Performance-based seismic design of a spring-friction damper retrofit system installed in a steel frame

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Abstract. This study investigates a new seismic retrofit system that utilizes rotational friction dampers and axial springs. The retrofit system involves a steel frame with rotational friction dampers (RFD) at beam-column joints and linear springs at the corners, providing energy dissipation and self-centering capabilities to existing structures. The axial spring acts as a self-centering mechanism that eliminates residual deformations, while the friction damper mitigates seismic damage. To evaluate the seismic performance of the proposed retrofit system, a series of cyclic loading tests were carried out on a steel beam-column subassembly equipped with the proposed devices. An analytical model was then developed to validate the experimental results. A performance point ratio (PPR) was presented to optimize the design parameters of the retrofit system, and a performance-based seismic design strategy was developed based on the PPR. The retrofit system's effectiveness and the presented performance-based design approach were evaluated through case study models, and the analysis results demonstrated that the developed retrofit system and the performance-based design procedure were effective in retrofitting structures for multi-level design objectives.

Keywords: performance-based seismic design; seismic retrofit; self-centering; steel frame

1. Introduction

In order to build a sustainable society that can withstand various hazards and recover quickly after disastrous events, it is important to improve structural safety and decrease the socioeconomic effects of earthquakes. In many countries, earthquakes have caused severe social costs, making retrofitting existing buildings essential. However, conventional design practices have limitations on adaptable construction, implementable repair and maintenance, and health monitoring (Tabrizikahou et al. 2021). A superior option for vital and important buildings is the performance-based design, which uses optional choices to place multi-limit states of performance with respect to the hazard levels (ASCE-41 2017). Therefore, a superior option for vital and important buildings is the performance-based design which considers multi-hazard performance assessment of building structures and allows for integrated retrofit strategies.

According to Gkournelos et al. (2021), the selection of an appropriate seismic retrofit plan for a vulnerable building is a multi-dimensional process. ASCE-41 (2017) presents both demand-based and PBSD principles (Abdalla 2007) for strengthening buildings against earthquake effects. In previous studies, researchers have investigated the use of novel materials, reinforcements, and connections for retrofitting methods (Cao et al. 2021, Dereje et al. 2022). Several energy dissipators have been developed to retrofit building structures against seismic hazards, with various types of dampers transferring damage and deformations to specific parts (Zahrati et al. 2015, Mohammadi et al. 2020). Noureldin et al. (2018) conducted tests on steel slit damper and friction pads under cyclic loading, while Javidan and Kim (2020) developed and tested steel hysteretic column dampers for RC frames. Furthermore, a hybrid linked-column steel (HLCS) system was proposed, which consists of a steel plate shear wall coupled to two columns adjacent using link beams (Azzandari et al. 2021). Recently, Colajanni and Pagnotta (2022) suggested a friction-based beam-to-column connection for RC moment resisting frames made with hybrid steel-trussed concrete beams (HSTCBs).

The use of seismic energy dissipation devices having self-centering capability is becoming increasingly popular in enhancing the seismic performance of existing structures. Their ability to retrofit old structures makes them an economical means of improving their resilience to seismic activity. Many researchers (Naeem and Kim 2018; Yousef et al. 2020) investigated the self-centering systems to retrofit buildings. Noureldin et al. (2021-c) utilized concentric braced frames with friction dampers and disc springs to retrofit RC structures. Noureldin et al. (2023b and 2021b) employed re-centering friction devices to retrofit steel moment frame structures.

In the current investigation, a new seismic retrofit system composed of rotational friction damper and axial springs is studied. The presented retrofit system is...
constructed of steel members, friction pads, and springs assembled into a single frame. The combined system offers the advantage of reducing both residual and maximum displacements as a result of seismic retrofitting (Gharagoz et al. 2023). It also has the advantage of being easily transported to the site, as it can be divided into pieces.

