These functions are shown in Figure 20. Membership functions for the output variable are shown in Figure 21, and the fuzzy rules are presented in Table 6. The surface of the fuzzy rules is illustrated in Figure 22.

Figure 20. Membership functions for the input variable (base displacement and acceleration)

Figure 21. Membership functions for the output variable (current)

Table 6. Fuzzy rules
In Figure 23, the force-displacement curve and force-velocity curve of the MRE isolator are illustrated for the Tabas near-field earthquake.

In Figure 24, the maximum relative displacements and floor accelerations for the three control cases are illustrated for different earthquake in the base isolated benchmark building. These controllers are the adaptive isolator (the MRE isolator), passive isolator (the elastomeric isolator) and semi-active MR damper (the hybrid system of the passive isolator and MR damper). The properties of the passive isolator are $K = 919.422 \frac{KN}{m}$ and $C = 27.717 \frac{KN \cdot S}{m}$ [59].

In all the earthquakes, except for the Tabas earthquake, the relative displacements and floor accelerations in the adaptive isolator are reduced more than those in the passive isolator and hybrid system. The distribution of relative displacement and floor accelerations in the passive isolator and hybrid system in the different earthquakes indicates the dependence of these controllers on the type of earthquake. In Figures 25 and 26, the time history of base displacement and roof acceleration of this building is shown.

It is observed that in all the earthquakes, except for the Tabas earthquake, the relative displacements and floor accelerations in the adaptive isolator are reduced more than those in the passive isolator and hybrid system. The distribution of relative displacement and floor accelerations in the passive isolator and hybrid system in the different earthquakes indicates the dependence of these controllers on the type of earthquake. In Figures 25 and 26, the time history of base displacement and roof acceleration of this building is shown.

It is observed that the maximum base displacement in the hybrid control system is smaller than that in the other two controllers, but the maximum roof acceleration in the adaptive isolator is smaller than that in the other two controllers. The maximum base displacement of the adaptive isolator is smaller than that of the passive isolator.

Maximum structural responses (base displacement, story drift, story acceleration, base shear, story shear) are calculated for comprehensive discussion of the MRE isolator behavior. In Tables 7 and 8, the maximum structural responses are shown for different control systems. Various control systems are presented below:
Case 1: 92 elastomeric isolators (The properties of the elastomeric isolator are $K = 919.422 \frac{KN}{m}$ and $C = 27.717 \frac{KN \cdot S}{m}$).

Case 2: 92 elastomeric isolators and 16 MR dampers (8 dampers in the $x$ direction and 8 dampers in the $y$ direction) (hybrid control system).

Case 3: 92 MRE isolators (The parameters of the MRE isolator are according to table 3).

In Case 2, the clipped optimal control is applied for specifying the voltage MR dampers. The parameters of the MR damper are according to table 4. The properties of the elastomeric isolator are $K = 919.422 \frac{KN}{m}$ and $C = 27.717 \frac{KN \cdot S}{m}$.

Table 7. Maximum structural responses for different control systems for the earthquake direction FPX-FNY

Table 8. Maximum structural responses for different control systems for the earthquake direction FPY-FNX

In Table 9, MRE isolator responses and elastomeric isolator responses are compared. In Table 10, MRE isolator responses and semi-active MR damper responses are compared.

Table 9. Comparison of MRE isolator responses with the elastomeric isolator (percent)

Table 10. Comparison of MRE isolator responses to the semi-active MR damper (percent)

It is observed that the MRE isolator in the near-field earthquake has a better control than the elastomeric isolator to reduce the base displacement, story drifts and floor accelerations. The semi-active MR damper, in contrast to the MRE isolator, has a better control in reducing base displacement, but causes to increase floor accelerations and story drifts. The MRE isolator, for both far-field and near-field earthquakes, has a better performance in reducing story acceleration, story drift and story shear compared to the semi-active MR damper.

