Seismic Retrofit Using Rocking Walls and Steel Dampers

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ABSTRACT

A retrofit system of prestressed concrete rocking walls and steel dampers is used to control the seismic damage mode and increase the strength and energy dissipating capacity of an 11 story steel reinforced concrete frame in Japan. Important details of the retrofit design are introduced. The seismic performance of the structure before and after the retrofit is evaluated through extensive nonlinear time history analysis. Results show that the rocking system can significantly reduce both the seismic responses to different earthquake ground motions and their scattering. This makes the damage mode and the seismic performance of the retrofitted building more predictable, leading to a possibility of more reliable performance-based seismic design.

INTRODUCTION

Despite decades of development of earthquake engineering in both theory and practice, damage is still inevitable for ordinary building structures subjected to unpredictable violent earthquakes. Ductility, as a form of damage, has long been considered helpful in reducing the structural seismic response, while it is unfavorable for the building owners to see apparent damages after the quake. Moreover, the seismic performance of building structures can be hardly predicted if the damage is arbitrarily distributed or concentrated in the structure. Hence, the control of structural damage has become a major topic in earthquake engineering, especially while the performance-based seismic design is getting more and more popular.

As suggested by many researchers, controlled rocking systems are effective in preventing the damage (or large deformation) to concentrate at some specified locations despite the variability of earthquakes ground motions, in which way the deformation pattern of the building is under control. By inserting high-efficient damping devices in these locations, the energy dissipating capacity of the structure can be significantly increased and the damage of these damping devices would be more acceptable if they are made easy to replace after the quake. Various rocking systems with added damping devices have been proposed such as in Ajrab *et al* (2004), Midorikawa *et al* (2007), Marriot *et al* (2008) and Deierlein *et al* (2009).

A rocking wall system is proposed in this paper and to be used in a retrofit project. In the following pages, the basic concept of this retrofit design is first explained, focusing on the control of possible failure modes and energy dissipating capacity of moment-resisting frames. The background and details of the retrofit project are then introduced. Extensive nonlinear time history analysis is carried out to assess the seismic performance of both the existing and retrofitted buildings.

DESIGN CONCEPT

The importance of controlling the failure mode of structures can be traced back to the plastic theory, in which the upper and lower bound theorems make it possible to readily estimate the ultimate plastic strength of structures, only if the real failure mode is under control. For a free moment-resisting frame with strong columns and weak beams as shown in Figure 1, possible failure modes under combined shear forces can be summarized as 5 cases, i.e. C1, C2, B1, B2 and CB3 in Figure 1, where solid circles represent plastic hinges.

Mode C1, C2, B1 and B2 are all partial failure modes, among which Mode C1 and C2 are column failure modes, Mode B1 and B2 are beam failure modes.

It is most dangerous for moment-resisting frames to perform Mode C1 or B1, where the energy dissipation is inadequate and the plastic rotation of the plastic hinges will be very large, leading to severe and uncontrollable plastic deformation of the structure. So these modes are not preferable in the structural design. In Mode C2 and B2, the frame has larger but still inadequate energy dissipating capacity. The plastic deformation of the structure will still be very large and difficult to control in the earthquake.

By contrast, Mode CB3 is a global failure mode which produces a maximum energy dissipating capacity in the structure. And the plastic rotation of each yielded part will not be too large.