To validate its seismic performance, the behavior of the steel frame sub-assembly equipped with a rotational friction damper and axial coil spring were investigated by cyclic loading tests. In the proposed retrofit system, the rotational friction damper dissipates seismic energy while the spring provides additional stiffness and self-centering force. To observe the seismic performance of the retrofit system and to develop an analysis model, a steel beam-column subassembly with a spring and a friction damper was tested under cyclic loads. Then parametric study was conducted to find the optimum friction damper/spring properties, and the performance point ratio (PPR) based seismic retrofit design procedure was developed for multi-limit states. The effectiveness of the presented retrofit system was evaluated by analyzing a case study structure before and after seismic retrofitting. Various demand parameters, such as maximum inter-story displacement and residual drift, were compared to assess the system's performance.

2. Configuration and analysis model of the proposed system

Fig. 1 depicts the proposed spring-rotational friction damper (SRFD) seismic retrofit system and its installation scheme. The retrofit system is composed of steel wide flange sections, coil springs, and the beam-column connections of the steel frame were equipped with friction dampers. High-strength bolts are used to secure the friction pads and provide a pre-defined clamping force. The rotational friction force is generated by the friction pads when the retrofit frame experiences lateral displacement. The system possesses both a hysteretic friction damper mechanism and a re-centering capability. The retrofit frame is fastened to the exterior surface of existing buildings at each floor level using anchor bolts. Using an outer steel frame is generally considered a cost-effective and labor-saving retrofit option in comparison to other methods.

Inertia force is generated at floor levels of a building during an earthquake. When the bending moment in the retrofit frame exceeds its frictional yield moment, the retrofit frame will deform, and the hysteretic behavior of the friction pads will dissipate seismic energy. During earthquakes, the spring undergoes deformation, thereby activating the re-centering capability of the retrofit system.

Fig. 2 illustrates the friction pad operated in the rotational friction damper. The pretension force in the bolt tightened by a torque wrench, known as preload, causes friction between components to withstand shear force and enhances the fatigue resistance of bolted links. A torque meter can be used to measure the bolt tension. Material properties for steel bolts are given in SAE standard J1199 and by bolt manufacturers. To calculate the force generated in the bolt by a torque wrench, the following equations were used (Oberg et al. 2000):

\[ T = K F d \left(1 - \frac{L}{100}\right) \]  

(1)

where \( T \) is the torque applied by the wrench to tighten the bolt (Nm), \( K \) is a constant factor that considers the bolt size and material, \( F \) is the clamping force the bolt applies to the surfaces being bolted, \( d \) is the diameter of the bolt (m), and \( L \) is the amount of lubrication which is considered to be zero in this study. The activation moment of the two friction pads can be calculated as (Javidan and Kim 2022):

\[ M_Y = \frac{2NF(R^2 - R^2)}{3(R^2 - R^2)} \]  

(2)

where \( N \) is the number of friction pads, \( \mu \) is the friction coefficient, and \( R_1 \) and \( R_2 \) are the inner and the outer radius of friction pads, respectively.

Fig. 3 depicts the analytical model of the proposed retrofit system, in which the spring and friction damper are linked in parallel. The rotational friction dampers dissipate seismic energy, while the axial springs provide additional stiffness and the re-centering force that will reduce or eliminate residual drifts. To obtain the load-deformation behavior, the spring and the friction damper were arranged in parallel in the analysis model, resulting in a polygon-shaped load-deformation curve. The lateral force at which the friction damper yields, \( F_{fY} \), can be obtained from the equivalence of the external and internal works as follows:
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Fig. 2 Friction pad used in the rotational friction damper

Fig. 3 Analysis model of the retrofit system

Fig. 4 Free-body diagram of the test specimen

\[ F_{fy} \Delta = M_y \theta \]  

(3)

where \( M_y \) is the yield moment of the friction damper, \( \Delta \) is the lateral displacement of the frame, and \( \theta \) is the corresponding rotation of the friction damper as depicted in Fig. 4. This study utilized the structural analysis software SAP2000 to develop a nonlinear analysis model of the spring-rotational friction damper. The axial spring was modeled using the ‘multi-linear elastic link’, and the rotational friction damper was modeled using the ‘multi-linear perfect plastic link’ with isotropic hysteresis.

