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SEISMIC REHABILITATION OF DEFICIENT STEEL MOMENT RESISTING FRAMES THROUGH STIFF ROCKING CORES

B. Qu[(1)], J.C. Sanchez [(2)], H. Hou[(3)] and M. Pollino[(4)]

[(1)] *Dept. of Civil and Environmental Engineering, California Polytechnic State University, San Luis Obispo, CA 93407,USA, E-mail:bqu@calpoly.edu.*

[(2)] *Puget Sound Naval Shipyard & Intermediate Maintenance Facility, Bremerton, WA 98314 z, E-mail: sanchezanc@hotmail.com.*

[(3)] *School of Civil Engineering, Shandong University, Jinan, Shandong Province, China, 250061, E-mail: houhetao@sdu.edu.cn.*

[(4)] *Dept. of Civil Engineering, Case Western Reserve University, Cleveland, OH 44106, USA, E-mail: mcp70@case.edu.*

Abstract

Based on the research outcome of a project recently funded through the U.S. NSF-NEESR program, this paper assesses adequacy of a seismic rehabilitation technology for Steel Moment Resisting Frames (SMRFs) vulnerable to drift concentrations and soft-story failures. The technology installs a single or multiple Stiff Rocking Core (SRC) pinned to the foundation and connected to a deficient multi-story SMRF to re-distribute seismic forces along its height and create more uniform inter-story drift and ductility demand distributions. This investigation implemented the SRC technology in two archetype SMRFs including one three-story and one nine-story. Results from nonlinear static analyses show that the SRC technology can reduce inter-story drift concentration in both low-rise and mid-rise SMRFs regardless of the seismic force distributions and drift limits considered in design. Additionally, the influence of SRC configuration was studied. It was found that the SRC extending along the entire height of a SMRF is more preferable than the one extending over the bottom potion of the system, although these two SRC options can be both valid.

Keywords: steel moment resisting frames; soft story; seismic rehabilitation and retrofit.

1. Introduction

Steel Moment Resisting Frames (MRFs) are an important type of seismically designed structural steel buildings. The open spaces provided by steel MRFs and their ease of design and construction attract owners and architects in many cases, making them one of the most popular seismic force resisting systems in the world. Although implementation of steel MRFs was significantly impeded due to the unexpected brittle ruptures of welded beam-to-column connections in steel MRFs discovered in the aftermath of the 1994 Northridge Earthquake and the 1995 Hyogoken-Nanbu (Kobe) Earthquake [1-4], numerous analytical and experimental investigations have been conducted in the past two decades to overcome these problems. Improved alternatives have been developed, offered and placed into practice [5], promoting the use of steel MRFs in regions of moderate and high seismicity. To date, steel MRFs have been accepted as a viable system, as evidenced by the fact that the most ductile type of steel MRF is assigned the highest structural response modification factor (i.e., the *R* factor) of 8 in the United States and many other countries [6].

Although the research outcomes and evolution of seismic design provisions have improved seismic performance of steel MRFs, observations from a recent E-Defense shake table test on a full-scale four-story steel MRF revealed that a multi-story steel MRF designed with ductile detailing, based on the strong-column weak-beam criterion and in compliance with the state-of-the-art seismic provisions may exhibit the soft-story collapse mechanism at its bottom story under over design level earthquakes [7]. When such a failure occurs, large inelastic inter-story drift concentrates at a single story while much smaller inter-story drifts occur at the other stories. The concentrated inelastic inter-story drift coupled with the gravity load trigger the P-Δ effect, eventually leading to collapse of the building.

Following the E-Defense test, a few strategies for collapse mitigation have been proposed and validated from the perspective of enhancing column adequacy [8]. This paper focuses on an alternative seismic rehabilitation strategy for the steel MRFs vulnerable to the soft-story failure mechanism. The technology, consists of a single or multiple Stiff Rocking Cores (SRCs) added to an existing steel MRF building to create more uniform height-wise inter-story drift and ductility demand distributions in the system. Fig. 1 illustrates the SRC technology. As shown, it includes a single or multiple walls or trusses (i.e., SRC) pinned to the ground and connected to an existing multi-story steel MRF vulnerable to the soft-story failure. The links connecting the steel MRF and the SRC are assumed to be pinned on each end. The walls or trusses, when designed to be stiff and strong enough, can redistribute the seismic forces from different floors. The rotational flexibility at the bases of the walls or trusses combined with their high inter-story stiffness and strength enable the rehabilitated system to form the more favorable sway mechanism, which has more uniform inter-story drift distribution and distribution of structural damage along the vertical direction.

