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Seismic Behavior of Concrete Buildings Using A Controlled Rocking Walls

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Abstract: *These days buildings are designed to support life safety performance level. Widespread damage caused by severe earthquakes due to permanent displacements in buildings, requires a great deal of time and effort to rebuild and rehabilitate these buildings. low damage systems classified in the category of inactive control systems are responsible for controlling permanent displacements and distribution of faults in the structure. In these systems, with the help of energy dissipation systems and pre-stressed cables, it is attempted to direct the damages to predetermined locations in the structure. In this paper, the seismic performance of different systems with rocking shear walls using pre-tensioned cables and dampers in the structure is examined with the view of improving the existing structure, and their performance is compared to the conventional use of fixed shear walls. By Using nonlinear dynamics analysis, we will examine various parameters in a two-dimensional frame with rocking systems. The results obtained in this study indicate that rocking systems are better suited rather than conventional systems used in terms of performance and other important parameters in structural responses and can be used as an alternative retrofit scheme.*

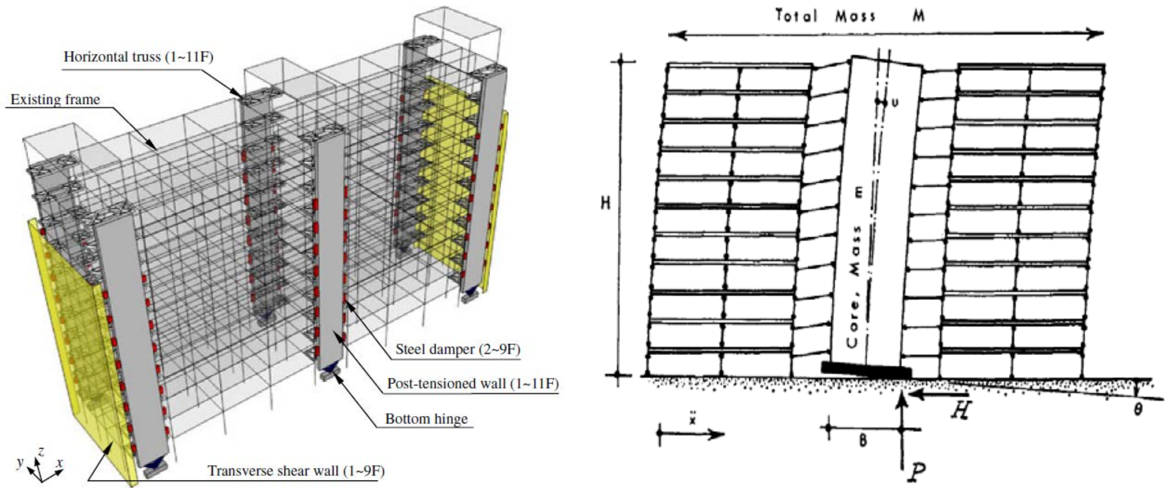
Keywords: Low Damage Systems, Rocking Shear Wall, Energy Dissipating Fuses, Post Tensioned Tendons, Concrete Building

INTRODUCTION

strength has been recognized as the most important characteristic of structures against external forces including earthquake. With the emergence of formable moment-resisting frames in the 1950s, formability was also introduced as another fundamental characteristic to confront severe earthquakes. Being entirely dependent on formability of moment-resisting frames, energy dissipation capacity imposes positive impacts on structural responses to external forces. In addition, the formability allows individual or groups of structural elements to participate in improving overall strength of the structure, so that the structure exhibits a more uniform performance against applied forces. Another point to note is that, the mechanism of plastic hinge formation in a structure imposes significant effects on formability demand of different elements under external forces.

