Innovative semi-active storey isolation system utilising novel magneto-rheological elastomer base isolators

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INNOVATIVE SEMI-ACTIVE STOREY ISOLATION SYSTEM UTILISING NOVEL MAGNETO-RHEOLOGICAL ELASTOMER BASE ISOLATORS

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ABSTRACT

Seismic base isolation has been a widely adopted technique for earthquake protection of civil infrastructures. As the technology matures, new innovative designs of the base isolation systems become increasingly attractive to researchers, especially storey base isolation systems due to its design flexibility and better performance for seismic protection. Moreover, considering the unpredictable and diverse nature of earthquakes, the conventional base isolation systems have reached their limit due to their inherent passive nature which is incapable to adjust their isolation frequencies according to the characteristics of the earthquakes. A recent advance on the development of an adaptive magneto-rheological elastomer (MRE) base isolator provides an opportunity for the research and development on new adaptive base isolation systems. In this paper, an innovative semi-active storey isolation system utilising the novel magneto-rheological elastomer base isolator has been proposed. The proposed isolation system design incorporates adaptive magneto-rheological elastomer isolators under each storey of the structure instead of being only installed beneath of the entire structure. Such innovative system allows high authority semi-active control of storey responses by instantly changing stiffness of the isolator. Extensive simulation has been conducted to investigate such system using 5-storey international benchmark model under four benchmark earthquakes.

KEYWORDS

Semi-active control, storey isolation, magneto-rheological elastomer, five-storey benchmark model.

INTRODUCTION

Since the advent of the concept of base isolation, it has been fascinating to the researchers to adopt base isolation system in seismic protection for civil structures, due to its distinguished effectiveness (Komodromos, 2001). The base isolation system is to decouple the superstructure from the ground motion by changing the stiffness and therefore the natural frequency of the structure and consequently reflecting the energy of the earthquake (Kelly, 1986). During the last century, a variety of ingenious base isolation strategies and mechanisms have been proposed and implemented into structures, which has saved countless lives and great properties (Symans et al., 2002).
However, owing to its intrinsic passive characteristic, the conventional base isolation system is incapable of coping with different types of earthquakes. Different solutions, such as active variable stiffness (AVS) system (Yang et al., 1994), hybrid base isolation system with tunable damping (Wongprasert and Symans, 2005; Kim et al., 2006), tunable stiffness and damping isolator (Liao et al., 2011) etc. have been proposed and comprehensively studied. Among them, the adjustable magnetorheological elastomer (MRE) base isolator (Li et al., 2012; Li et al. 2013a; Li et al. 2013b) is the first adaptive laminated base isolator prototype in the world. With the advantages of great MR effect, highly controllable stiffness, low manufacturing cost and simple implementation, the adaptive MRE base isolator shows promising seismic resistance performance. Therefore, innovative isolation system is demanded to fully utilise the uniqueness and merits of the MRE isolator.

With the development and maturation of the technique, the mid-storey isolation system is recently launched as a branch and innovation of base isolation system. At the moment, the mid-storey isolation system is mainly equipped in the high-rise buildings where overturning is one of the significant concerns with the isolation system (Chey et al., 2009). By incorporating the isolation interface into a middle level of the whole building according to architectural and structural design, the mid-storey isolation system can validly reduce the vibration responses caused by earthquake and secure the stability of the high-rise building at the same time. Many residential-commercial buildings with mid-storey isolation system have been put into use around the world, especially in China, Korea and Japan (Fu et al., 2001; Ko et al., 2008; Sueoka et al., 2001; Kawamura et al., 2000).

Inspired by the concept of mid-storey isolation system, this study proposed an innovative semi-active storey isolation system. By inserting the MRE isolator between every floor, the storey isolation system is able to directly alter the stiffness of building structure by changing the applied current of the isolators of the corresponding floor and thus endows the building with largest flexibility and high control authority. Therefore, such storey isolation system solves the problem that the base isolation system can hardly control the responses of higher levels above ground directly with the control force only applied on the ground floor. A five-storey benchmark building model has been utilised for numerical evaluation of the performance of this design. Comprehensive optimisation work has been conducted in order to explore the optimal solution for structural parameters under passive control. Simulation results indicate that the seismic resistance performance of the building with optimal storey isolation system is significantly superior to the bare frame and building with passive base isolation system under different types of earthquakes.