3. Cyclic loading test of the subassembly

To assess the seismic performance of the presented system, the steel beam-column subassembly was equipped with a spring-rotational friction damper and subjected to cyclic loading tests. The observed behavior of the seismic retrofit system during the test was evaluated using an analysis model of the retrofit system. Fig. 5 illustrates the subassembly of the presented steel frame retrofit system and the dimension of each component. The friction damper was installed in the steel beam-column joint of the subassembly. The rotational friction damper utilized two circular friction pads, with an outer diameter of 150 mm and an inner diameter of 30 mm. The friction pads had a thickness of 5 mm, density of 1.62 g/cm³, and were assumed to have a friction coefficient of 0.35. To generate compressive force on the friction pads, a high-strength bolt with a diameter of 30 mm and tensile strength of 1.0 kN/mm² was installed at the center of the friction damper. The torque of 1.3 kNm was applied to the high-strength bolt using a torque wrench to generate friction force in the damper, and the bolt pretension generated by the torque was calculated to be 167 kN using Eq. (1). The activation moment was calculated by Eq. (2) to be 6.3 kNm. To ensure even distribution of clamping force over the pads, circular steel plates were inserted between the bolt head and the steel plate of the beam-column joint.

A heavy-duty coil spring with stiffness of 1.2 kN/mm was used at the corner of the subassembly to generate a recovery force. Table 1 presents the specifics of the experimented spring. The test setup and the force-displacement curve of the spring obtained from the loading test are shown in Fig. 6. It can be observed that the initial stiffness of the spring is quite close to the nominal value provided by the manufacturer. However, the stiffness slightly increased when the displacement exceeded 15 mm. The spring remained elastic up to the displacement of 42 mm, which is the maximum displacement generated by the universal testing machine.

Fig. 7 illustrates the test setup of the subassembly for the cyclic loading tests. The end of the beam is rigidly fixed to the strong frame, while the joint of the beam and column lies on the support. The beam has a length of 1520 mm, while the column has a height of 1570 mm. The subassembly column was subjected to cyclic lateral loads in both positive and negative directions using a 1,000 kN hydraulic actuator mounted on a concrete wall.
A network of instrumentation, including load cell, LVDTs (linear variable differential transformers), and strain gauges was used to monitor the response of the test. The loading protocol for the quasi-static cyclic test was defined according to ACI 374.2r and consisted of repeated cycles of increasing deformation amplitudes. Fig. 8 illustrates the loading history.

To observe the force-displacement relationship of the subassembly with the friction damper and the spring, a displacement-controlled cyclic loading test was carried out on the specimen. The obtained force-displacement relationships from the cyclic loading tests are plotted in Fig. 9. It is evident from the plot that the overall stiffness of the system decreases when the spring is subjected to tension, which is one of the characteristics of the heavy-duty coil spring.

### Table 1 Specifics of the spring used in the subassembly

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Stiffness (kN/mm)</th>
<th>Yield Force (kg)</th>
<th>Yield Disp. (mm)</th>
<th>Length (mm)</th>
<th>Outer Diameter (mm)</th>
<th>Young's modulus (GPa)</th>
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<td>7852</td>
<td>65</td>
<td>325</td>
<td>200</td>
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</tbody>
</table>

4. **Seismic retrofit design procedure of the proposed system**

In this section the seismic retrofit design process of the proposed retrofit system is developed to meet multiple limit states for various levels of seismic hazards. To satisfy these requirements with minimum cost, the design parameters of the retrofit device, the stiffness of the spring and the yield force of the friction damper, need to be accurately determined. However, finding optimal design parameters can be a complex and difficult process that often requires automated design algorithms. In this study, a novel hybrid performance-based seismic retrofit design approach is presented based on the Latin Hypercube Sampling (LHS), NLTH analysis, and a performance point ratio (PPR).

LHS is a statistical technique widely used in various
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In engineering fields, including seismic design, LHS is used to examine how input variables affect the performance of a structure under seismic loads. By using LHS, it is ensured that a representative sample of the entire range of possible variable values is found, while the number of tests that need to be performed is minimized. This can save time and resources in the design process, while still providing a comprehensive analysis of the problem. Previous research indicates that LHS is effective in generating ground motion records for different seismic hazard levels and capturing the uncertainty in input variables efficiently during the design process (Vamvatsikos 2014). Masoomzadeh et al. (2023) utilized LHS in seismic hazard analysis, providing more precise estimates of seismic hazards than traditional methods. However, LHS has limitations such as computational cost when dealing with multiple input variables and the assumption that the probability distributions of each input variable are known, which may not always be the case in practice. In summary, LHS is a valuable tool for seismic design engineering as it can create informative and representative samples of input variables while capturing uncertainties in the design process; nevertheless, it is important to acknowledge its limitations and complement its use with other methods to achieve a more comprehensive solution of the seismic design problem.