In many of severe earthquakes in history (e.g. Mexico City Earthquake in 1985 and Hanshin-Awaji Earthquake in 1995), it has been witnessed that, the failure to occur an appropriate form of damage mechanism has imposed drastic damages to reinforced concrete frames (R. Villaverde, 1985; AIJ, 1997), and the issue has remained a serious challenge. This type of damage mechanism in reinforced concrete frames was also observed in other earthquake events such as Wenchuan Earthquake in 2008 with a magnitude of 8 Ms (X. J. U. a. B. J. U., 2008) and Tohoku Earthquake in 2011 with a magnitude of 9 Ms (AIJ, 2011). In order to avoid the formation of soft story, numerous attempts has been made to enhance inter-story integrity in formable frames. Among these activities, an acceptable method called “strong column-weak beam” was proposed and widely discussed by (T. Paulay, et al., 1992). For several decades, this method has been adopted in many credible codes around the world (Building code requirements, 2005; Concrete structures standard, 2004). Other researchers focused on the impact of a continuous vertical stiff mass on reduced concentration of damages along the height of structure. Akiyama and Takahashi proposed a relationship between the concentration of damage and stiffness which is known as “spreader column” (H. Akiyama, et al., 1984; H. Akiyama, et al., 1986). It is clear that, having larger cross-sectional areas, structural walls are way more effective than a column in providing the structure with higher bending stiffness. As was suggested by Paulay and Priestly (T. Paulay, et al., 1992), soft story formation is avoidable in structures with structural walls due to the creation of large bending stiffness. Alavi and Krawinkler proposed the use of integrated wall for improving seismic performance of structural frames under near-field records (B. Alavi, et al., 2004) In that study, a 20-story frame was modeled once with fixed base wall and once more with the wall connected to the ground via a joint; the model was subjected to nonlinear dynamic analysis using a pulsating motion simulating near-fault ground motion during an earthquake. Subsequently, performance of the jointed wall was compared against structural walls which are commonly used in fixed mode. Finally, it was found that, the jointed wall contributes to reduction of maximum relative displacement in the structure and more uniform distribution of relative displacement across the structure. In addition, shear and bending demands were much lower in jointed walls rather than fixed walls.

Energy dissipation capacity is another important parameter for improving seismic performance of these dual systems. Presentation of novel methods for further improvement of energy dissipation capacity in walls with flexible supports (the walls that are not fixed to the ground) has been long studied, ending up with the recognition of rocking walls. The idea of reciprocating motion in a structure during an earthquake event was first raised by Housner (G. W. Housner, 1963) who developed the idea based on the damages caused by Chile Earthquake in 1960. Housner was the first to investigate free oscillation response of a rigid frame exhibiting reciprocating motion. In the mentioned earthquake, it was found that, several structures had unintentionally exhibited rocking motions and this prevented them from a possible collapse. Parameters of the response of this system were evaluated by Meek in 1978 who considered formability of elements in the course of rocking wall motion (Figure 1-B); such structures were then-introduced as stiff-core structures (J. W. Meek, 1978). In 1978, Aslam et al. utilized computer-assisted modeling and verified their model with an experimental model and suggested that, strength of rocking walls can be enhanced using bars between the wall and the ground for dissipation. They also used pre-stressing in the bars connecting the wall to the ground. Pre-manufactured rocking walls were examined by (T. Holden, et al., 2003). Later on, Restrepo and Rahman constructed an experimental model wherein cable was used to provide the model with elasticity. Moreover, reinforcements were provided on the wall base for energy dissipation (J. Restrepo, 2007). Ajrab et al. introduced a wall-frame system equipped with a cable system wherein pre-stressed cables were connected to the top of rocking walls and a number of energy dissipating devices absorbed energy along the height of the structure. Various models of incorporating the cables into the model were considered (j. J. Ajrab, et al., 2004). (D. Marriott, et al., 2008) presented an experimental study on other solutions for energy dissipation in rocking walls. Steel and viscous energy dissipating devices were installed at the support of the wall to dissipate energy when the wall was lifted. (Z. Qu, et al., 2012) used six walls with jointed connections to design a rehabilitation plan for a 12-story structure in Japan (Figure 1-A). In this plan, steel dissipating devices were adopted all along the wall. Moreover, six pre-stressed cables were incorporated into each wall to maintain the wall integrity. Results of these studies indicated that, the use of this system results in enhanced integrated performance of the structure even under severe earthquakes.

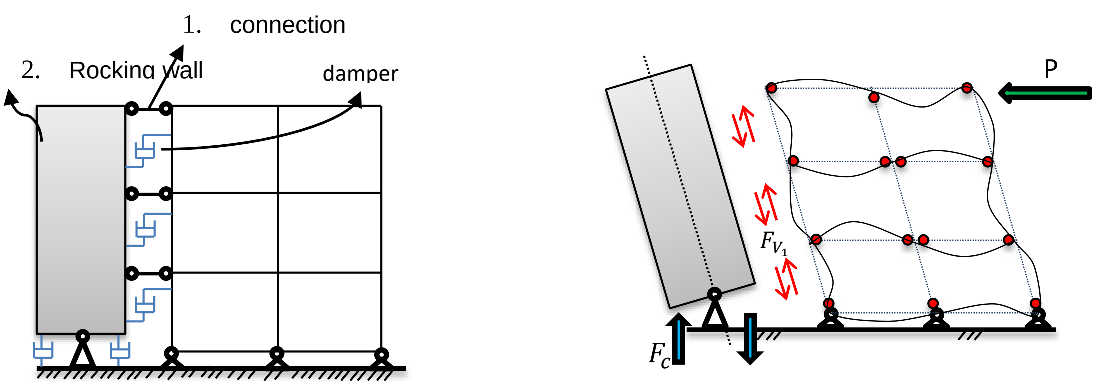


(A) (B)

