

Structural performance evaluation of a new energy-dissipation and light-weight rocking frame by numerical analysis and experiment

D. Wu & X.L. Lu

State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China

ABSTRACT: The light-weight energy-dissipation rocking frame (EDLRF) is proposed by the authors and it is an innovative earthquake-resistant system that provides a resilient response by integrating self-centering energy-dissipation brace (SCED) as energy-dissipation unit and additional rigid frame as stiffness unit while minimizing residual drift and confining the damage mode of conventional structures. Supplemental stiffness is supplied for the original structure under small earthquakes and the self-centering energy-dissipation mechanism is activated under stronger earthquakes. This concept could be applied to some lifeline projects which should remain operational after major seismic events and reduce downtime. To characterize the response of EDLRF, a new design method was put forward, and it included story stiffness demand in term of story stiffness ratio between EDLRF and structure. Then the member section of EDLRF and damping demand were calculated according to the stiffness ratio and the configuration of SCED was decided. The design of a 6-story RC frame with EDLRF was conducted and verified through nonlinear dynamic time-history analysis. Results showed that EDLRF gave the structure additional capability of dissipating a large amount of energy and reduced or even eliminated residual drift; existing weak-story damage mode was replaced with an improved uniform damage mode. The results produced by fragility assessment showed that the controlled structure reduced the probability of all limit states in term of drift. Small scale model test on shaking table showed that the proposed system could compel the structure to deform as the shape of fundamental mode.

1 INTRODUCTION

During recent decades, much research has focused on resilient structure, because it has the ability to prevent the structure from causing damage to structural and non-structural elements and eliminate residual drift after earthquake. One strategy for implementing this system is to reduce or prevent structural damage to non-replaceable elements by softening the structural constraints through elastic gap opening mechanisms instead of yielding in primary structural elements. Furthermore, it is known that adding energy dissipation elements and post-tensioning elements as a part of this system can help the structure gain the ability to absorb energy and return the structure to a plumb, upright position after earthquake (Chancellor, et al. 2014).

A great amount of self-centering systems were put forward for newly-built structures and rehabilitation of existing buildings. A rocking wall-frame structures coupled with a separate nonload bearing nonlinear supplemental damping system was proposed by Ajrab et al. (2004). Alavi and Krawinkler (2004) described that strengthening with hinged walls was very effective in reducing drift demands for multi-story frame structures with a wide range of periods and at various performance levels. Concept of a system proposed by Wada et al. (2009) was that the rocking walls were strong enough to suppress the partial failure modes, a more preferable global failure mode could be achieved. However, previous work has focused on the sufficiency on reducing the reaction caused by earthquake, few researchers have addressed the problem of efficiency and practicability. As a rehabilitation method, especially in the life-line project, a emergent rehabilitation need to be done without too much downtime, which is why the technical difficulty in construction should be reduced as much as possible. Moreover, near-field ground motions with fling and forward directivity effects are found to excite systems primarily in their fundamental mode and higher modes respectively, the former effect amplifies the drift response of higher stories while the latter generates large deformation in the lower stories (Yang, et al. 2010). An

efficient method to overcome this local failure mode is to add external stiff element which can confine ductility demand concentration in moment resisting frames, and MacRae et al. (2004) verified the validity of this method in steel concentrically braced frames.

This paper introduced a concept and an implementation of a novel energy-dissipation and light-weight rocking frame (EDLRF) which consisted of a controlled-rocking stiff frame and a SCED brace. To characterise the response of the system, a stiffness-based design was proposed (Du & Wu 2014), and it was used to design the 6-story building analysed in this paper. Performance evaluation were performed based on nonlinear dynamic analysis under near-field and far-field ground motions. Moreover, a small scale shaking table test was conducted to confirm the behaviour of the proposed system.

2 CONCEPT OF EDLRF

The residual deformation has been regarded as a critical measure of post-earthquake performance (Ruiz-Garcia & Miranda 2006) which indicates whether it is worth repairing the damaged building or not. Hence post-earthquake structural resilience is of particular interest, especially the post-disaster operation of lifeline infrastructure such as hospitals and communication buildings. These buildings require constant operation, even after moderately sized earthquakes, because out of services and long durable downtime caused by severely damaged structural members are unacceptable. In view of these disadvantages, in this paper, an alternative design and rehabilitation strategy was motivated, which had the features of resilience and construction flexibility.