AN INNOVATIVE SEMI-ACTIVE STOREY ISOLATION SYSTEM

An adaptive MRE Base Isolator

Li et al. (Li et al. 2013b) designed and manufactured a highly adjustable adaptive MRE base isolator transformed from a traditional laminated rubber bearing structure, utilising the distinct characteristics and merits of MRE material. This design overcomes the shortcomings of the traditional base isolator caused by its intrinsic passive property by substituting the ordinary rubber element with the new soft MR elastomer whose shear modulus can be changed by the applied magnetic field. Figure 1 shows the schematics of the MRE isolator prototype. As shown in the cross-section view, 26 layers of steel sheet and 25 layers of MRE sheets both with thickness of 1 mm are alternately arranged in the device. A solenoid is equipped outside the laminated structure to provide a uniform magnetic field. The change of isolator’s stiffness with the increase of applied current under different external excitations is presented in Table 1.

Design and Application of the Storey Isolation System

As shown in Figure 2 (a), the proposed storey isolation system is formed by incorporation the MRE isolators with controllable stiffness under superstructure and between adjacent floors. Therefore, this storey isolation system is able to operate in two modes: 1) isolating mode, which means isolate every floor from the structure beneath it; 2) variable stiffness mode, which means the stiffness of the whole
structure can be adjusted at each DOF by altering the applied current on the MRE isolator. In order to demonstrate the effectiveness of the proposed system, a five-storey benchmark model building (Samali, B. 1999) is utilised. Schematics of the bare building, base-isolated building and storey-isolated building, where the MRE isolator and structural supporting elements of each floor are in series connection, are shown in Figure 2 (b).

Table 1. Effective stiffness of the MRE base isolator

<table>
<thead>
<tr>
<th>Effective Stiffness (Normalized, kN m⁻¹)</th>
<th>Δ = 4 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1 Hz</td>
</tr>
<tr>
<td>0.0 A</td>
<td>3.63</td>
</tr>
<tr>
<td>1.0 A</td>
<td>19.35</td>
</tr>
<tr>
<td>2.0 A</td>
<td>33.73</td>
</tr>
<tr>
<td>3.0 A</td>
<td>46.64</td>
</tr>
<tr>
<td>Increase (0-3 A) (%)</td>
<td>1186</td>
</tr>
</tbody>
</table>

Figure 1. Schematics of adaptive MRE

Figure 2. (a) Sketch of NDOF storey isolated structure  
(b) Schematic graphs of models in three cases

Assume that \( k_{0} = \alpha k_{0} \) and \( k'_{0} = 2k_{0} \), where \( k_{0} \) is the average of the original stiffness of each floor and \( k'_{0} \) is the assumed structural stiffness of the storey-isolated building so as to represent the stiffness matrix of the storey isolation system. Thus, the equivalent stiffness between each floor above ground floor can be given as:

\[
k = \frac{k_{b} k'_{0}}{k_{b} + k'_{0}} = \frac{2\alpha k_{0} k_{0}}{\alpha k_{0} + 2k_{0}} = \frac{2\alpha}{2+\alpha} k_{0}
\]