Figure 1: Structural models using rocking wall motion: (A) rigid concrete core (adapted from Meek (1978) (J. W. Meek, 1978)), and (B) rehabilitation plan using jointed walls (adapted from (Z. Qu, et al., 2012))

1. Rocking wall-frame system

This system is composed of an integrated wall together with a concrete frame, with the wall connected to each story long height of the structure via particular connections. One of the advantages of using the rocking system in this wall is that the system provides spaces for energy dissipation in the structure, so that energy dissipating devices can be installed in the space between wall and frame and also below the wall to reduced applied forces to the structure. Upon application of an external force onto the structure, the wall rotates around its support, subjecting the system to a uniform lateral deformation. The lateral movement of the wall results in a vertical displacement difference between wall and frame, which is the basis on which energy dissipating devices work; performance of the dissipating devices has been defined in two directions, namely shear (between wall and frame) and axial (below the wall) directions.



(A) (B)

Figure 2: A rocking wall –frame system: (A) elements of the system, and (B) internal forces.

In this system, it is anticipated that a major portion of the energy applied to the structure is absorbed by dissipating devices. Figure 2-A shows the arrangement of elements of the frame in the system, and Figure 2-B demonstrates forces and resultant deformation in the frame under earthquake force P.

As was mentioned earlier, various models of rocking walls in structures have been studied. In order to provide the wall with elasticity, some of models used pre-stressed cables in the body of wall.

In this paper, we begin with investigating the influence of different elements used in this system such as energy dissipating devices and cables. Then, responses of different popular models when using this system are compared to those of conventional methods for modeling structural walls in fixed mode.

2. Introduction of analytic model

Structural wall was modeled as a nonlinear shell element in the software. In order to investigate nonlinear behavior of the elements in the frame, plastic hinges were used on both sides of the elements. All of beam-to-column connections across the frame were assumed as rigid.

In order to model the lift at wall base, gap element was used in the wall support, which resists against compression only. This element exhibits a similar performance to that of a jointed support when the value of stiffness, *k*, is assumed to be very large. This is while, a gap element can be displaced along its axial direction, with the axial stiffness of the element being zero in this direction. This element was used at both ends and also along the span at wall base. Configuration of this element is depicted in Figure 3.

$$f = \begin{cases} k & \text{اگر}\ n < 0 \\ 0 & n \geq 0 \end{cases}$$

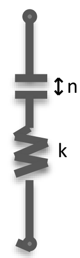


Figure 3: Configuration of gap element.

Post-tensioning and elasticity of the wall was provided using cable element. Characteristics of the used cable can be observed in Figure 4. A stress-strain curve with hardening was used to model the employed cable with the yield being considered at 85% of rated ultimate tensile strength of the cable, after which ultimate strength of the cable at 1.8 GPa was reached following a hardening trend.

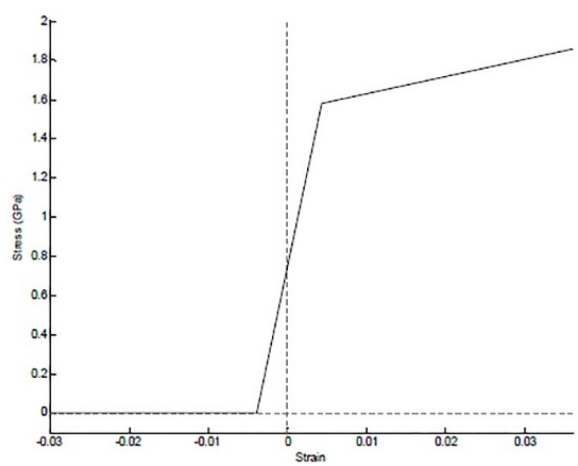


Figure 4: Stress-strain curve of the pre-stressed cable.

In order to undertake initial investigations about the effect of energy dissipating and restoring elements on overall performance of the frame, six model were used:

1. Wall with fixed support
2. Wall can exhibit rocking motion
3. Rocking wall with shear fuses between wall and frame
4. Rocking wall with shear fuse and axial fuses below the wall
5. Rocking wall with axial shear fuses between wall and frame and axial fuses at wall supports
6. Rocking wall, shear fuse, axial fuse at base, and cable.