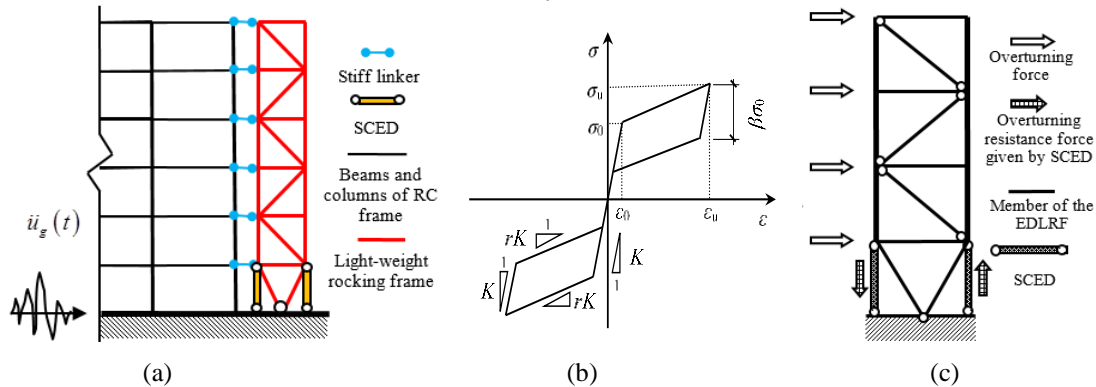


Figure 1 (a) Configuration of the EDLRF (b) Hysteretic model of SCED system in OpenSees (Christopoulos, et al. 2008) (c) Mechanics of the EDLRF

As shown in the illustrative sketch of Figure 1(a), The EDLRF system consisted of two parts, a light-weight rocking frame (LRF) and a self-centering energy dissipative (SCED) steel brace. As a stiffness element of the EDLRF, the purpose of the LRF was to confine the deformation distribution along the building so that the damage mode and the seismic performance of the building were more predictable. It could reduce significant ductility demand in local story and redistribute this demand to other stories (Qu, et al. 2014). Especially for these buildings in near-filed regions, the fling effect and forward directivity effect would result in weak stories in both lower stories and higher stories (Alavi & Krawinkler 2004). Compared with concrete walls, the LRF could be made in factory and assembled in site so that downtime could be reduced as much as possible. Another part of the system was the SCED. As can be seen from Figure 1(b), the SCED had the typical flag-shaped hysteretic response. When the initial pretensioning force and the force required to activate the friction mechanism were surpassed, the inner and outer tube started moving relative to each other, and the stiffness of the system was significantly reduced to that of the tensioning elements. Christopoulos et al. (2008) developed and tested this new self-centering energy dissipative (SCED) steel brace, and it played a key role in reducing peak story drifts and residual lateral deformations (Tremblay, et al. 2008). In addition, Wiebe, et al. (2013) showed that deploying a SCED brace at one or more levels could reduce the higher mode effect in structures. Due to these features, it was used as a damper to provide self-centering capability for EDLRF.

Figure 1(c) illustrated the mechanics of the EDLRF, when the original structure was subjected to small earthquake, the EDLRF could provide overturning resistance force, make the original structure a little

stiffer and reduce the response of the original structure, but in this case there was no energy dissipation happening in SCEDs; when moderate earthquakes or more severe earthquakes happened, the overturning force was large enough to activate the energy dissipation mechanism, then the SCEDs could reduce the energy absorbed by the main structure and prevent the structural member from being damaged. What's more, the tensioning elements in SCED could provide the structure with the self-centering ability through reducing and even eliminating residual deformation caused by strong ground motions.

In this paper, the EDLRF was attached to the original structure as a rehabilitation strategy which can improve the performance of the original building, but it could also be integrated into the newly-built structures, therefore the new building had an inherent quality of resilience.