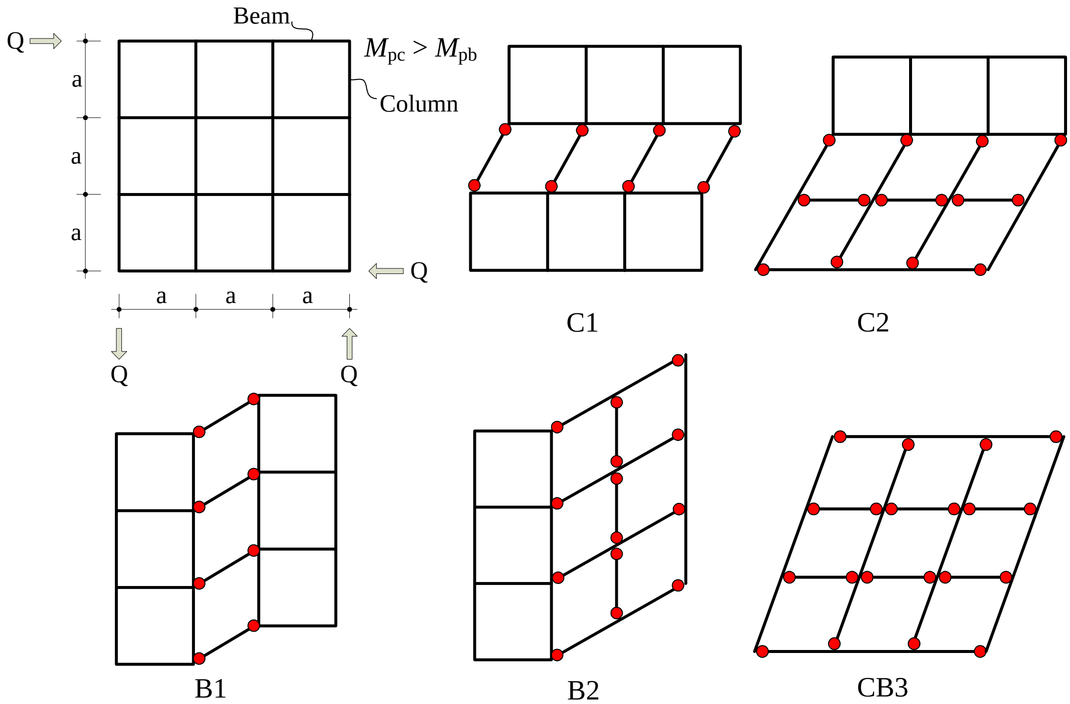
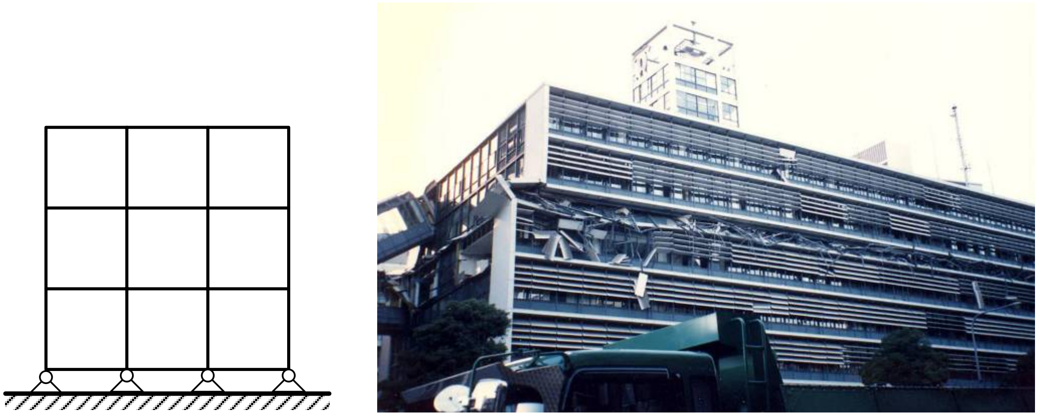


Figure 1. Possible failure modes for a free moment-resisting frame under combined shear forces

For real buildings resting on their foundations as shown in Figure 2(a), it's obvious that the beam failure modes B1 and B2 are hardly possible to occur in the earthquakes. In the past 40 years, almost no beam failure modes happened in structures subjected to strong earthquakes. Only Mode C1, C2 and CB3 are actually possible for frames resting on the foundations. As mentioned above, Mode C1 and C2 are not preferable for their inadequate energy dissipating capacity and consequent severe plastic deformation. Unfortunately, these two modes are much more likely to happen than the preferable global mode CB3, as observed in real building damages in historical significant earthquakes. The story collapse of the City Hall of Kobe as can be seen in Figure 2(b) is a well known example of Mode C1.