Therefore, the stiffness matrix of the proposed storey isolation system \( \tilde{R} \) can be written as:

\[
\tilde{R} = \begin{bmatrix}
0.005 + \frac{2a}{2+\alpha} k_{0} & -\frac{2a}{2+\alpha} k_{0} & 0 & 0 & 0 & 0 \\
-\frac{2a}{2+\alpha} k_{0} & \frac{4a}{2+\alpha} k_{0} & -\frac{2a}{2+\alpha} k_{0} & 0 & 0 & 0 \\
0 & -\frac{2a}{2+\alpha} k_{0} & \frac{4a}{2+\alpha} k_{0} & -\frac{2a}{2+\alpha} k_{0} & 0 & 0 \\
0 & 0 & -\frac{2a}{2+\alpha} k_{0} & \frac{4a}{2+\alpha} k_{0} & -\frac{2a}{2+\alpha} k_{0} & 0 \\
0 & 0 & 0 & -\frac{2a}{2+\alpha} k_{0} & \frac{4a}{2+\alpha} k_{0} & -\frac{2a}{2+\alpha} k_{0} \\
0 & 0 & 0 & 0 & -\frac{2a}{2+\alpha} k_{0} & \frac{4a}{2+\alpha} k_{0}
\end{bmatrix}
\]

It is obvious that \( \alpha \) is the only variable in \( \tilde{R} \) and \( \alpha \) shows the relationship between the stiffness of MRE base isolator and original structure, which provides the possibility to easily control the structural stiffness by altering the applied current to the isolator.

**Optimisation of Model Parameters**

Finding out the optimal parameters of the system under passive control situation is of great significance in generating the guideline for structural design. Hence, the optimisation algorithm employed called Non-Dominated Sorting Genetic Algorithm, type II (NSGAII) and two objectives respectively indicating the reduction level of floor acceleration and inter-storey drift are adopted. These two objectives shown in equations (3) and (4) describe the maximum value of the peak...

\[
O_1 = \max_{\text{center, Hachinohe, Northridge, Kobe}} \left\{ \max_{t=1:5} \left( \frac{\max_{t} x_{\text{a}}(t)}{g_{\text{max}}} \right) \right\}
\]

\[
O_2 = \max_{\text{center, Hachinohe, Northridge, Kobe}} \left\{ \max_{t=1:5} \left( \frac{\max_{t} d_{\text{i}}(t)}{d_{\text{max}}} \right) \right\}
\]

Where \(x_{\text{a}}(t), d_{\text{i}}(t)\) are the isolated building’s floor acceleration, inter-storey drift of the \(i\)-th floor over the time history, while \(x_{\text{a}}^{\text{max}}, d_{\text{i}}^{\text{max}}\) are the maximum absolute acceleration, inter-storey drift of the corresponding floor of the bare building (Ohtori et al., 2004). The optimal results of \(O_1\) and \(O_2\) and their corresponding values of \(\alpha\) are summarised in Table 2.

<table>
<thead>
<tr>
<th>(\alpha)</th>
<th>0.8436</th>
<th>0.8775</th>
<th>0.9708</th>
<th>0.9796</th>
<th>1.2648</th>
<th>1.2927</th>
</tr>
</thead>
<tbody>
<tr>
<td>(O_1 (g))</td>
<td>0.8847</td>
<td>0.8848</td>
<td>0.8849</td>
<td>0.8849</td>
<td>0.8850</td>
<td>0.8851</td>
</tr>
<tr>
<td>(O_2 (\mu m))</td>
<td>27.001</td>
<td>26.054</td>
<td>24.113</td>
<td>23.913</td>
<td>20.619</td>
<td>20.438</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>1.4188</td>
<td>1.4863</td>
<td>1.5155</td>
<td>1.5311</td>
<td>1.6006</td>
<td>2.0000</td>
</tr>
<tr>
<td>(O_1 (g))</td>
<td>0.8851</td>
<td>0.8852</td>
<td>0.8857</td>
<td>0.8859</td>
<td>0.8861</td>
<td>0.8895</td>
</tr>
<tr>
<td>(O_2 (\mu m))</td>
<td>19.827</td>
<td>19.289</td>
<td>18.538</td>
<td>18.257</td>
<td>17.742</td>
<td>15.913</td>
</tr>
</tbody>
</table>

**PERFORMANCE EVALUATION**

Comparative simulation analysis has been conducted by introducing scaled time histories of 4 benchmark earthquakes respectively into the models of bare building, base-isolated building and storey-isolated building so as to numerically assess the performance of these models. Moreover, matrices of mass, stiffness and damping of the storey isolation system where \(\alpha\) is 0.8436 are adopted as inputs to simulate the responses.