3 PRELIMINARY DESIGN METHOD BASED ON STIFFNESS DEMAND

In order to implement the concept mentioned above, the stiffness of EDLRF should be large enough to confine the drift concentration, and its stiffness should also meet the target performance that the structure deformed as the shape of foundational mode. Hence, the present paper quantified the relationship between the stiffness demand and target drift concentration factor (DCF) through nonlinear time history analysis. 4-, 8-, 12-story reinforced concrete structures were analyzed under 3 sets ground motions. This ratio was unity when the frame moved over linearly with height, otherwise it was greater than unity. The definition of DCF was $DCF = \theta_{\max} / (u_r/H)$. Here DCF is drift concentration factor; θ_{\max} is the maximum value among the interstory drift of the stories; u_r is roof displacement; H is the height of the building.

A total of 30 earthquake ground motions, recommended by FEMA-P695 (2009), were considered. The ground motions were categorized into 3 sets, 10 far-field ground motions, 10 near-field ground motions with velocity pulses and 10 near-field ground motions without velocity pulses. Spectral acceleration at foundational period $S_a(T_1, 5\%)$ was chosen as the intensity measure. The $S_a(T_1, 5\%)$ of all the ground motions were scaled to 0.04g which was about 1/5 of the rare earthquake intensity according to Chinese code for seismic design of buildings. The equations used to calculate the stiffness were given here, $\alpha = k/K$, $k = 12E_s I_s / h^3 + E_s A l^2 / L^3$, $K = n \cdot 12E_c I_c / h^3$, where α is the stiffness ratio between the LRF and the main structure; k is the story stiffness of the LRF; K is the story stiffness of the main building; E_s and I_s are the modulus and inertia moment of the steel member section; A is the section area of the steel member; l is the span of the LRF; L is the length of the diagonal brace; n is the number of columns at each story; E_c and I_c are the modulus and inertia moment of the column member section; h is the story height.

The primary mode of the multistory building is the fundamental mode, then the target performance is to make the structure deform as the shape of the fundamental mode. The target DCF of the 4-, 8-, 12-story structure were 1.3087, 1.4095 and 1.3960 respectively. In the case of the far-field earthquakes, the stiffness demand of these structures were 0.04765, 0.2138 and 0.5513 respectively, then a relationship between α and n was given below through curve fitting: $\alpha_{FF} = 0.0054n^2 - 0.0227n + 0.0529$. In addition, the stiffness demands under near-field earthquakes were 0.0538, 0.2119, 0.6684 respectively, the relationship could be obtained here: $\alpha_{NF} = 0.0093n^2 - 0.0724n + 0.1941$. From the results of the 4-, 8-, and 12-story building, the stiffness demand under near-field ground motions was about 17% higher than that of the far-field ones, hence, a magnification coefficient β was multiplied to α_{FF} while taking the near-filed effect into consideration. Considering the uncertainty in the analyzing, a margin factor γ was introduced, and the final stiffness demand α_{NFU} was given below, and the recommended value through trial calculation of β , γ were 1.3, 1.5 respectively.

$$\alpha_{NFU} = \beta \cdot \gamma \cdot \alpha_{FF} \quad (1)$$

4 PERFORMANCE EVALUATION

4.1 Properties of 6-story RC building and the EDLRF

The 6-story RC building was designed and detailed according to Chinese code. The elevation was shown in Figure 2(a). The structure was simulated in 2D using the nonlinear dynamic modeling software *OpenSees* (McKenna & Fenves 2004). The LRF was made of Q390 I-shaped steel according to Chinese

steel code. The beam, column and brace section from the second story to the roof were 50a, 50c and 32a respectively; the brace section of the first story was 25a. The calculated stiffness ratio was 0.324, while the stiffness demand given by equation (1) was 0.223. The SCED was designed according to the method proposed by Christopoulos, et al. (2008). The SCED was made of Q235 square steel tube, and had an interior tube of 250 mm × 250 mm × 8 mm and exterior tube of 300 mm × 300 mm × 6 mm. The tensioning elements which offered initial prestress force 335.8 kN were comprised of four 10-mm-diameter tendons while the friction dissipative mechanisms were included to produce an expected friction force of 300 kN. In OpenSees, the SCED was simulated with truss element and self-centering material object. The characteristic parameter of this material is the initial stiffness, the post-activation stiffness and the hysteresis width parameter $\beta_{\sigma 0}$. In this paper, as shown in Figure 1 b), the initial stiffness was $K = 468.7 \text{ kN/mm}$, the post-activation stiffness is $rK = 6.95 \text{ kN/mm}$, and $\beta_{\sigma 0} = 0.95$ (Christopoulos, et al. 2008). In Figure 2(b), a relationship between the axial force and axial strain was a typical flag-shape, and the yielding force was 635.8 kN.