7. Conclusion

This study investigated the performance of a new type of seismic isolator called MRE. Based on the past experimental results, a mathematical model is presented for this isolator. In this study, the MRE isolator is utilized in the benchmark base isolation building. Since the benchmark base isolation building is three-dimensional, the effects of bilateral interaction are considered in the MRE isolator behavior. The parameters
necessary to adapt the isolator analytical model to the isolator experimental model are specified in the past 
researches, and the same values have been used in this study. Three control cases are considered for different 
earthquakes in the base isolated benchmark building. The distribution of relative displacement and floor 
accelerations in the passive isolator and the semi-active MR damper in different earthquakes indicates the 
dependence of these controllers on the type of earthquake. Three far-field and three near-field earthquakes are 
investigated. It is observed that all the three control systems have the most responses for the Tabas earthquake. 
Due to the fact that the isolation period (the passive isolator) is equal to 3 seconds and the predominant 
frequency of this earthquake is equal to 0.22 HZ, the responses of passive isolator have increased and occurred a 
resonance phenomenon. Increasing the responsiveness of the adaptive isolator in this earthquake can be 
explained by factors such as the inability of the controller to create a proper current and time delay problem. 
Due to the non-designability of the adaptive isolator for the particular period and change of isolation stiffness 
and damping during the earthquake, the controller is unable to create a proper current during the peak time of 
the earthquake, which can lead to a lack of proper stiffness and damping. The adaptive isolator does not apply 
additional forces to the structure, although stiffness and damping of the isolator vary during earthquake thus it 
has better control of the structure and does not increase the floor accelerations and story drifts. The semi-active 
MR damper has a better control in reducing base displacement, but causes to increase floor accelerations and 
story drifts. From the trends of the observed results in form of structural response, the following conclusions can 
be made:

1- The semi active MR damper has a better performance to reduce base displacement compared to both 
passive isolator and adaptive isolator, but the adaptive isolator has a better performance to reduce base 
displacement compared to the passive isolator.

2- The adaptive isolator to reduce roof acceleration is more successful than that of the other two 
controllers.

3- The MRE isolator, in comparison with the elastomeric isolator, has better performance in near-field 
earthquakes than in far-field earthquakes to reduce the base displacement, story drifts and floor 
accelerations for example the average of responses in near-field earthquakes indicates that the MRE 
isolator, in comparison with the elastomeric isolator, can reduce base displacement (27.75%), floor 
acceleration (8.80%) and story drift (25.80%).

4- The semi-active MR damper for both far-field and near-field earthquakes has a better control to reduce 
base displacement, but causes to increase floor accelerations, story drifts and story shear. For example
the average of responses in near-field earthquakes indicates that the MRE isolator, in comparison with the semi-active MR damper, can increase base displacement (24.47%) while reducing floor acceleration and story drift by 20.29% and 20.42%, respectively. The average responses of far-field earthquakes indicate that the MRE isolator, in comparison with the semi-active MR damper, can increase base displacement (293.07%) while reducing floor acceleration and story drift by 66.30% and 31.63%, respectively. Note that base displacement is much less in far-field earthquakes than in near-field earthquakes for example the maximum base displacement in near-field and far-field earthquakes is 138 cm and 22 cm, respectively.

5- According to the results of this study, it can be observed that MRE isolator can be used instead of MR damper. The MRE isolator can reduce the base displacement without increasing other responses.

Reference

44. Gu, x., Yu, Y., Li, J. and Li, Y. "Semi-active control of magnetorheological elastomer base isolation


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**Figure 3.** The suggested model for the MRE isolator [46]

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### Tables

**Table 1.** Periods of the benchmark building [47]

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**Table 2.** The optimum values of the parameters of the MRE isolator [46]

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<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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<td>$\alpha_b$</td>
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**Table 3.** The parameters of the MRE isolator utilized in this study

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<th>Parameter</th>
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</table>

**Table 4.** The parameters of the MR damper utilized in the benchmark base isolation building [47]

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<th>Value</th>
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Table 5. Specifications of the earthquakes used in this study

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<th>PGD (cm)</th>
<th>PGV (cm/s)</th>
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Table 6. Fuzzy rules

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Table 7. Maximum structural responses for different control systems for the earthquake direction FPX-FNY

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<th>J4</th>
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</tr>
<tr>
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<td>Case 2</td>
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<td>1768</td>
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</tr>
<tr>
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<td>Case 3</td>
<td>651.1</td>
<td>573.2</td>
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<td>0.15</td>
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<td>0.01</td>
</tr>
<tr>
<td>Tabas</td>
<td>Case 1</td>
<td>10150</td>
<td>8549</td>
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</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>8063</td>
<td>6642</td>
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<td>0.001</td>
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<tr>
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<td>6463</td>
<td>5169</td>
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<td>0.001</td>
<td>0.41</td>
<td>0.08</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 8. Maximum structural responses for different control systems for the earthquake direction FPY-FNX