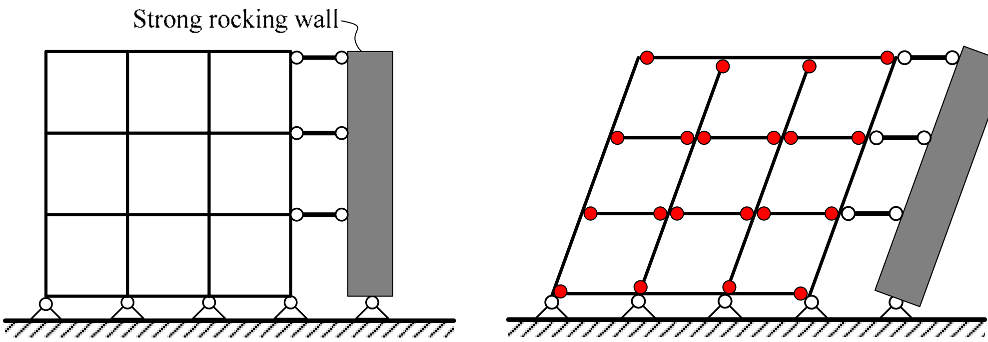
In the seismic design of multistory buildings, it's been well recognized by both researchers and practical engineers that the columns are much more important than beams for the seismic safety of building structures. This importance lies not only in their vertical load-bearing capacity, but also in the capability of columns to suppress the partial failure modes such as Mode C1 and C2.



(a) Generic frame (b) Story failure of the City Hall of Kobe

Figure 2. Moment resisting frames on the foundations

Based on this understanding, strong rocking walls are attached to the moment-resisting frame as shown in Figure 3(a). The rocking wall is pinned at the bottom to prevent damage when rocking. When the rocking walls are strong enough to suppress the partial failure modes such as Mode C1 or C2, a more preferable global failure mode in Figure 3(b) with maximum energy dissipating capacity and smaller plastic deformation can be achieved.



(a) Frame with rocking wall (b) Global failure mode

Figure 3. Moment resisting frame with strong rocking walls

RETROFIT DESIGN

G3 Building is a complex of the Graduate School of Science and Engineering located inside the Suzukakedai campus of Tokyo Institute of Technology in Japan. It was built in 1979 before the major revision of the seismic design provisions in the Building Standard Law of Japan in 1981. It has 11 stories above the ground and the roof elevation is 39.70m. The existing structure consists mainly of SRC frames as shown in Figure 4.