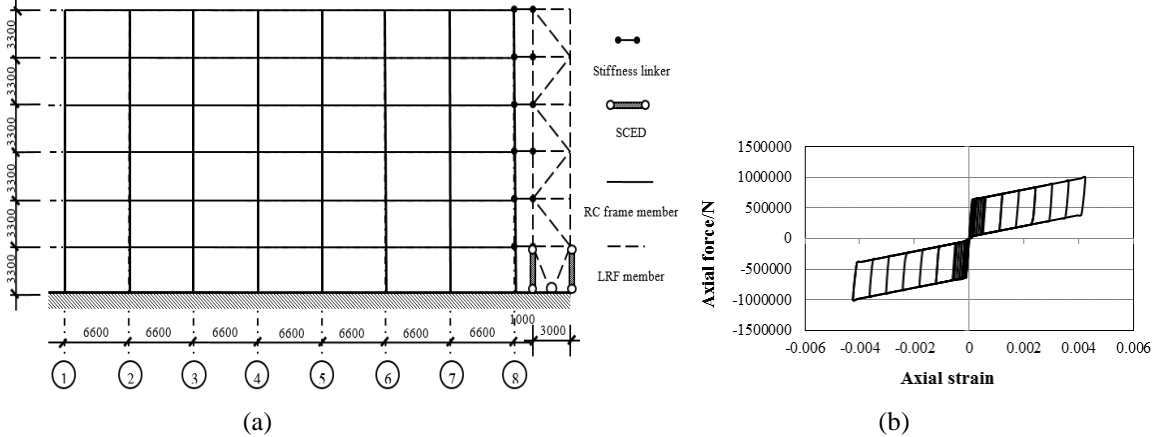


Figure 2 (a) Elevation of the 6-story building and EDLRF (b) OpenSees model of the SCED hysteresis

4.2 Effect of EDLRF on DCF control

In this paper, the 6-story RC building with and without EDLRF were referred as the controlled structure and the uncontrolled structure respectively.

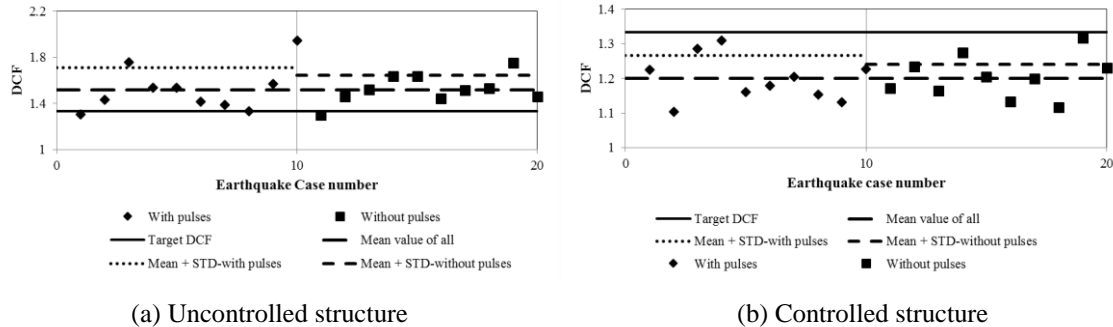


Figure 3 DCF under near-field ground motions having the exceedance probability of 2% in 50 years with and without pulses

The controlled performance target was 1.334, which was shown in Figure 3 as black bold line. The scattered points in Figure 3 represented DCF values of different earthquakes. Almost all DCFs of uncontrolled structure were larger than the performance target, but after adding the EDLRF, all the DCFs were smaller than the target. What’s more, the mean value of the uncontrolled structure under all the earthquakes was 1.52 while the mean value of controlled structure was 1.2, the reduction was as large as 21%. The results revealed that the EDLRF was reliable and efficient in controlling the deformation concentration. Furthermore, the mean value plus one standard variation of the ground motions with pulses was larger than those without pulses, which meant that the velocity pulses made the DCF have larger variation, and special consideration should be taken on the consequences caused by the fling and forward directivity effect.