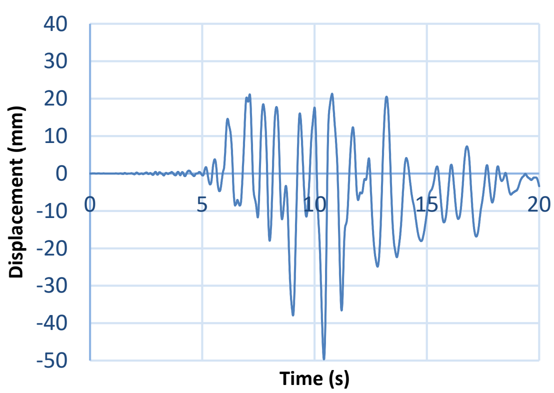
In the model No. 5, a rigid diagram is considered separately in the wall and frame at story levels, allowing for decreasing or increasing the wall-frame distance. This is while, using the axial energy absorption capacity at the fuse, an attempt was made to further enhance energy dissipation across the structure. In the last model, two cables are provided on the two sides of the wall.

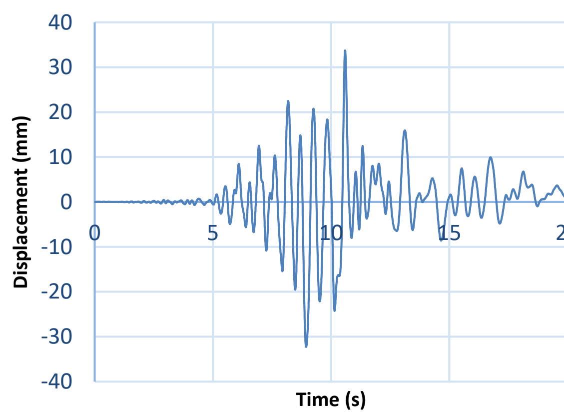
3. Results of the Analysis

The responses considered to investigate performance of the systems included maximum displacement at different stories, peak horizontal acceleration and vertical acceleration along the structure height, and frame performance against applied forces.

By leaving rocking walls free at support, displacements along the height increase. However, using properties of the elements comprising the system considering the applied force and characteristics of consumed material, regulatory requirements in the design of this system can be satisfied. Application of energy dissipating device in the considered frame left the system with some permanent displacement, which was a result of the dissipating devices yielding under the applied force. Figure 5 shows roof displacement history during El Centro Earthquake. As can be observed, the use of pre-stressed cables in the last model inhibited the permanent displacement from the system.

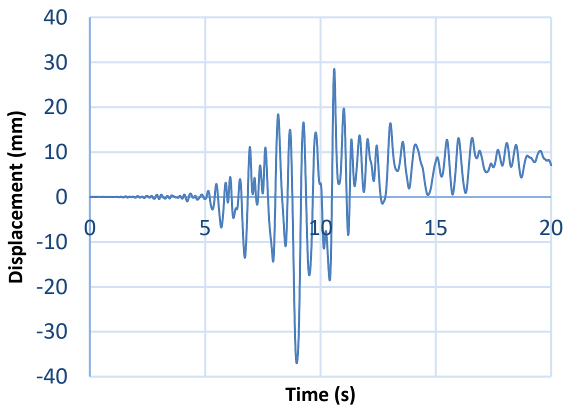
Figure 6 shows average displacements under the used records. In the second model, the use of rocking wall in the frame increased maximum displacement by more than 40%.