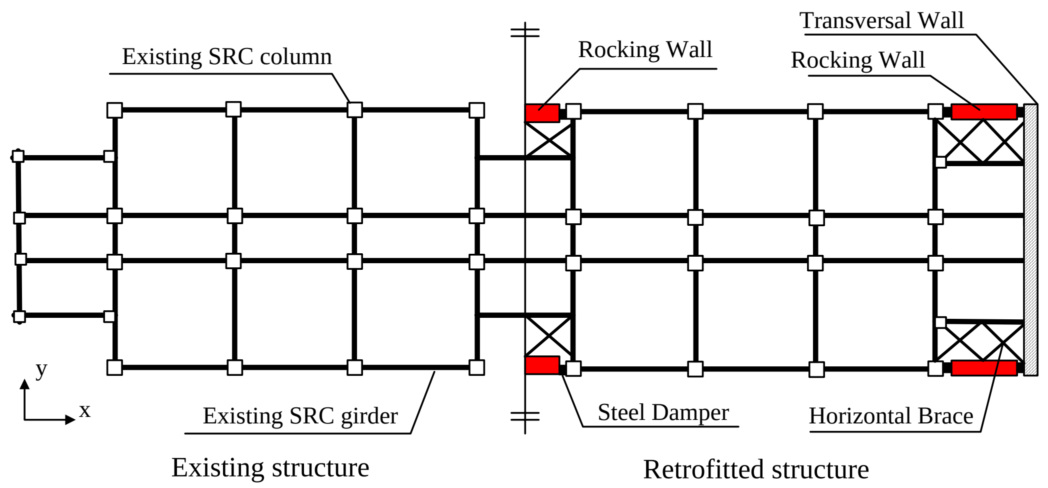


Figure 4. Structural plan layout of the existing and retrofitted building

According to a seismic inspection carried out in 2006, the existing structure can not fulfill the current requirements of the Japanese Building Standard Law and related specifications, especially in its longitudinal direction i.e. *x*-direction in Figure 4.

The seismic capacity index I_s of the existing structure along both its *x* and *y* direction given by the seismic inspection is shown in Figure 5. According to the Japanese codes (Japan Building Disaster Prevention Association 1997-2001), the building has to be demolished if I_s is below 0.3. Otherwise, retrofit is required if I_s is below 0.7. It can be seen in Figure 5 that I_s in the *x*-direction of the building below the 9th story is only around 0.4, which leads to an urgent effort to strengthen the structure.

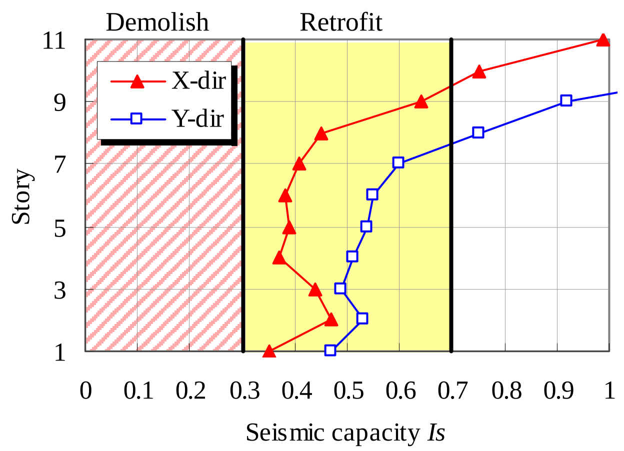


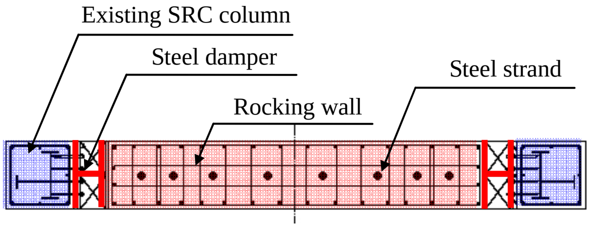
Figure 5. Seismic capacity *Is* of the existing building according to seismic inspection

Instead of strengthening individual members of the existing SRC frame, a different retrofit concept is adopted, which emphasizes the control of the global behavior rather than increasing the strength and deformation capacity of individual stories of the building. 6 pieces of very strong prestressed concrete (PC) walls with pin connections at the bottoms are to be attached to the building in the existing slots (Figure 4) in the hope of effectively controlling the global deformation pattern. These walls are connected at their centers to the floor slabs by horizontal steel braces as can been seen in Figure 4. When the structure is subjected to severe earthquakes along its *x*-direction, these PC walls are expected to rotate around their bases without being damaged or even cracking. The deformation pattern of the whole building is expected to be well controlled by these rocking walls and any weak story mechanism to be suppressed.