4.3 Effect of EDLRF on residual interstory drift

Following the framework of residual displacement damage index (RDDI) (Pampamin, et al. 2002) and based on the recommendation of FEMA 356 (2000), Kam (2008) proposed three damage limit states for RC frames: residual interstory drift 0.2% , 0.4%, and 1.0% for instant occupancy limit state, repairable limit state and life safety limit state respectively.

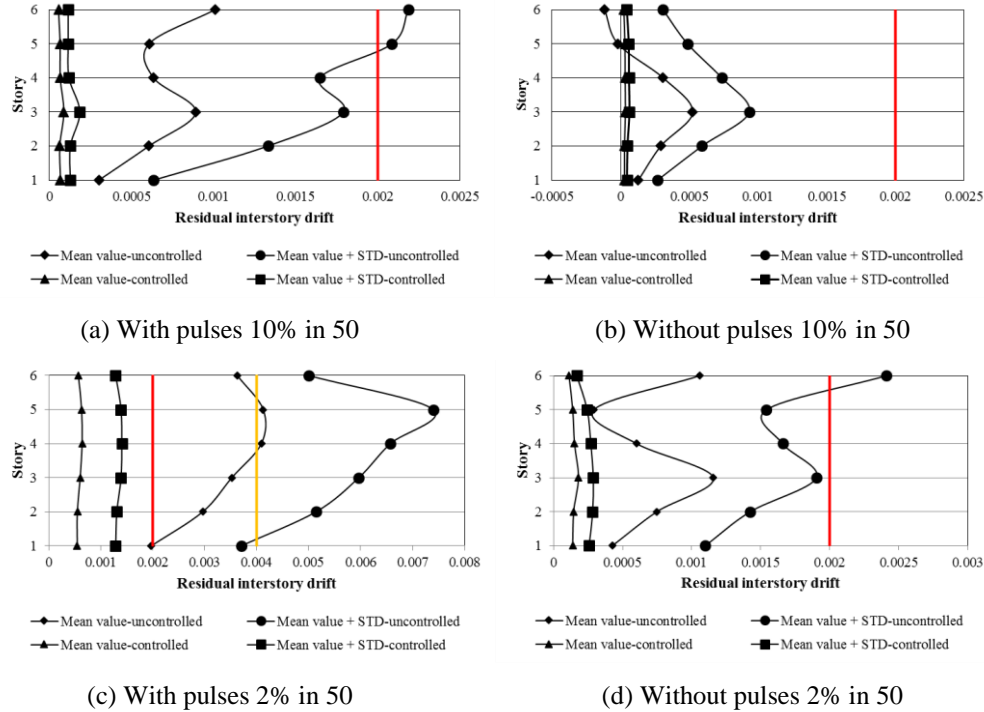


Figure 4 Mean value and mean value plus one standard variation (STD) for residual interstory drift of near-field ground motions scaled to have a probability of exceedance of 10% in 50 years and a probability of exceedance of 2% in 50 years

Kam recommended three different performance levels, and they were demonstrated as red bold lines in Figure 4 from left to right at each figure. Inspection of Figure 4 indicated that adding EDLRF not only reduced residual interstory drift but also made the distribution along the height of the building more even. When the structure were under the records having 10% in 50 years, it was within the instant occupancy limit state. However, when subjected to earthquakes which have the exceedance of 2% in 50 years, the results showed that the uncontrolled structure deteriorated seriously, especially the structure under earthquakes with velocity pulses. In Figure 4 (c) and (d), the uncontrolled structure had the residual interstory drift of 1/244 and 1/1000 respectively, but after adding EDLRF, these results declined to 1/1667 and 1/5556 respectively. The reduction was as large as 50%, and the structure was at the instant occupancy limit state. This state met the demand that the controlled structure should remain operational after strong earthquakes without repairing.