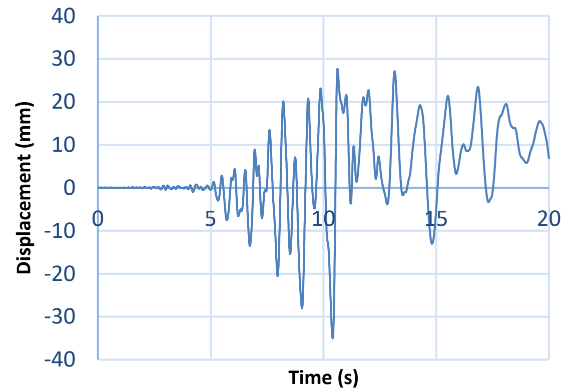


(b) model 2

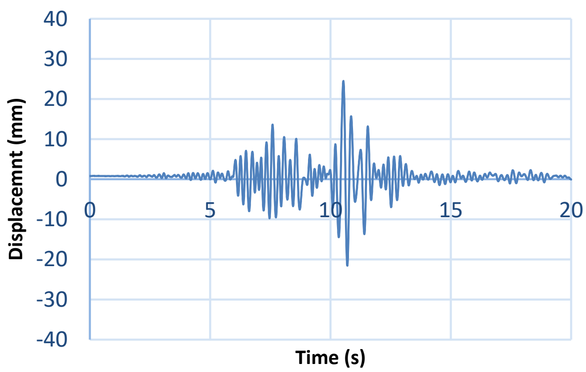
(a) model 1



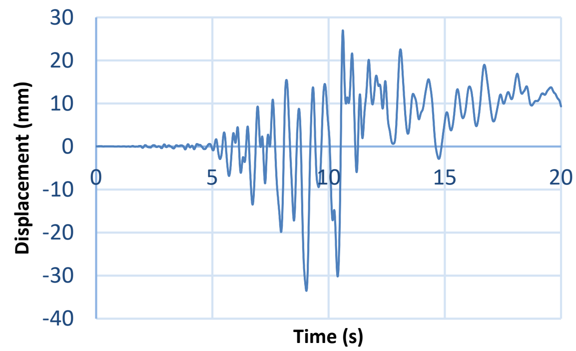
(d) model 4



(c) model 3



(f) model 6



(e) model 5

Figure 5: History of horizontal displacement on the roof under El Centro record.

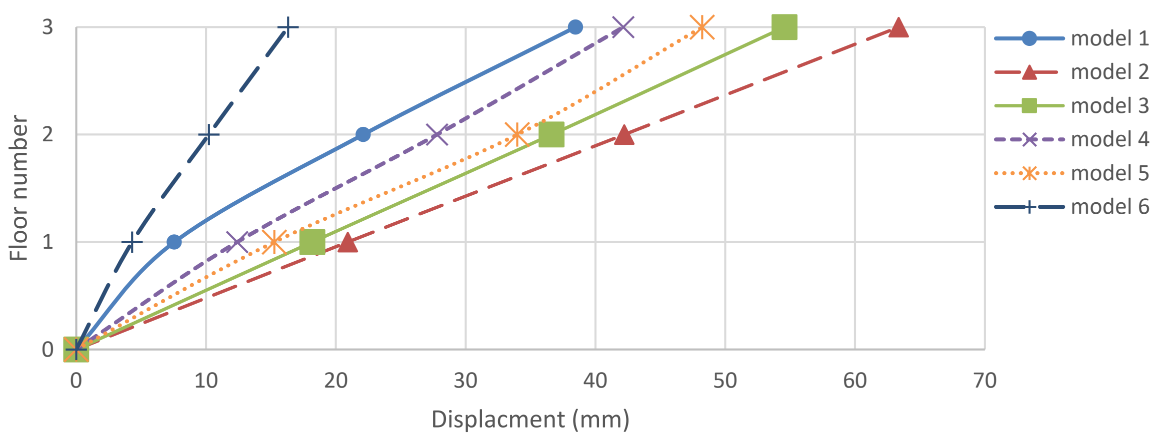


Figure 6 : Average relative displacement for each story

Using horizontal and vertical dissipating devices, one can greatly decrease the energy applied to the structure. On the meantime, the vertical dissipating devices used at wall supports play a more significant role.

Average horizontal and vertical accelerations in the considered stories are presented in Figure 7 and Figure 8, respectively. In the last model, due to the use of the cable, horizontal acceleration of the frame has increased remarkably. The lowest vertical acceleration was observed in model No. 5 into which energy dissipating devices were incorporated in both axial and shear directions.

Regarding the vertical acceleration, two important points shall be considered:

1. In the conventional design of structures with fixed structural walls, large shear forces are generally developed in boundary columns of the wall, which necessitate the design of larger columns. In this study, due to the establishment of equal conditions in modeling, boundary elements were located far from either sides of the wall. Indeed, the shear force in horizontal energy dissipating devices is the key driver of axial forces in the adjacent columns to the wall. As can be seen in Figure 8, in the first two model where no shear dissipating device is used between the wall and frame, no vertical acceleration was developed at the adjacent column to the wall.

2. Seismic records were applied one-directionally along the length of the frame. The presence of vertical component of seismic acceleration can result in the generation of an initial vertical acceleration in all structural elements.

In order to prevent transformation of high horizontal accelerations from the rocking wall to adjacent elements, one can use shear keys to separate shear performance of the wall from other parts of the structure (Z. Qu et al, 2012). Application of energy dissipating connections is another method used to prevent the creation of high velocities in adjacent elements.