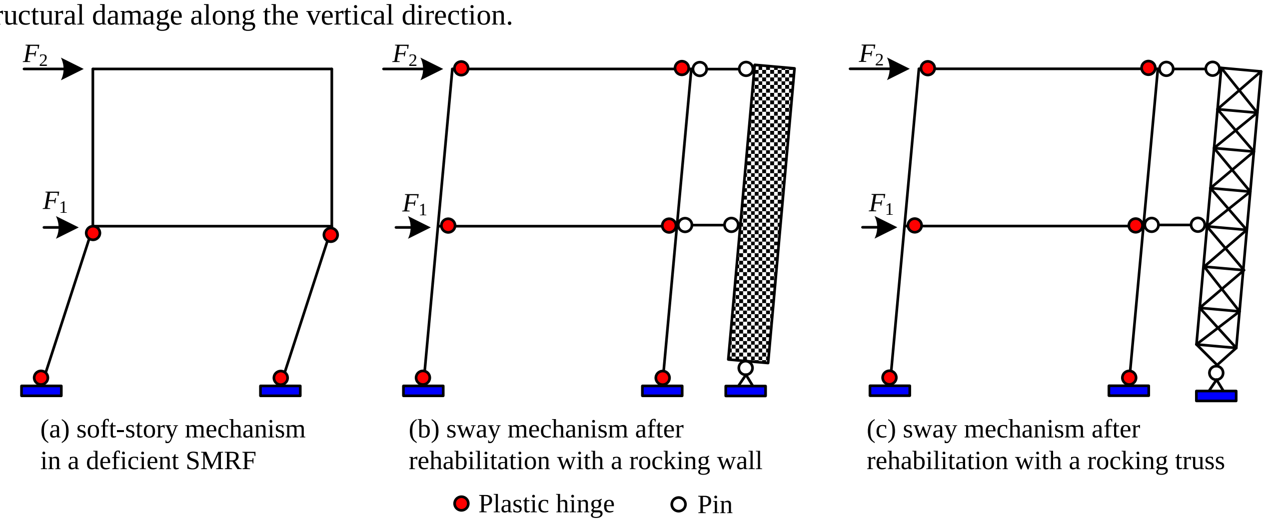

Fig. 1 – Illustration of the SRC technology.

It is noteworthy that the SRC technology was proposed by Wada et al. [9] and has been recently validated for deficient Steel Concentrically Braced Frames (SCBFs) through a series of analytical and experimental investigations [10-12]. However, given that the nonlinear behavior and expected seismic drift of steel MRFs, which may affect efficacy of the SRC technology, are significantly different from those of SCBFs, further validation work is necessary before implementing the technology in deficient steel MRFs. The objective of this study was to analytically assess the contribution of SRC in preventing inter-story drift concentration in representative steel MRF buildings. The following describes selection of archetype steel MRF buildings, development and validation of numerical models, simulations conducted and discussion of analysis results.

2. Archetype Buildings

This investigation focused on deficient low-rise and mid-rise steel MRF buildings. Two archetype steel MRF buildings were selected based on the following criteria: 1) the steel MRFs should be designed for a region of high seismicity; 2) story height, bay width, reactive weights, plan view and elevation of the steel MRFs should be representative; 3) structural components in the steel MRFs should be designed according to typical seismic design practice; 4) properties of the buildings should be available for validating the developed numerical models; 5) the steel MRFs should have the potential to form the soft-story mechanism. To this end, pre-Northridge steel MRFs considered in the SAC Steel Project [13] including one three-story and one nine-story steel MRFs respectively representing low-rise and mid-rise, were selected. More detailed design information about the two buildings can be found elsewhere [13].

Due to symmetry, only one steel MRF from each archetype building was investigated in this research. The selected steel MRFs from the three-story and nine-story archetype buildings are referred to as LA3 and LA9 hereafter, respectively. LA3 and LA9 both have the same span of 9.14 m and constant story height of 3.96 m except that the first story of LA9 has a height of 5.49 m. The column bases in LA3 are considered as fixed and LA9 has a single-level basement in the original design. To better suit the need of this project (i.e., demonstrating the beneficial contribution of SRC in preventing soft-story failures) and for simplicity, the following modifications were made in LA3 and LA9: the basement of LA9 was excluded from consideration; and the columns of LA9 and LA3 were assumed to be pinned to the ground. The modified steel MRFs are referred to as LA3M and LA9M hereafter, respectively. It is recognized that the modifications made at the column bases of LA3M and LA9M trigger drift concentration in their bottom stories.

3. Rehabilitated Systems and Computer Models

Fig. 2 illustrates three rehabilitation plans including one for LA3M and two for LA9M. The rehabilitated systems are referred to as LA3M-R, LA9M-RA and LA9M-RB hereafter. As shown, LA3M-R and LA9M-RA respectively represent the three-story and nine-story steel MRFs rehabilitated by the SRCs along the entire heights of the structures. LA9M-RB represents an alternative rehabilitation plan for the nine-story steel MRF in which the SRC only extends along the bottom four stories. LA9M-RB was included here because the first story of LA9M was identified as the soft story concentrating inelastic drift and it would be interesting to investigate if a shorter SRC (which could be more economical and practical) attached to the bottom portion of the building would be adequate or not. The objective of this research was to demonstrate the beneficial contribution of SRC and identify the key design parameters affecting performance of the rehabilitated system. Hence, the SRC was considered through a beam element along its centerline for simplicity (see Fig. 2). It is recognized that such a model can also be extended to a system with multiple SRCs. In these cases, the property of each individual SRC such as strength or stiffness should be combined into the beam element. If needed, the continuous columns as part of the gravity frames in the archetype buildings can be similarly considered through the beam element. It should be noted that the beam element neglects the width of SRC and the rehabilitated system modeled as such can not provide accurate predictions of some local responses (such as rotation demands at the ends of the links connecting the SRC to the existing steel MRF); however, it will help understand the contribution of SRC in improving uniformity of inter-story drift distribution of the rehabilitated structure and therefore suits the primary need of this research.