4.4 Performance evaluation based on fragility curves

Table 1 Structural Damage State Thresholds

Limit state	Slight(L1)	Moderate(L2)	Extensive(L3)	Complete(L4)
Drift	0.0033	0.0067	0.0200	0.0533

Incremental Dynamic Analyses (IDA) using the selected suite of earthquake records were performed. Spectral acceleration at fundamental period $S_a(T_1, 5\%)$ was chosen as the intensity measure (IM). The seismic intensity levels were increased according to the hunt and fill algorithm (Vamvatsikos & Cornell 2004). Software developed by Vamvatsikos and extended by the author was used to perform the IDA analysis and postprocess the inelastic responses. Fragility curves were developed with the method given by Nielson and DesRoches (2007). The ground motions used in this paper for the development of

fragility curves were from FEMA-P695 (2009). Limit states listed in Table 1 were from HAZUS (2010). According to model building types in HAZUS, the building analyzed in this paper was mid-rise concrete moment frame which was labelled as C1M.

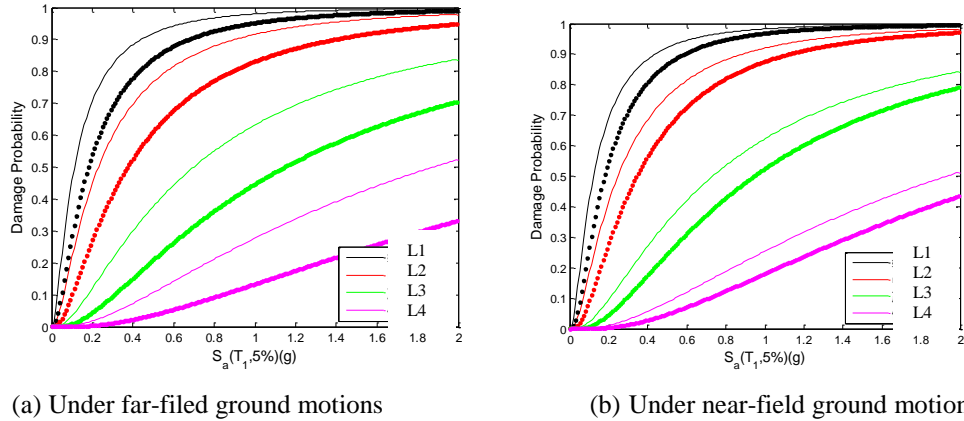


Figure 5 Fragility curves of the uncontrolled and controlled structure (the bold lines represent the controlled structure while the fine lines represent the uncontrolled structure)

In Figure 5, due to the fling effect and forward directivity effect in near-field ground motions, the reduction in far-field ground motions were much better than that in near-field ones. Taking the third level as an example, in Figure 5 (a), the exceedance probability of the uncontrolled structure and controlled structure was 0.45 and 0.27 respectively, the reduction was 0.18, but for the near-field ones, the counterpart results were 0.42, 0.31 and 0.11. The results revealed that when the structure was under near-field ground motions, the EDLRF should enlarge its section if the design wanted to obtain the same effectiveness as the far-field ones.

5 CONCEPT VALIDATION BY SMALL SCALE SHAKING TABLE TEST



Figure 6 Setup of the frame and damper

The basic concept of the EDLRF was that the LRF reduced the probability of causing weak story damage mode caused by the fling effect and the forward directivity effect of near-field ground motions. Here, this concept was validated through a small scale test. Limited by capacity of the shaking table, it was difficult to design a model according to the theory of similarity, hence a miniature of 5-story steel frame was produced to model the original structure. What's more, a viscous damper used as vibration reduction device was taken as the SCED. However, the results were qualitatively useful in validating the concept. The setup of the shaking table test was shown in Figure 6. The ground motions used in this test were scaled to have the exceedance probability of 2% in 50 years.

As shown in Figure 7, the amplitude of the higher modes was larger than the fundamental mode, but after adding EDLRF, the higher mode effect was controlled and the fundamental mode became the largest one. The controlled model frequency was 3.75 Hz while the controlled was 4.06Hz, hence the period was 8% larger. What was the most important was that after adding EDLRF, the model deformed as the mode of the fundamental period so that the higher mode effect which can be stimulated by forward

directivity effect was under control.