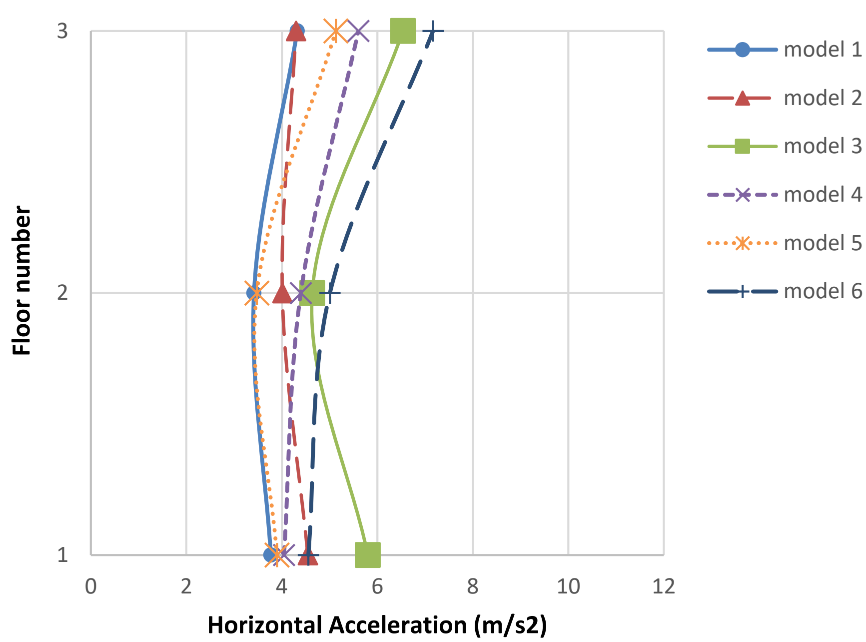


Figure 7: Average horizontal acceleration at different stories.

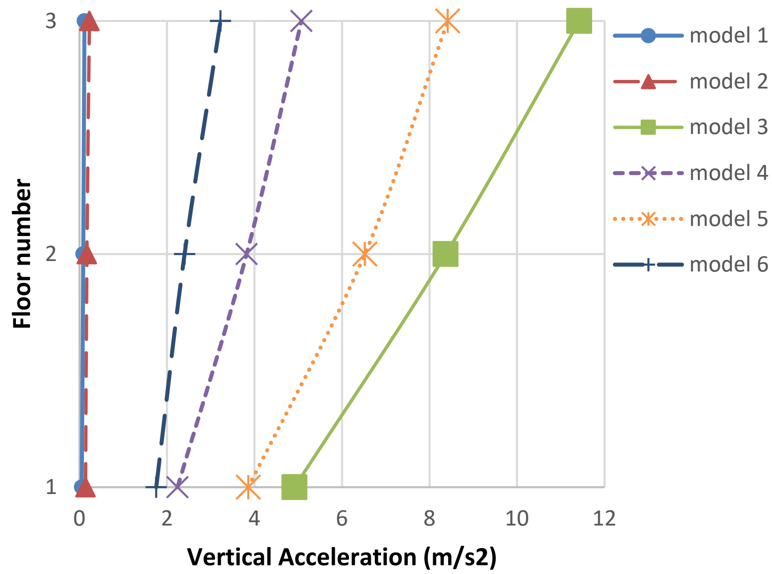


Figure 8: Average vertical acceleration at different stories

Conventional lateral force-resisting systems take advantage of inelastic behavior of structural elements (permanent damages) for energy dissipation. For instance, steel moment-resisting frame is designed based on input energy reduction by yielding the materials close to the end of beams. In metal frames with concentrically-braced frames, energy is dissipated via inelastic buckling or yielding of the braces. Concrete shear walls dissipate energy via yielding of bars and concrete failure at shear wall support. All of these energy dissipation mechanisms and other mechanisms used in conventional methods for designing structural strength against lateral forces are based on damage in primary structural elements in the base structure. Figure-9 shows failure mechanism occurred in some of common designs (N. B. Chancellor, et al., 2014).

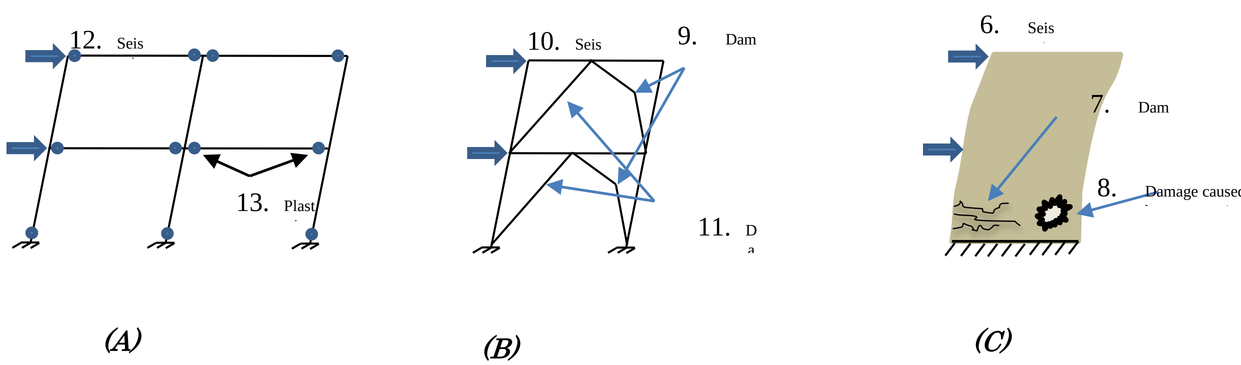


Figure 9: Mechanism of damage in conventional systems due to application of lateral force: (A) steel moment-resisting frame, (B) steel frame with convergent bracing, and (C) concrete shear wall (N. B. Chancellor, et al., 2014).