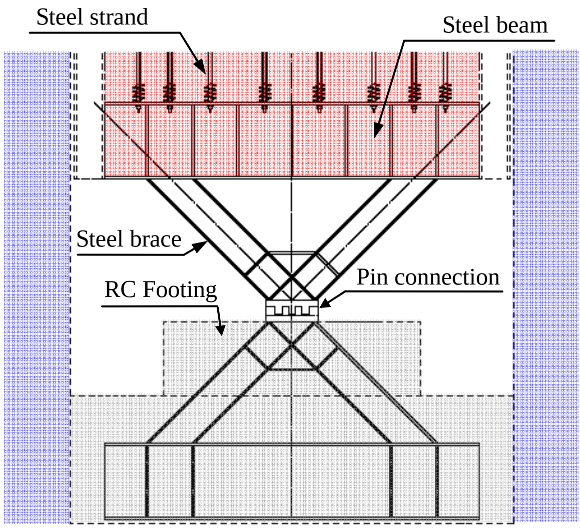
In the gaps between the rocking walls and the existing SRC frame, dozens of steel dampers are to be inserted (Figure 4). When the rocking walls rotate, severe yielding is supposed to happen in these dampers due to the incompatible vertical displacement between the rocking walls and their adjacent SRC columns. These dampers will provide considerable additional moment-resisting capacity as well as energy dissipating capacity. Figure 6 gives a visual 3D demonstration of this retrofit design. More details of the rocking walls and steel dampers are given in Figure 7. All the 6 rocking walls have identical cross-sections of 4400mm in width and 600mm in depth. The total cross section area of the rocking walls in each story is about 51% to 62% of that of the existing SRC frame from the bottom to the top. To increase the cracking strength of the rocking walls, post-tension prestressed strands with yield strength of 1230MPa are to be applied (Figure 7a). The control prestress is determined to be 837.4MPa, which is 68% of the strand's yield strength.

(a) Existing (b) Retrofitted

Figure 6. 3D view of G3 Building before and after retrofit



(a) Cross Section



(b) Elevation

Figure 7. Detailing of the rocking wall and steel damper

To prevent severe damage at the bottom of the walls when rocking, pin connection as shown in Figure 7(b) is proposed. The rocking wall is resting on a steel beam on which the steel strands are anchored. The steel beam is supported by two opposite pairs of steel braces connected in the center by a tooth-shaped pin connection, which allows for no lateral translation but rotation. The lower pair of steel braces is encased in a reinforced concrete footing.

For the rocking walls at the center, steel dampers are inserted from the 2nd to the roof story while from 2nd to 9th story for walls at both ends. All the steel dampers have identical depths of 350mm, which is equal to the distance between the rocking wall and its adjacent column. The thickness of the web plates of all the dampers are 6mm. The widths of the dampers vary from 1500mm at lower stories to 750mm at upper stories for the walls at the center, and from 1000mm to 750mm for the walls at both ends.

SEISMIC PERFORMANCE EVALUATION

The seismic responses of both the existing and retrofitted structure to a suite of 10 earthquake strong ground motion records are evaluated through nonlinear time history analysis with ABAQUS 6.7-1. Most of the ground motion records are selected from PEER/NGA database while one recorded by China Strong Motion Networks Center (CSMNC) in the Wenchuan Earthquake in May, 2008 in China is also included. All the records are scaled to PGV=50cm/s corresponding to the Level II earthquake in Japanese seismic design practice. The pseudo velocity spectra of the scaled records are shown in Figure 8, where the fundamental periods of the numerical models of the existing and retrofitted structure are also marked.