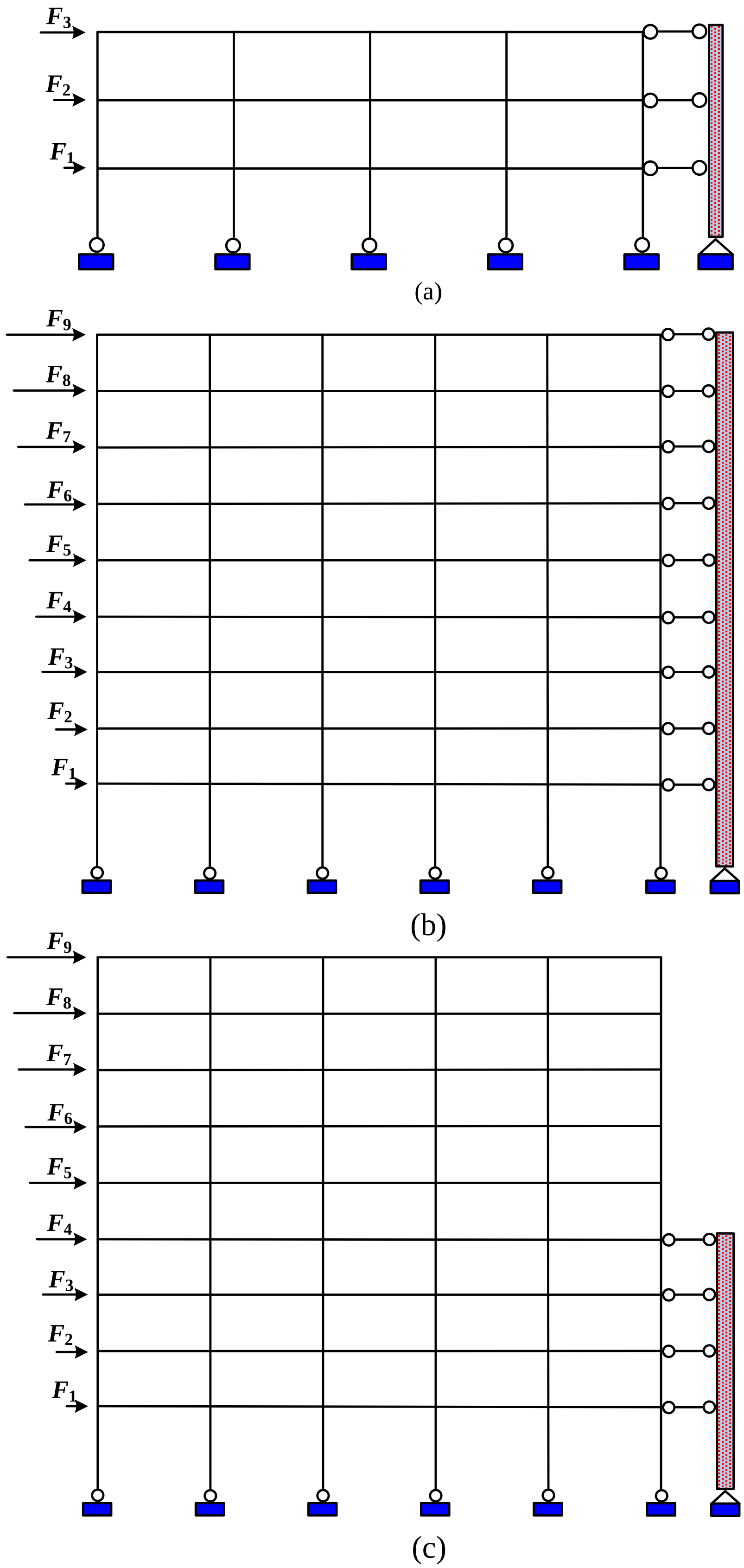

Fig. 2 – Rehabilitation plans: (a) LA3M-R; (b) LA9M-RA; (c) LA9M-RB.