The steel retrofit frame in the proposed retrofit system is designed to behave elastically during earthquake excitation, while the rotational friction damper (RFD) serves as a fuse that activates when the inertia forces induced by earthquakes exceed the friction yield capacity of the system. Once the friction dampers yield, the re-entering capability is activated by the springs. The primary design parameters of the retrofit system are the stiffness of the springs, $K_s$, and the yield moment of the friction damper, $M_r$, in each story. The remaining design parameters are dependent on these critical parameters. Fig. 10 shows the overall design process for the retrofit system, where the optimum values of the yield friction moment, $M_r$, and the stiffness of the spring, $K_s$, are obtained considering the required seismic hazard and limit states.

The first step of the retrofit design procedure is to determine a practical range of the spring stiffness $K_s$ and friction damper yield moment $M_r$, considering their availability in the market. The second step is to establish 100 random samples using the Latin Hypercube Sampling (LHS). This involves dividing the ranges of the input variables into equal intervals and randomly selecting one value from each interval, creating informative and representative samples. In this study, 10 samples were selected for each of the $K_s$ and $M_r$, and total of 100 sample pairs of $K_s$ and $M_r$ were generated by using the LHS for parametric study. The third step involves determining the limit states for the maximum inter-story drifts, $D_{\text{limit}}$, that correspond to the desired performance objectives. This is done based on the risk classification of the structure, the desired objective structural performance status, and the seismic hazard limit states. The maximum inter-story drift (MIDR) of the retrofitted structure, $D_{\text{frmax}}$, must be lower than $D_{\text{limit}}$, which means:

$$D_{\text{frmax}} < D_{\text{limit}}$$  \hspace{1cm} (4)

The fourth step involves conducting nonlinear time history analyses of the retrofitted structure using 15 earthquakes (EQs) scaled to the target response spectrum for each limit state to get the optimum spring stiffness $K_s$ and the yield moment of the friction dampers $M_r$ of the retrofit system. Three limit-states are considered in this research; namely, immediate occupancy (IO), life safety (LS), and collapse prevention (CP), which correspond to service level earthquake (SLE; 50%/50), design basis

Fig. 8 Loading protocol for cyclic loading test

Fig. 9 Force-displacement curves of the subassembly subjected to the cyclic load
Fig. 10 Flowchart of the proposed performance-based seismic retrofit design procedure

earthquake (DBE; 10%/50), and the maximum considered earthquake (MCE; 2%/50), respectively (ASCE-41 2017).

The subsequent step involves defining and computing the performance point ratio (PPR) for each pair of $K_s$ and $M_r$. The PPR incorporates the structure's drift and base shear for each limit state, and it is calculated as follows:

$$PPR = 1 - \frac{1}{6} \left( \frac{D_1}{D_{10}} + \frac{D_2}{D_{LS}} + \frac{D_3}{D_{CP}} + \frac{V_1}{V_{10}} + \frac{V_2}{V_{LS}} + \frac{V_3}{V_{CP}} \right)$$

(5)

where $D_1$, $D_2$, and $D_3$ are the maximum drift of the retrofitted system for each performance level (immediate occupancy, life safety, collapse prevention); $D_{10}$, $D_{LS}$, and $D_{CP}$ are the drift limit for each level; $V_1$, $V_2$, and $V_3$ are the maximum base shear of the retrofitted structure at each level; and $V_{10}$, $V_{LS}$, and $V_{CP}$ are the design base shear determined using the code formular at each performance level. After seismic retrofit of a structure, the drift of the system generally decreases while the base shear may increase. The maximum PPR will provide the optimal $K_s$ and $M_r$, which are applied to the seismic retrofit to enhance the seismic performance of the structures.

The steel elements of the retrofit frame are designed using the capacity design concept so that they remain elastic throughout the earthquakes. The maximum shear force created in the friction damper is used for designing the steel members and the anchor bolts which are used to attach the retrofit frame to the existing structure.