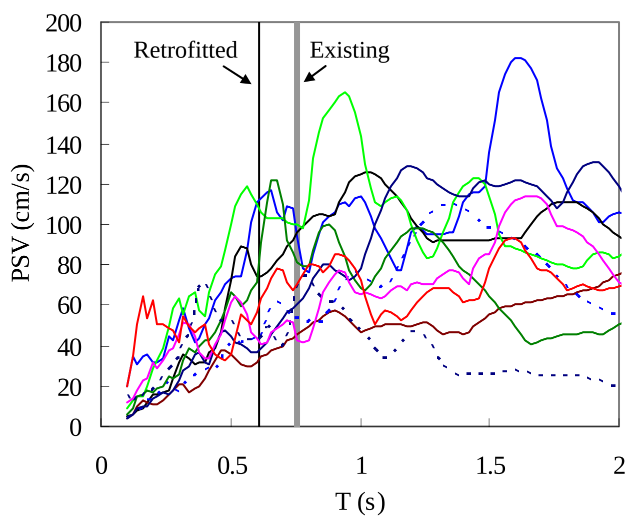
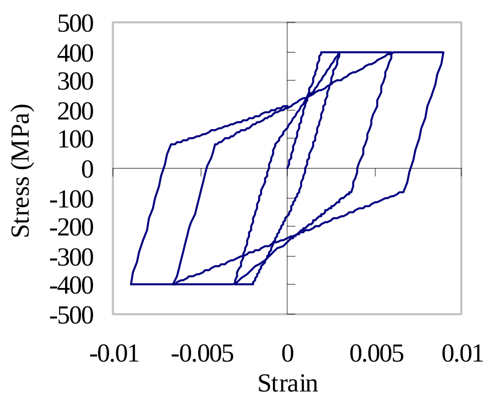
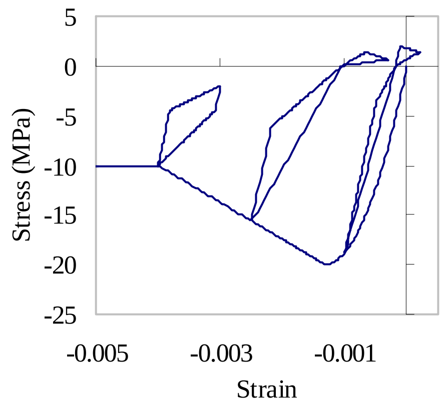


Figure 8. Pseudo spectral velocity of the 10 ground motion records

Due to the symmetry, only half of the structure along the *x*-direction is modeled by a 2D model which consists of 3 SRC frames. Nodes in the same story of the three frames are constrained to perform the same lateral translation in the *x*-direction. User-defined uniaxial hysteresis models for steel and concrete (Figure 9) are employed in the fiber beam element to simulate the behavior of the SRC frame members under axial loads and bending.



(a) Reinforcement



(b) Concrete

Figure 9. User-defined uniaxial hysteretic models

Since the rocking walls are designed to keep elastic during severe earthquakes, they're modeled by elastic beam elements with rigid horizontal beams connected with the dampers as can be seen in Figure 10. Steel dampers are modeled by pairs of springs (Figure 10) with elastic-perfectly plastic behavior for the vertical spring and elastic behavior for the horizontal braces and stiffeners.