SRC stiffness is a key parameter affecting performance of the rehabilitated system. Conceptually, if the SRC is ideally stiff, it will remain straight when rotating about its base under seismic loading, enabling formation of the preferable sway mechanism in a rehabilitated system. To consider the SRC stiffness relative to that of an existing structure, the following stiffness ratio, *a*, was defined:

$$\alpha = \frac{EI_{\mathrm{SRC}}}{k_1 h_{\mathrm{S1}}^3} \tag{1}$$

where E = modulus of elasticity of the material used in SRC;

I_{SRC} = moment of inertia of SRC;

k_1 = elastic stiffness of the first story of the considered structure; and

h_{s1} = height of the first story of the considered structure.

It is noted that k_1 can be identified from the analysis of the first story of the system under consideration. Accordingly, the values of k_1 were determined to be 40.1 and 41.3 kN/mm for LA3M and LA9M, respectively. Rearranging Eq. (1), I_{SRC} can be calculated as:

$$I_{\mathrm{SRC}} = \frac{\alpha k_1 h_{\mathrm{S1}}^3}{E} \tag{2}$$

As indicated in Eq. (2), the SRC with different stiffness levels can be achieved through calculation of I_{SRC} based on a target stiffness ratio of α. Note that a larger value of α corresponds to a stiffer SRC.

Finite Element (FE) models were developed for the rehabilitated systems using the Open Systems for Earthquake Engineering Simulations (OpenSees) [14]. Each frame member (i.e., beam or column) was considered by a force based fiber element with seven integration points along its longitudinal direction. The fiber arrangement shown in Fig. 3 was assigned to all the wide flange frame members. Original designs of the archetype buildings adopted A36 and A572 Gr.50 steel for the beams and columns, respectively. The nominal yield strengths of A36 and A572 Gr.50 are 248 MPa (36 ksi) and 345 MPa (50 ksi), respectively. However, as reported [13], the expected yield strength of A36 steel is typically on the order of 345 MPa (50 ksi). Given that material overstrength in beams tends to trigger formations of the plastic hinges in columns and hence inter-story drift concentration, the material overstrength factor of 1.5 recommended for A36 steel in ANSI/AISC 341-10 [15] was assigned to the steel used in the beams. However, overstrength of A572 Gr. 50 steel was not considered. The Giuffre-Menegotto-Pinto steel model with isotropic strain hardening was assigned to the frame members. The steel strain hardening ratio was assumed to be 2%. Note that limited shear yielding is permitted in panel zones per the current seismic design provisions [15]. However, inelastic responses of panel zones in the beam-to-column connections were neglected in the FE models for simplicity. Rigid truss elements were used for the links connecting the existing steel MRF and the SRC. The SRC was considered by an elastic beam element with its moment of inertia determined through Eq. (2).

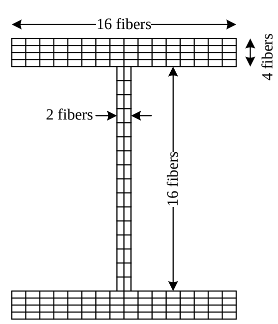

Fig. 3 – Fiber arrangement in wide-flange member

4. Nonlinear Static Analyses

Nonlinear Static Analyses (NSA), also known as the "pushover" analyses, were conducted using the FE models for accessing seismic performance of the rehabilitated systems. To illustrate the impact of SRC, the stiffness ratio, α, was gradually increased over a practical range in the analyses. For each specific value of α, the seismic force distribution was varied in NSA to discuss the robustness of the SRC technology. The following introduces determination of seismic force distributions and target inter-story drift considered in NSA.

Seismic force distribution, which affects yielding progression and inter-story drift distribution along the height of a structure, is an important parameter for NSA. When an earthquake occurs, the seismic force distribution may not be the same as that assumed in design due to many reasons such as 1) redistribution of seismic masses; 2) progressively developed nonlinear behavior of the system that cause stiffness deterioration; and 3) unexpected and non-uniform overstrength distribution in the system. Moreover, the actual force distribution varies with time. Although the "dynamic" seismic force distribution can not be accurately captured by the NSA method due to its "static" nature, the seismic force distributions were varied to partially include the influence of varying seismic force distributions on seismic response of the systems in the computer simulations.

Specifically, to account for the uncertainties in seismic force distributions, the seismic mass at each floor of the considered systems was assumed to follow the uniform probabilistic distribution over a range in which the upper and lower bounds were determined such that the seismic mass randomly sampled over the range is not greater than 150% of the masses of its adjacent floors. It is noted that this sampling criterion will generate random reactive mass distributions along the height of the building; but will not introduce any mass irregularities per ASCE/SEI 7-10 [6]. The generated reactive mass distributions were converted to the seismic force distributions, C_{vx} , based on the following equation provided in ASCE/SEI 7-10 [6]:

$$C_{vx} = \frac{w_x h_x^k}{\sum_{i=1}^{n} w_i h_i^k} \tag{3}$$

where

w_i and w_x = the portion of the total effective seismic weight of the structure located or assigned to Level i or x;

h_i and h_x = height from base to Level i or x; and

k = an exponent related to the fundamental period of the structure.