5. Case-study structures

The current study employs distinct structural models to validate and evaluate various configurations of structures. These models include a 3 story 2D reinforced concrete (RC) frame and a 3D asymmetric RC benchmark building as illustrated in Fig. 11. The design gravity loads for the 2D frame consist of a live load of 2.5 kN/m² and a dead load of 4.1 kN/m². The compressive strength of the concrete is 20.7 MPa, and the yield strength of the reinforcement steel is 413 MPa. Table 2 provides the structural details of the 2D model, and based on the information the fundamental period of the model was determined to be 0.35 second. The 3D asymmetric RC benchmark building model with plan asymmetry, which was originally proposed by Fajfar et al. (2006) and used in other studies (e.g., Noureldin et al. 2022b), has the fundamental period of 0.58 sec in the y-direction and 0.45 sec in the x-direction. The dynamic analyses considered the modal damping ratios of the RC models to be 5% of the critical damping.

W10 × 30 and W10 × 19 wide-flange sections were utilized as columns and beams of the retrofit frame, respectively. The sections of the steel members were selected to remain in the elastic range during earthquake ground excitation, and they are made of A992 structural steel with a nominal yield strength of 345 MPa. The stiffness of the springs and the yield moment of the rotational friction dampers in the retrofit frame were determined using the performance-based optimum design procedure explained in the previous section. The boundary conditions of all structures are considered fixed at base and no soil-structure interactions (Noureldin et al. 2023b, Ali et al. 2023a) is considered in the analysis.

6. Ground-motion records used for analysis

The seismic performance of the model structures was assessed before and after the seismic retrofit using three levels of seismic hazards. These levels corresponded to a 50%, 10%, and 2% probability of exceedance in 50 years (shortened to 50%/50, 10%/50, and 2%/50, respectively) or a return period of 75, 475, and 2475 years. These levels are associated with immediate occupancy, life safety, and collapse prevention limit states, respectively. Fifteen earthquakes were obtained from the PEER NGA Database (2021) for each hazard level. The response spectra of earthquakes with a 2475-year return period are illustrated in Fig. 12, along with their arithmetic mean and the target response spectrum. The target spectra are for a location in Los Angeles with a stiff soil profile and latitude and
7. Parametric study for the performance point ratio

Finding optimum parameters of the retrofit device is important for seismic performance of the device and for saving of seismic retrofit cost. In this study the optimum values for the friction damper capacity and the spring stiffness were determined based on the performance point ratio (PPR). To find the PPR of the parameters, the initial populations of the practical range of $K_s$ and $M_r$ were determined first.

The spring stiffness applied in structural engineering ranges from 100 kN/m to 3000 kN/m (JEES 2000). The yield friction moment of friction dampers in structural engineering depends on factors such as the structure's purpose, seismic loads, and safety requirements (Latour et al. 2014). The yield friction moment can range from 1 kNm for building and 100 kNm for bridge seismic retrofit. In this study, a range of 1-50 kNm was considered for $M_r$. Ten samples were selected for each of $K_s$ and $M_r$, total of 100 pairs of $K_s$ and $M_r$ samples were generated by using the LHS for parametric study. To find the PPR of the system using Eq. (5), fifteen earthquakes were used as ground motions compatible with the service level earthquakes (50%/50 years), design basis earthquakes (10%/50 years), and the maximum considered earthquakes (2%/50 years). The PPR was calculated using the mean values of the fifteen maximum drifts and the base shears of the structure.
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for each performance level. The limit states for the immediate occupancy (IO), life safety (LS), and collapse prevention (CP) performance levels were determined to be the maximum drift ratio of 1%, 2%, and 3%, respectively. The limit states for the base shear, determined based on the code formula for the design base shear at each performance level, were 150, 300, and 450 kN for the IO, LS, and CP performance levels, respectively. To find the optimum retrofit device parameters, it was assumed that the retrofit system was installed at mid-bay of the 2nd story.