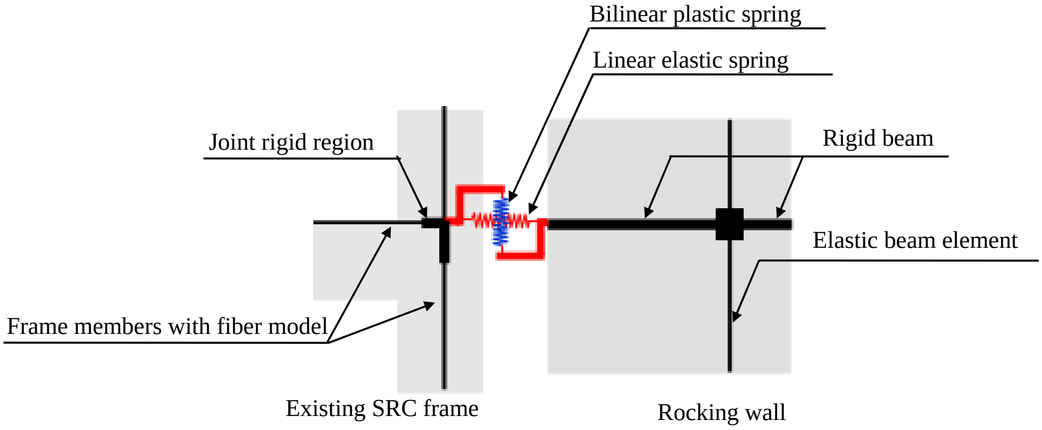
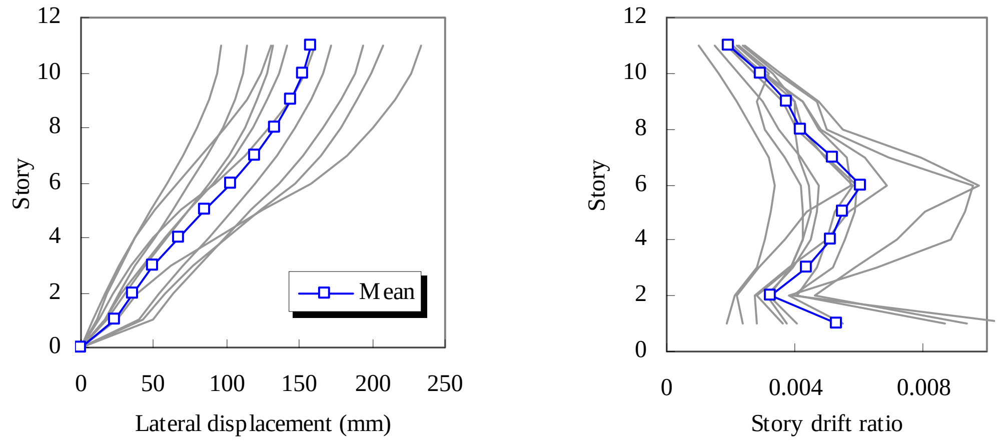
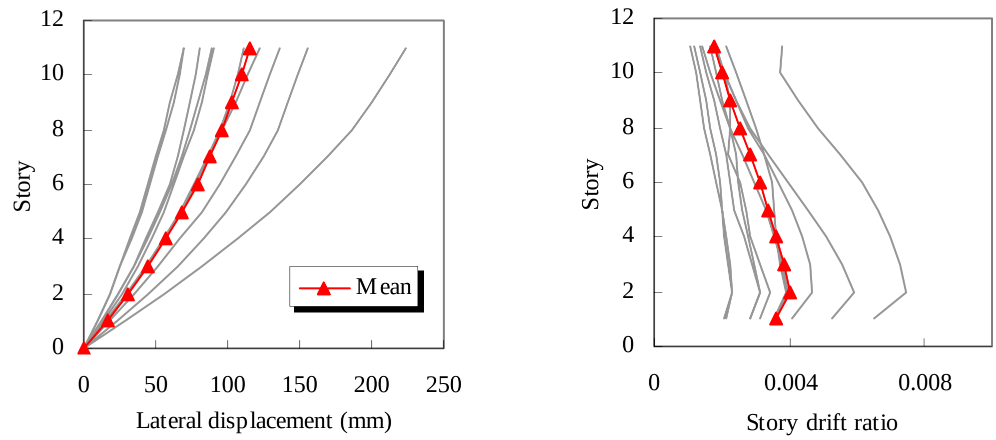


Figure 10. Modeling of rocking walls and steel dampers

Peak lateral displacement and story drift ratios of both existing and retrofitted structures subjected to the 10 ground motions are illustrated in Figure 11. For the existing structure, the first story is vulnerable to some of the ground motion records while some middle story, such as the 4th, 5th, 6th or 7th story becomes weak story when the structure is subjected to other ground motions. The distribution of deformation as well as the location of deformation concentration is quite arbitrary and hence unpredictable (Figure 11a). After retrofit, the deformation patterns of the structure subjected to different ground motions are almost the same, where the 2nd story suffers the largest story drift and the deformations decrease monotonically for higher stories (Figure 11b).