![Image](image-url)

**Figure 3.** Time histories of acceleration of the 5th floor, variations of accelerations (peak acceleration @ top floor) and inter-storey drifts (peak drift @ top floor) under 4 earthquakes

The time histories of the acceleration at the 5th floor in 3 cases under different earthquakes are shown in Figure 3. Clearly, the optimised storey isolation system exhibits much better capability in reducing the floor acceleration than base isolation system. Moreover, the acceleration responses of storey-
isolated building maintain a very low value in the whole duration of different earthquakes, while the base-isolated building is not as effective in controlling the response along the entire time history, especially under Kobe and Hachinohe Earthquakes, where the response of the base-isolated building’s even exceeds that of the bare frame at some time point.

Figure 3 also displays the variations of floor accelerations when the peak acceleration occurs at the top floor in the 3 cases. As shown in all variations, the acceleration of the bare building increases with the floor height except under Kobe earthquake where the maximum acceleration occurs at the 3rd floor. It can be clearly observed that both storey and base isolation systems achieve considerable reduction of floor acceleration contrasted to the bare building but the values of acceleration in the storey-isolated building are smaller than those of the base-isolated one in every floor. Besides, under different earthquakes, the shapes of the acceleration graphs of the base-isolated building are different, which demonstrates a strong dependence on the external excitation of the base isolation system resulted from its inherent passive nature.

Figure 4. Building profiles of maximum relative displacement at the top floor under 4 earthquakes

Additionally, Figures 3 and 4 illustrate the variations of inter-storey drifts and the building profiles when the top floor witnesses the maximum relative displacement. Inter-storey drift shows the deformation between the adjacent floors while the relative displacement intuitively reveals the shape of the building. As can be seen from Figure 3, under all earthquakes, the peak inter-storey drift of the bare building always occurs between the first and second levels, which implies the existence of a soft floor in the model. The performance of base-isolated building is not quite ideal. In that the inter-storey drifts between 5th and 4th floor are much larger than bare building’s corresponding drifts under all earthquakes and the drift between 4th and 3rd floor is also larger than that of the bare building under Kobe earthquake. However, the variations of the storey-isolated building exhibit a rather similar trend to those of the bare building with much smaller value showing a much superior inter-storey drift reduction performance to the base isolation system. Furthermore, the drifts of storey-isolated building between each floor are almost the same and very close to zero, which indicates a rigid body motion of the superstructure.

It can be clearly observed in Figure 4 that either the base or storey isolation system achieves the goal of reducing the relative displacement in each floor. However, the storey isolation system exhibits much better performance than the passive isolation system with much smaller accelerations in every floor than those of the passive isolated building. In addition, the profiles of the passive base isolated building are quite different under each earthquake, which is consistent with the dependency of variations of acceleration on the type of the earthquakes. Besides, matching with the observations in Figure 4, the profiles of storey-isolated buildings are almost vertical lines, showing that the inter-storey drifts are nearly zero and that every floor of the superstructure is moving synchronously like a rigid body.
CONCLUSION

By employing a novel highly adaptive MRE base isolator whose horizontal stiffness can be greatly changed by simply altering the applied electric current, an innovative semi-active storey isolation system has been developed and studied by the authors. Non-Dominated Sorting Genetic Algorithm has been adopted to conduct the optimisation work so as to obtain the guidelines for the design of structural parameters resulting in good performance under different types of earthquake attacks. Extensive simulation has been conducted utilising a five-storey benchmark building model. The simulation results demonstrate that, compared to bare building and base-isolated building models, the storey-isolated building is able to minimise floor acceleration and inter-storey drift of each floor at the same time. Moreover, the structural stiffness of each floor in the storey isolation system can be easily controlled by modifying the applied current to each isolator. Therefore, such isolation system allows high authority semi-active control of floor responses, which is the next stage of this study.

REFERENCES