The closer the structural deformation gets to that of the first mode of the structure, the further soft story-caused damage can be prevented, because the higher number of formed plastic hinges dissipate larger deals of the energy applied to the structure. Figure 10 shows various cases of plastic hinge formation in the structure upon applying a lateral force. Using rocking motion of structural walls and appropriately designing energy dissipating elements, one can approach to the ideal performance demonstrated in Figure 10-D.

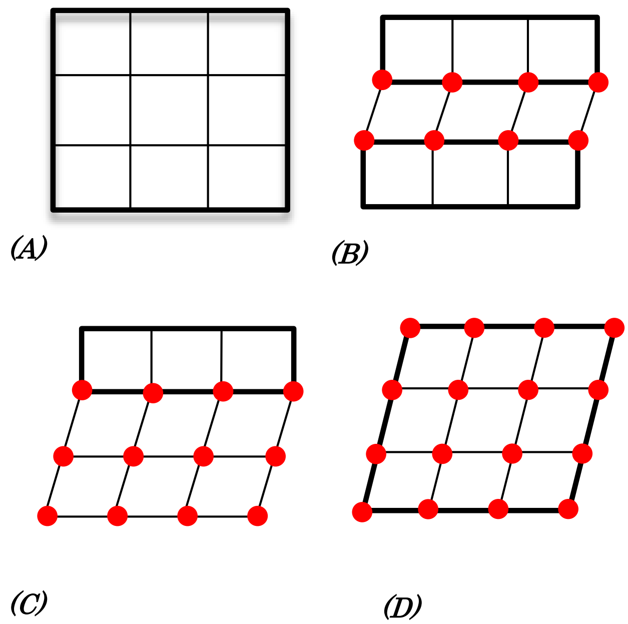


Figure 10: Plastic hinge formation mechanism upon application of increasing lateral force. Red points indicate the plastic hinges (D. Seymour, et al., 2011)

In order to better understand overall performance of the frame and investigate the effect of using rocking motion of the wall along with energy dissipating devices, performance levels of all models are graphed in Figure 11. As is mentioned in this figure, application of the cable in model No. 6 has constrained displacement of the structure, thereby getting the structural performance closer to the systems with fixed support.

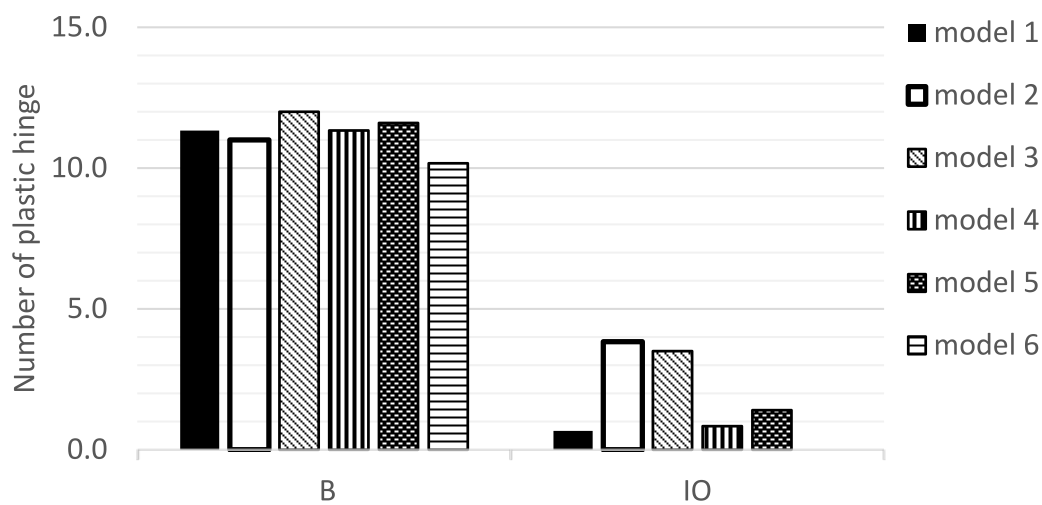


Figure 11: Frame performance levels in all of the studied models

4. Conclusion

1. In all of the models, the rocking wall reduced the deal of damage to the wall, because of integrated motion of the wall.
2. Using the rocking wall, differences in relative displacement among different stories across the structure decrease; this inhibits the formation of soft story in the structure and maximizes the number of plastic hinges and maximum energy dissipation across the system.
3. Adoption of energy dissipating devices between wall and frame imposes positive impacts on both acceleration and horizontal displacement of the structure.
4. Application of a well pre-stressed cable gets rocking performance of the wall closer to that of fixed case; there are cases where this imposes negative impacts on stresses developed in the body of the shear wall and the elements adjacent to the wall.