(a) Existing structure



(b) Retrofitted structure

Figure 11. Seismic performance of G3 Building before and after retrofit

To better demonstrate the seismic contribution of the rocking walls and the steel dampers, the responses of the existing structure retrofitted with only the rocking walls is further analyzed for comparison. The mean values and the standard deviations of the peak story drift ratios of the existing structure, the structure with only the rocking walls, and the structure with both the rocking walls and steel dampers given by numerical analysis are compared in Figure 12. In Figure 12(a), by adding only the rocking walls, the maximum peak story drift ratio of the existing structure is reduced while more importantly, the deformation pattern becomes much more uniform since the rocking walls are effective in suppressing higher mode vibrations and preventing weak story mechanism. The story drifts are further reduced by setting up the steel dampers, which, together with the rocking walls, provide additional lateral force resisting capacity and energy dissipating capacity.

It is seen that the rocking walls play an essential role in this retrofit scheme, which effectively controls the deformation pattern and hence the damage mode of the structure. On one hand, once the damage mode is under control, dampers and other strengthening members can be located so as to make full use of their energy dissipating capacity and strengths to reduce the overall seismic response. On the other hand, the controlled damage mode becomes much more predictable. Figure 12(b) compares the standard deviations divided by the mean story drifts for the structures subjected to the 10 ground motions. For each structure, the story drifts are scaled so that the same roof displacement is achieved under all the ground motions. This is to remove the variability of the ground motion intensity. It's clearly seen that the rocking walls significantly reduce the scattering of the story deformation, especially for the possible weak stories in the existing structure.

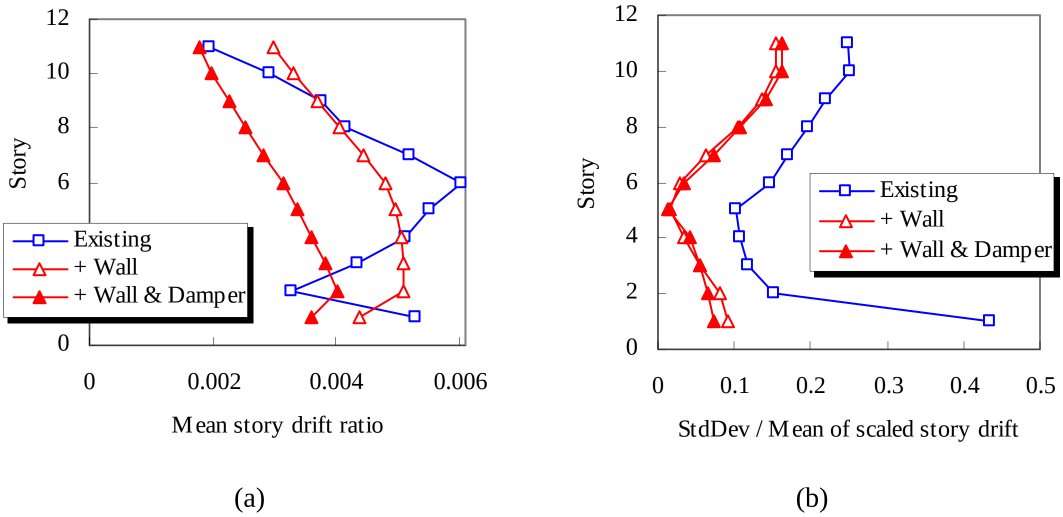


Figure 12. Seismic benefits of using rocking walls and steel dampers

CONCLUDING REMARKS

The retrofit scheme of G3 Building as introduced above re-recognizes the importance of controlling the structural damage mode. In static design, the ultimate strength of the structure can be readily estimated by the upper-bound theorem once the actual failure mode is known. In seismic design, however, it is believed that more than one failure mode are possible for a given structure since the seismic ground motion is always variable and unknown, which leads to great difficulties in estimating the ultimate strength and seismic performance of the structure and conducting the performance-based seismic design. Controlling the damage and failure mode of the structure by some robust methods, which are expected to cover much of the ground motion variability, is essential to overcome these difficulties. The strong rocking walls in G3 Building retrofit give us a good example of doing so. Engineers and researchers are encouraged to propose more innovative solutions to control the damage modes of various types of structures.

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