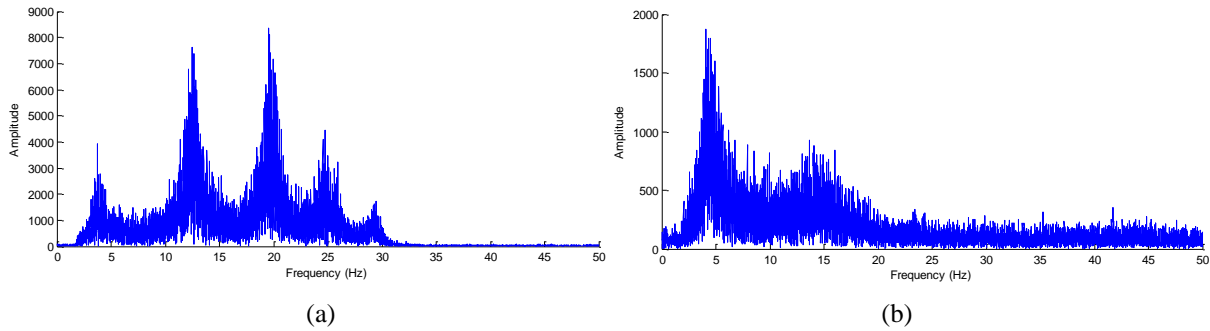


Figure 7 Frequency-response curve of the model (a) without and (b) with EDLRF

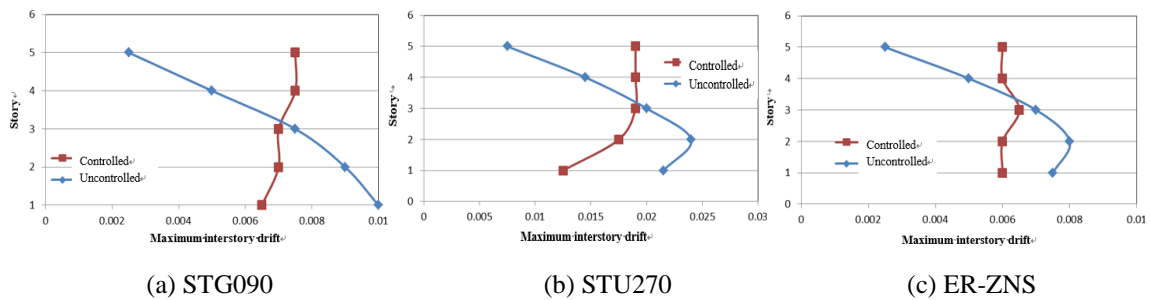


Figure 8 Interstory drift of the model without (uncontrolled) and with (controlled) EDLRF

From the results given in Figure 8, the interstory drift along the height of the model was even, it reduced the probability of the development of weak story. But due to the link between the damper and shaking table, the energy dissipation was less ideal.

6 CONCLUSIONS

This study presented a concept of the EDLRF, the concept was that the stiff frame was to control the damage mode of the structure through reducing the effect of higher mode caused by the fling effect and forward directivity effect, and the SCED provided the ability of energy dissipation and self-centering. To characterize the response of the LRF, a relationship between the stiffness demand and the story number of the building was obtained through a series of analysis and curve fitting.

Performance evaluation showed that the EDLRF could not only control the interstory drift concentration at a local story caused by the higher mode effect but also could reduce response to the instant occupancy limit state even under the earthquakes with the exceedance probability of 2% in 50 years. This is important for lifeline project which requires less repair cost and downtime, furthermore, it is the key feature of the resilient structures. From the perspective of probability, the fragility curves revealed the EDLRF could reduce the probability of damage, especially in the collapse state. The shaking table test validated the numerical results that the LRF could control the damage mode of the structure. Because of the resilient ability and construction flexibility, this system can be used in the rehabilitation after earthquake for saving time and also can be integrated into a new building which requires higher performance.