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Control case</th>
<th>J1</th>
<th>J2</th>
<th>J3</th>
<th>J4</th>
<th>J5</th>
<th>J6</th>
<th>J7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bam</td>
<td>Case 1</td>
<td>50040</td>
<td>42040</td>
<td>0.79</td>
<td>0.011</td>
<td>2.83</td>
<td>0.21</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>50740</td>
<td>42270</td>
<td>0.50</td>
<td>0.011</td>
<td>3.48</td>
<td>0.07</td>
<td>0.44</td>
</tr>
<tr>
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<td>Case 3</td>
<td>27090</td>
<td>21660</td>
<td>0.52</td>
<td>0.005</td>
<td>1.99</td>
<td>0.12</td>
<td>0.26</td>
</tr>
<tr>
<td>Manjil</td>
<td>Case 1</td>
<td>38830</td>
<td>32570</td>
<td>0.61</td>
<td>0.007</td>
<td>2.04</td>
<td>0.20</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>35690</td>
<td>31100</td>
<td>0.34</td>
<td>0.008</td>
<td>2.78</td>
<td>0.09</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>Case 3</td>
<td>17350</td>
<td>14330</td>
<td>0.62</td>
<td>0.004</td>
<td>1.05</td>
<td>0.24</td>
<td>0.30</td>
</tr>
<tr>
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<td>67570</td>
<td>57680</td>
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<td>0.017</td>
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<td>0.59</td>
<td>1.69</td>
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<tr>
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<td>47850</td>
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<tr>
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<td>76550</td>
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<td>0.022</td>
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<td>1.43</td>
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<tr>
<td>Loma Perita</td>
<td>Case 1</td>
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<td>3469</td>
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<tr>
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<td>Case 2</td>
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<td>3222</td>
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<td>0.01</td>
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<tr>
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<td>Case 3</td>
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<td>2207</td>
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<td>0.05</td>
</tr>
<tr>
<td>San Frando</td>
<td>Case 1</td>
<td>8394</td>
<td>706.1</td>
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<td>0.001</td>
<td>0.05</td>
<td>0.01</td>
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</tr>
<tr>
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<td>Case 2</td>
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</tr>
<tr>
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<td>573.4</td>
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<td>0.001</td>
<td>0.15</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
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<td>Case 2</td>
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<td>5808</td>
<td>0.09</td>
<td>0.001</td>
<td>1.83</td>
<td>0.03</td>
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</tr>
<tr>
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<td>Case 3</td>
<td>5903</td>
<td>4944</td>
<td>0.18</td>
<td>0.001</td>
<td>0.36</td>
<td>0.07</td>
<td>0.13</td>
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</table>
### Table 9. Comparison of MRE isolator responses with the elastomeric isolator (percent)

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>J1</th>
<th>J2</th>
<th>J3</th>
<th>J4</th>
<th>J5</th>
<th>J6</th>
<th>J7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average near-field</td>
<td>FPX-FNY</td>
<td>-24.70</td>
<td>-25.18</td>
<td>-33.53</td>
<td>-30.56</td>
<td>-4.60</td>
<td>-42.70</td>
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<tr>
<td>Average near-field</td>
<td>FPX-FNY</td>
<td>-34.39</td>
<td>-37.27</td>
<td>77.71</td>
<td>-27.86</td>
<td>39.16</td>
<td>102.08</td>
</tr>
<tr>
<td>Average Far-field</td>
<td>FPY-FNX</td>
<td>-29.39</td>
<td>-29.47</td>
<td>75.86</td>
<td>-2.62</td>
<td>59.38</td>
<td>82.63</td>
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</tbody>
</table>

### Table 10. Comparison of MRE isolator responses to the semi-active MR damper (percent)

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>J1</th>
<th>J2</th>
<th>J3</th>
<th>J4</th>
<th>J5</th>
<th>J6</th>
<th>J7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average near-field</td>
<td>FPX-FNY</td>
<td>-12.90</td>
<td>-14.21</td>
<td>2.27</td>
<td>-24.99</td>
<td>-20.62</td>
<td>44.79</td>
</tr>
<tr>
<td>Average near-field</td>
<td>FPX-FNY</td>
<td>-34.36</td>
<td>-38.01</td>
<td>310.45</td>
<td>-30.68</td>
<td>-62.24</td>
<td>739.80</td>
</tr>
<tr>
<td>Average Far-field</td>
<td>FPY-FNX</td>
<td>-32.63</td>
<td>-33.09</td>
<td>275.69</td>
<td>-32.57</td>
<td>-70.36</td>
<td>739.62</td>
</tr>
</tbody>
</table>

**Abbas Karamodin** received his B.S. and M.S. degrees in Structural Engineering from the University of Tehran (UT), in 1986, and his Ph.D. degree in Structural Engineering from Ferdowsi University of Mashhad (FUM), in 2009, with a minor in Structural Control. He has served in FUM as faculty member, since 1987. He has had 3 books published in his related field and more than 10 papers in respected journals and conference proceedings. His areas of research are earthquake engineering and structural control.

**Saeed Taghizadeh** is a Ph.D. degree student of Structural Engineering at Ferdowsi University of Mashhad (FUM). He received his M.S. degree from FUM in 2013. His research interests are earthquake engineering and structural control.