Based on the above procedure, for each stiffness ratio, α, a total of 500 and 250 seismic force distributions were generated for the three-story and nine-story steel MRFs, respectively. Note that Eq. (3) essentially only captures the seismic force distribution associated with the first vibration mode; however, given that this research primarily focuses on low-rise and mid-rise steel MRFs in which the higher mode effect in drift distribution is typically less significant compared with the high-rise steel MRFs, the higher mode effect was neglected in this investigation.

Another important parameter for NSA is the target inter-story drift (i.e., stopping criterion for the pushover analyses). In this investigation, each building model was monotonically pushed until the maximum inter-story drift in the system reached a target value. The target inter-story drifts were selected to be 0.7%, 2.5% and 5%. Note that these inter-story drift limits are associated with Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) performance levels according to ASCE/SEI 41-06 [16]. It should be recognized that the higher mode effect and the stiffness and strength degradations due to low-cycle fatigue induced ruptures in beam-to-column connections can not be captured in NSA. Further research opportunities exist to investigate their impacts on different aspects of the rehabilitated systems.

5. Result Discussions

Based on the seismic force distributions and inter-story drift limits described in Section 5, NSA were conducted. To investigate the impact of SRC stiffness on effectiveness of the technology, the stiffness ratio, α, was gradually increased. A total of 31 and 16 values of α were considered for the three-story and nine-story systems, respectively. As a result, a total of 46500, 23250 and 23250 numerical simulations were conducted for LA3M-R, LA9M-RA and LA9M-RB, respectively.

To quantify uniformity of inter-story drift distributions, Drift Concentration Factor (DCF), which is essentially ratio of the maximum inter-story drift to the roof drift in a system, was adopted in this research:

$$\mathrm{DCF} = \left.\frac{\max(\delta_1/h_{s1},\ \delta_2/h_{s2}\ \cdots\delta_n/h_{sn})}{\Delta_{roof}/H}\right|_{\max(\delta_1/h_{s1},\ \delta_2/h_{s2}\ \cdots\delta_n/h_{sn})=\text{target drift limit}} \tag{3}$$

where δ_i = inter-story displacement of the i^{th} story;

h_{si} = height of the i^{th} story;

Δ_{roof} = roof displacement relative to foundation;

H = height of the building; and

n = number of stories.

Fig. 4 shows how DCF evolves in LA3M-R under a selected seismic force distribution but to a broader range of α. As shown, when α increases, DCF consistently reduces regardless of the target inter-story drift limits, indicating that severe drift concentrations can be avoided through installation of sufficiently stiff SRC. Fig. 5 further compiles the results gleaned from the analyses assuming different seismic force distributions in LA3M-R. As shown, although at a given stiffness ratio, α, DCF varies due to adoption of different seismic force distributions in NSA; the rehabilitated system overall exhibits a more uniform inter-story drift distribution (as evidenced by the decrease of DCF) when the SRC becomes stiffer.

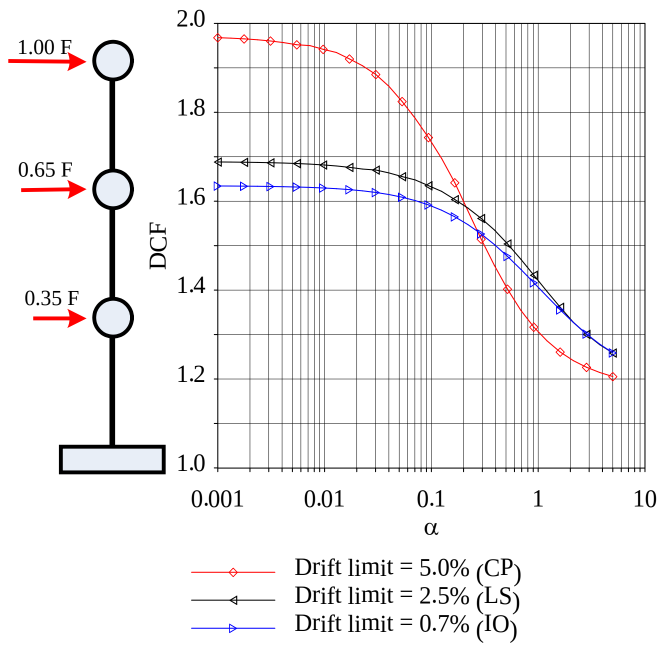

Fig. 4 – DCF evolutions of LA3M under a selected seismic force distribution.