Fig. 13 depicts the PPR of the model structure with varying Mr and Ks for the three performance levels, where it can be observed that the optimum Mr is 27 kN/m and the optimum Ks is 1200 kN/m for the three limit states. The model structure retrofitted with the proposed system achieved a PPR of 0.97. This indicates that the structure satisfies the given limit states with a narrow margin of acceptance.

8. Seismic performance evaluation of the example structures

As the model structures were mainly designed for gravity loads, they failed to satisfy the given limit states and needed seismic retrofit. Fig. 14 shows the case study structures retrofitted by the presented retrofit system. The performance of the presented retrofit system was evaluated by studying the maximum roof displacement, maximum inter-story drift ratio (MIDR), maximum residual drift, and energy dissipation of the bare and the retrofitted models. The stiffness of the springs and the yield moment of the rotational friction dampers were determined to be 1200 kN/m and 27 kN/m, respectively, based on the optimum PPR values.

NLTH analyses were conducted on the model structures to obtain the engineering demand parameters such as the maximum roof displacement, residual drift, and mean
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MIDR before and after the seismic retrofit (Noureldin et al. 2021a). Fifteen earthquakes were used in each hazard level for the performance evaluation of the structures as recommended by ASCE 41.

Fig. 15 indicates the maximum roof displacement of the 2D structure for the 15 earthquakes scaled to the CP hazard level. After the retrofit, the maximum displacement of the structure was observed to have decreased for all earthquakes considered. The mean residual drift of the 2D model subjected to the 15 earthquakes scaled to the three hazard levels is displayed in the histograms plotted in Fig. 16. After the seismic retrofit, a more significant reduction in residual drifts can be observed compared to the maximum displacements.

The mean MIDR of the bare and the retrofitted 2D and 3D structures subjected to the 15 earthquakes are depicted in Figs. 17-18, respectively.

The figure illustrates that in the bare 2D structure, the maximum MIDR was 1.41%, 2.8%, and 3.91% for the 50%/50, 10%/50, and 2%/50 hazard levels, respectively, exceeding the given limit states of all hazard levels; whereas these values decreased to 0.84%, 1.9%, and 2.76%, respectively, after the retrofit satisfying all limit states. Likewise, in the 3D model, the maximum MIDR values

Fig. 15 Maximum roof displacement of the 2D structure before and after retrofit for the 15 earthquakes of each limit estates

Fig. 16 Mean residual drift of the 2D model subjected to 15 earthquakes scaled to three hazard levels

(a) 475 years

(b) 2475 years

Fig. 17 Mean MIDR of the 2D model subjected to the 15 earthquakes scaled for various return periods
decreased from 1.9%, 2.68%, and 3.96% to 0.95%, 1.97%, and 2.95%, respectively, satisfying the limit states after the retrofit.

The energy dissipation of the 2D structure subjected to the Imperial Valley earthquake scaled to the CP hazard level is illustrated in Fig. 19. It is evident that the installation of the friction dampers has led to an increase in the maximum energy dissipation from 147 kNm to 328 kNm after the seismic retrofit.

9. Conclusions

In this research, a novel seismic retrofit system composed of rotational friction dampers for energy dissipation and axial springs for self-centering was studied. The seismic performance of the steel frame assembly, which was equipped with the retrofit devices, was evaluated by the cyclic loading test. The test results were used to develop an analysis model and a performance-based seismic design procedure for the retrofit system. The study used Latin hyperbolic sampling and performance point ratio to find optimal values for spring stiffness and friction damper yield moment. The effectiveness of the retrofit system was evaluated using a 2D and a 3D case study structure, with demand parameters such as maximum displacement, residual drift, mean maximum inter-story drift, and energy dissipation being compared.

The cyclic loading test of the beam-column subassembly test specimen confirmed that the proposed retrofit device functioned stably up to large displacement exceeding the limit states, and the analysis results of the model structures showed that the system effectively dissipates seismic energy and eliminates residual drift, when its parameter values were optimally determined. The proposed design procedure based on the PPR was identified as a useful tool for seismic retrofit design. Both in the 2D and 3D case study structures, the maximum inter-story drifts were diminished below the designated limit states for all three hazard levels, and the residual drifts were nearly eliminated after the retrofit. Based on the test and the analysis results, the proposed seismic retrofit system was concluded to be effective in enhancing the seismic safety of structures.

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