5. References

1. A. 3. M-05, Building code requirements for structural concrete and commentary, Michigan, US: American Concrete Institute: Farmington Hills, 2005.
2. AIJ, "Preliminary reconnaissance report of the 2011 Tohoku - Oki earthquake," Architectual Institute on Japan (AIJ), Tokyo, Japan, 2011
3. AIJ, "Report on the Hanshin-Awaji earthquake disaster-Building series volume 1: Structural damage to reinforced concrete buildings," Architectural Institute of Japan (AIJ), Japan, 1997
4. B. Alavi and H. Krawinkler, "Strengthening of moment-resisting frame structures against near-fault ground motion effects," Earthquack Engineering and Structural Dynamics, vol. 33, pp. 707-722, 2004.
5. D. Marriott, S. Pampanin and D. Bull, "Dynamic Testing of Precast, Post-Tensioned Rocking Wall Systems With Alternative Dissipating Solutions," Bulletin of the New Zealand Society for Earthquake Engineering, vol. 41, no. 2, pp. 90-103, 2008.
6. D. Seymour and S. Laflamme, "Quasi-Static Analysis of Rocking Wall System," Engineering Mechanics Institute, Boston, MA, June 2011.
7. G. W. Housner, "The behavior of inverted pendulum structures during earthquakes," Bulletin of the Seismological Society of America, vol. 53, no. 2, pp. 403-417, 1963.
8. H. Akiyama and M. Takahashi, "Ds-values for damage-dispersing type multi-story frames," Journal of Structural and Construction Engineering Transaction of AIJ, vol. 365, pp. 54-61, 1984 (in Japanese).
9. H. Akiyama and M. Takahashi, "Generalization of damage-dispersing type multi-story frames," Journal of Structural and Construction Engineering Transaction of AIJ, vol. 365, pp. 20-27, 1986 (in Japanese).
10. j. J. Ajrab, G. Pekcan and J. B. Mander, "Rocking Wall-Frame Structures with Supplemental Tendon Systems," Journal of Structural Engineering, vol. 130, no. 6, pp. 895-903, 2004.
11. J. Restrepo and A. Rahman, "Seismic Performance of Self-Centering Structural Walls Incorporating Energy Dissipators," Journal of Structural Engineering, vol. 133, no. 11, pp. 1560-1570, 2007.
12. J. W. Meek, "Dynamic response of tipping core building," Earthquake Engineering and Structural Dynamics, vol. 6, pp. 437-454, 1978.
13. N. B. Chancellor, M. R. Eatherton, D. A. Roke and T. Akbas, "Self-Centering Seismic Lateral Force Resisting Systems: High Perfomance Structures for the City of Tomorrow," buildings, vol. 4, no. 3, pp. 520-548, 2014.

14. R. Villaverde, "Explanation for the numerous upper floor collapses during the 1985 Mexico City earthquake," Earthquake Engineering and Structural Dynamics, vol. 20, pp. 223-241, 1991.
15. SNZ, Concrete structures standard (NZS 3101.1), New Zealand: Standards New Zealand: Wellington, 2004.
16. T. Holden, J. Resprepo and J. B. Mander, "Seismic Performance of Precast Reinforced and Prestressed Concrete Walls," Journal of Structural Engineering, vol. 129, no. 3, pp. 286-296, 2003.
17. T. Paulay and M. J. N. Priestley, Seismic Design of Reinforced Concrete and Masonry Buildings, New York: John Wiley & Sons, Inc., 1992
18. X. J. U. a. B. J. U. Civil and Structural Groups of Tsinghua University, "Analysis on seismic damage of buildings in the Wenchuan earthquake," Journal of Building Structures, vol. 29, no. 4, pp. 1-9, 2008
19. Z. Qu, A. Wada, S. Motoyui, H. Sakata and S. Kishiki, "Pin-supported walls for enhancing the seismic performance of building structures," Earthquake Engineering & Stuctural Dynamic, vol. 41, pp. 2075-2091, 2012.