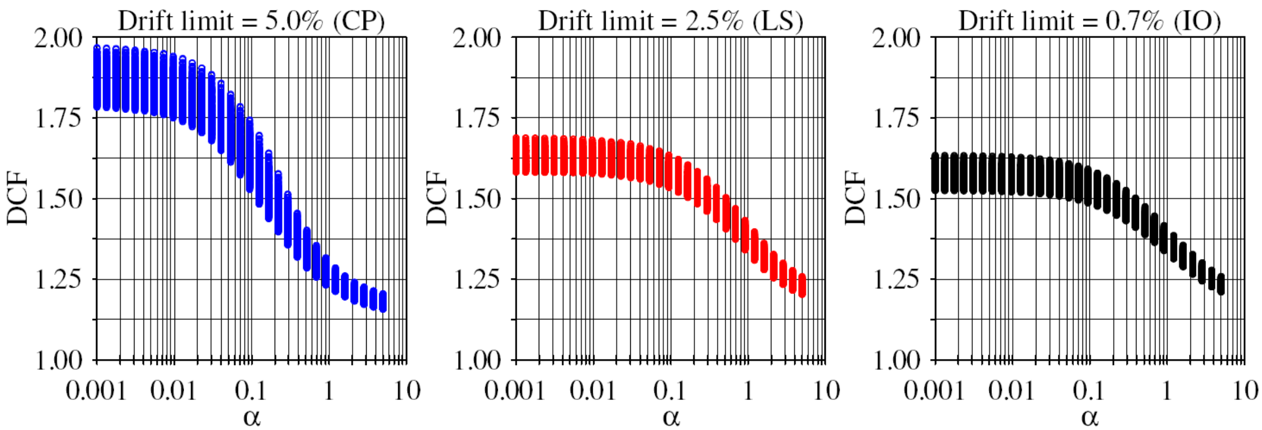

Fig. 5 – DCF evolutions of LA3M-R under random seismic force distributions.

Based on the entire result database from NSA, Fig. 6 illustrates the DCF results of each of the rehabilitated systems (i.e., LA3M-R, LA9M-RA and LA9M-RB). At each considered SRC stiffness ratio, NSA were conducted for different seismic force distributions. Here, the maximum, minimum and median DCF values at each considered value of α are extracted to illustrate trend of the results. When the SRC is not very stiff (i.e., when α is relatively small), the rehabilitated systems are similar to the original systems. It is observed that the maximum DCF values are fairly high in the archetype steel MRFs (particularly the nine-story building), indicating occurrence of severe drift concentrations. As α increases, DCFs of all the three rehabilitated systems tend to reduce and even converge to 1.0, indicating that more uniform inter-story drift distributions develop along the vertical direction in the systems.

Overall, DCF decreases more remarkably in the systems with a higher inter-story drift limit, indicating that the SRC technology may be more preferable in the systems likely exhibiting larger inter-story drifts during an earthquake event. Moreover, to achieve the same desirable DCF value, the required α value for the nine-story steel MRF is higher than the three-story steel MRF, indicating that the SRC needs to be stiffer in a taller system and the technology may become less applicable as height of the building increases. A larger α value generally leads to a more uniform inter-story drift distribution in the rehabilitated system; however, further increasing α beyond a certain threshold becomes less helpful in improving uniformity of the inter-story drift distribution. Focusing on the nine-story steel MRF, results shown in Fig. 6 indicate that the two rehabilitation plans which respectively have SRCs extending the entire height and the bottom four stories are both effective to improve the system inter-story drift distributions. However, when the stiffness ratio increases, the difference between the maximum and minimum DCF values are smaller in LA9M-RA than LA9M-RB, indicating that the effect of seismic force distribution is less significant in the mid-rise system rehabilitated with a SRC extending the entire height of the structure.