REFERENCES:

- Ajrab, J. J., Pekcan, G. & Mander, J. B. 2004. Rocking Wall-Frame Structures with Supplemental Tendon Systems. *Journal Of Structural Engineering*, 130(6), 895-903.
- Alavi, B. & Krawinkler, H. 2004. Strengthening of Moment-Resisting Frame Structures Against Near-Fault Ground Motion Effects. *Earthquake Engineering & Structural Dynamics*, 33(6), 707-722.
- Chancellor, N., Eatherton, M., Roke, D. & Akbaş, T. 2014. Self-Centering Seismic Lateral Force Resisting Systems: High Performance Structures for the City of Tomorrow. *Buildings*, 4, 520-548.
- Christopoulos, C., Tremblay, R., Kim, H. J. & Lacerte, M. 2008. Self-Centering Energy Dissipative Bracing

- System for the Seismic Resistance of Structures: Development And Validation. *Journal of Structural Engineering*, 134(1), 96-107.
- Du, Y. & Wu, D. 2014. Performance Analysis of Light Energy Dissipative Rocking Frame Designed on the Basis Of Stiffness Demand. *China Civil Engineering Journal*, 47(01), 24-35.(in Chinese)
- FEMA-356. 2000. Pre-Standard and Commentary for the Seismic Rehabilitation of Buildings. Federal Emergency Management Agency, Washington, D.C.
- FEMA. 2009. Quantification of Building Seismic Performance Factors. *Report No. FEMA P695*, the Federal Emergency Management Agency, Washington, DC.
- HAZUS-MH-MR5. 2010. Advanced Engineering Building Module (AEBM) Technical and User's Manual. FEMA, Washington, D.C.
- Kam, W. Y., Pampanin, S., Carr, A. J. & Palermo, A. 2008. Design Procedure and Behaviour of Advanced Flag-shaped. *2008 New Zealand Society of Earthquake Engineering (NZSEE) Conference*, University of Canterbury. Civil and Natural Resources Engineering, Wairakei, New Zealand.
- MacRae, G. A., Kimura, Y. & Roeder, C. 2004. Effect of Column Stiffness on Braced Frame Seismic Behavior. *Journal of Structural Engineering*, 130(3), 381-391.
- McKenna, F. & Fenves, G. L. 2004. Open system for earthquake engineering simulation (OpenSees). (<http://www.opensees.berkeley.edu/index.html>).
- Nielson, B. G. & DesRoches, R. 2007. Analytical Seismic Fragility Curves for Typical Bridges in the Central and Southeastern United States. *Earthquake Spectra*, 23(3), 615-633.
- Pampamin, S., Christopoulos, C. & Priestley, M. J. N. 2002. *Residual Deformations in the Performance-Based Seismic Assessment of Frame Structures*, IUSS Press.
- Qu, B., Sanchez-Zamora, F. & Pollino, M. 2014. Mitigation of Inter-Story Drift Concentration in Multi-Story Steel Centrically Braced Frames through Implementation of Rocking Cores. *Engineering Structures*, 70, 208-217.
- Ruiz-Garcia, J. & Miranda, E. 2006. Residual Displacement Ratios for Assessment of Existing Structures. *Earthquake Engineering & Structural Dynamics*, 35(3), 315-336.
- Tremblay, R., Lacerte, M. & Christopoulos, C. 2008. Seismic Response of Multistory Buildings with Self-Centering Energy Dissipative Steel Braces. *Journal of Structural Engineering*, 134(1), 108-120.
- Vamvatsikos, D. IDA Matlab running routines for OpenSEES. <http://users.ntua.gr/divamva/software.html>.
- Vamvatsikos, D. & Cornell, C. A. 2004. Applied Incremental Dynamic Analysis. *Earthquake spectra*, 20(2), 523-553.
- Wada, A., Qu, Z., Ito, H., Motoyui, S., Sakata, H. & Kasai, K. 2009. Seismic Retrofit Using Rocking Walls and Steel Dampers. *ATC/SEI Conference on Improving The Seismic Performance of Existing Buildings and Other Structures* San Francisco, CA, U.S.
- Wiebe, L., Christopoulos, C., Tremblay, R. & Leclerc, M. 2013. Mechanisms to Limit Higher Mode Effects in A Controlled Rocking Steel Frame. 1: Concept, Modelling, and Low-Amplitude Shake Table Testing. *Earthquake Engineering & Structural Dynamics*, 42(7), 1053-1068.
- Yang, D. X., Pan, J. W. & Li, G. 2010. Interstory Drift Ratio of Building Structures Subjected to Near-Fault Ground Motions Based on Generalized Drift Spectral Analysis. *Soil Dynamics and Earthquake Engineering*, 30(11), 1182-1197.