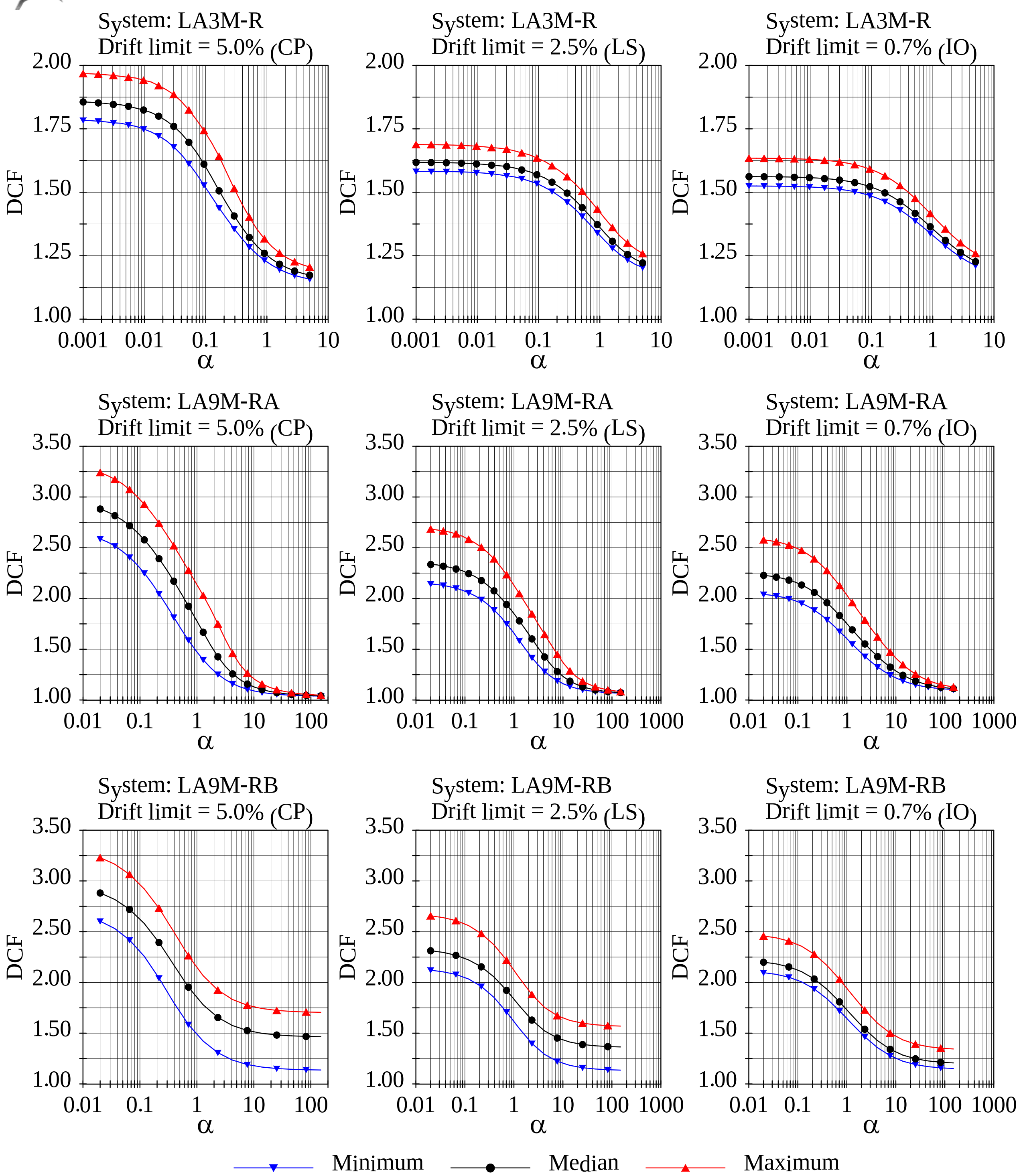

Fig. 6 – Maximum, minimum and median DCF values in rehabilitated systems.

To have a more direct comparison between the two rehabilitation plans for the nine-story steel MRF, the probability of DCF lower than an acceptable level was calculated for LA9M-RA and LA9M-RB, respectively. Assuming that DCF follows the lognormal probabilistic distribution at a given stiffness ratio, α_o , the probability of DCF not exceeding an acceptable level, DCF_o , can be calculated as below:

$$P\left[\mathrm{DCF}<\mathrm{DCF_o}\middle|\alpha=\alpha_o\right]=\Phi\left(\frac{\ln(\mathrm{DCF_o})-\theta}{\sigma}\right)\Bigg|_{\alpha=\alpha_o} \tag{3}$$

where Φ = the cumulative normal distribution function;

θ = mean of the natural logarithms of DCF; and

σ = standard deviation of the natural logarithms of DCF.

Fig. 7 compares the probabilities of DCF lower than 1.50 and 1.25 in LA9M-RA and LA9M-RB. Here, 1.50 and 1.25 were selected as the acceptable DCF levels associated with the inter-story drift distributions with moderate and practically ideal uniformities, respectively. As shown, to achieve a moderately uniform inter-story drift distribution (DCF lower than 1.5), both LA9M-RA and LA9M-RB can be considered. As identified by the point beyond which the probability curves start to rise, the minimum stiffness required in SRC to redistribute the drifts from story to story remains about the same in LA9M-RA and LA9M-RB. If the system is designed for the drift limit of 0.7%, LA9M-RA and LA9M-RB are probabilistically identical. However, if a larger inter-story drift is expected, LA9M-RA has a higher probability of limiting DCF within 1.5. When a more uniform inter-story drift distribution needs to be achieved (i.e., DCF lower than 1.25), LA9M-RA appears to be more effective in comparison with LA9M-RB. As shown, although LA9M-RB could limit DCF within 1.25 if the system is designed for the drift limit of 0.7%, this rehabilitation plan becomes inadequate if the system is designed for a larger drift limit. As illustrated, the target DCF of 1.25 can be only achieved in LA9M-RA (i.e., the one with SRC extending the entire height of the structure) if the system is designed for the drift limits of 2.5% and 5.0%.

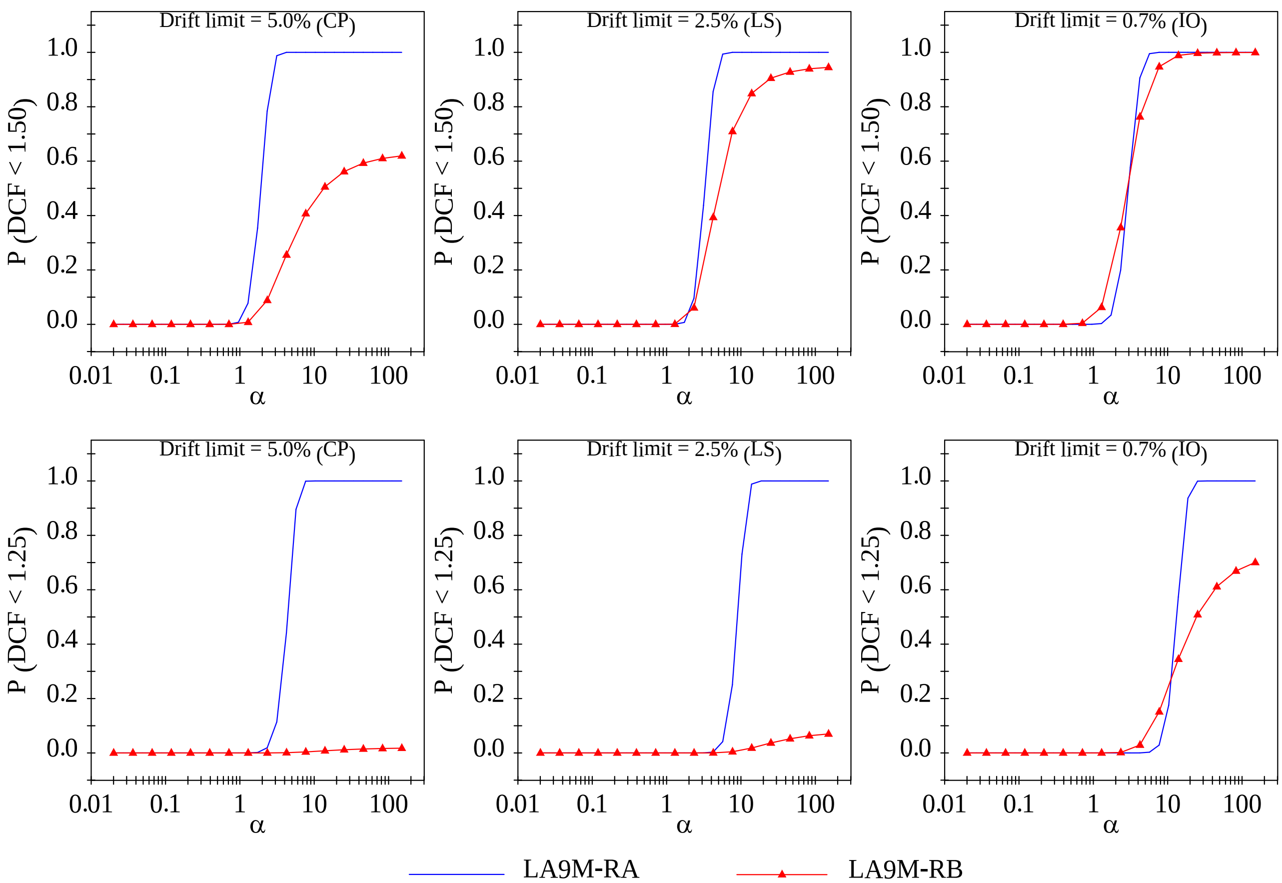

Fig. 7 – Comparison of probabilities of achieving expected DCFs: LA9M-RA vs. LA9M-RB.

6 Conclusions

This paper assessed adequacy of the SRC technology for reducing inter-story drift concentration in low-rise and mid-rise steel MRFs. Two representative archetype buildings including one three-story and one nine-story steel MRFs were selected and rehabilitated using the SRC technology. NSA taking into account different seismic force distributions and drift limits were conducted. Based on the result database, the following conclusions can be drawn from this study:

1. The SRC technology can reduce inter-story drift concentration in both low-rise and mid-rise steel MRFs regardless of the seismic force distributions and drift limits assumed in design. However, the technology may be less effective in a taller steel MRF.

2. A rehabilitated steel MRF generally exhibits a more uniform inter-story drift distributions when the SRC becomes stiffer. However, when excessively increasing the SRC stiffness beyond a certain limit, improvement in drift distribution become less remarkable.

3. For a mid-rise steel MRF, the system may be rehabilitated by the SRC extending either along the entire height or over the bottom portion of the structure. If a moderately uniform inter-story drift distribution (DCF less than 1.5) is expected in the rehabilitated system, both strategies can be used. However, if a more uniform inter-story drift distribution (DCF less than 1.25) is needed in the rehabilitated system, the SRC extending along the entire height of the structure is more preferable. In such a scenario, the SRC extending over the bottom portion of the structure should be used with caution since it helps only if a drift limit up to 0.7% is allowed in the rehabilitated system during an expected earthquake event.

4. The SRC technology is effective to improve uniformity of the inter-story drift distribution. However, its effectiveness to reduce the maximum inter-story drift response of rehabilitated system is limited. To further reduce the seismic response of a rehabilitated system, the SRC technology may be used with other energy dissipating devices. Research opportunities exist to further examine if a target performance can be achieved in a system rehabilitated as such.

7 Acknowledgements

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