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Modal pushover analysis of self-centering concentrically braced frames

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Abstract. Self-centering concentrically braced frames (SCCBFs) are emerging as high performance seismically resistant braced framing system, due to the capacity of withstanding strong earthquake attacks and promptly recovering after events. To get a further insight into the seismic performance of SCCBFs, systematical evaluations are currently conducted from the perspective of modal contributions. In this paper, the modal pushover analysis (MPA) approach is utilized to obtain the realistic seismic demands by summarizing the contribution of each single vibration mode. The MPA-based results are compared with the exact results from nonlinear response history analysis. The adopted SCCBFs originate from existing buckling-restrained braced frames (BRBF), which are also analyzed for purpose of comparison. In the analysis of these comparable framing systems, interested performance indices that closely relate to the structural damage degree include the interstory drift ratio, floor acceleration, and absorbed hysteretic energy. The study shows that the MPA approach produces acceptable predictions in comparison to the exact results for SCCBFs. In addition, the high-modes effect on the seismic behavior increases with the building height, and is more evident in the SCCBFs than the BRBFs.

Keywords: modal contribution; model pushover analysis; seismic performance; self-centering; braced frame

1. Introduction

Experimental and analytical results (Tremblay *et al.* 2008, Erochko *et al.* 2011, Vargas and Bruneau 2009) show that conventional dampers and the protected structures are usually able to withstand earthquakes through designated damping mechanism, but are tend to accumulate large residual deformation after earthquakes. According to a recent post-earthquake field reconnaissance (McCormick 2008), a residual drift ratio over 0.5% makes it more economical to rebuild a new structure than to repair the damaged one. Therefore, excessive permanent deformation in the structures will cause the post-event structures finally demolished and a long downtime to the affected area and city. In light of this, the past years saw a fast development of self-centering components and structures, with the aim to control or even eliminate the residual deformation for earthquake resistant structures.

Among various self-centering structural systems (Christopoulos *et al.* 2002, Chou *et al.* 2014, Weibe *et al.* 2012, Fang *et al.* 2017, Hou *et al.* 2017, Qiu *et al.* 2017, Qiu and Zhu 2017a, 2017b), self-centering concentrically braced frames (SCCBFs) gained wide attentions, due to the advantages of self-centering braces (SCBs), including convenient installation, noninterference with the gravity supporting system and avoidance of the floor expansion problem. To understand the seismic performance of SCCBFs, many analytical studies were carried out in the past years. McCormick *et al.* (2007) showed SCBs are superior to conventional steel braces by resulting in smaller peak interstory drift and nearly eliminated residual deformation. More importantly, SCBs were reported to be more favorable than BRBs in concentrically braced frames by several studies (Tremblay *et al.* 2008, Zhu and Zhang 2008, Chou *et al.* 2014), although SCBs have a much smaller damping behavior than BRBs. Besides, some studies unveiled other aspects of SCCBFs. For example, Xie *et al.* (2016) studied the effect of hysteretic parameters on the seismic responses of SCCBFs by parametric analysis. Qiu and Zhu (2016) pointed out that the SCCBFs are more sensitive to high modes effect than comparable BRBFs. Rahgozar *et al.* (2017) found near-fault pulse-like ground motions are more detrimental than far-field ones to the SCCBFs. In addition to this, those studies (Christopoulos *et al.* 2014, Seo and Sause 2005, Karavasilis and Seo 2011) that based on single-degree-of-freedom (SDOF) self-centering systems also shed light on the general dynamic characteristics of SCCBFs.

This study contributes to further explore the dynamic characteristics of SCCBFs upon earthquake ground motion records, from the viewpoint of modal behavior. The modal behavior of different vibration modes has been reported important in the seismic analysis of buildings. An effective method for analyzing the modal behavior is the modal pushover analysis (MPA) method (Chopra and Geol 2002). The MPA method has been applied to various types of structural systems, such as the regular steel frames (Chopra and Geol 2002), unsymmerical-plan frames (Chopra and Geol 2004), reinforced concrete special moment resisting frames (Bobadilla and Chopra 2008), buckling restrained braced frames (BRBF) (Nguyen *et al.* 2010), and multi-span bridges (Paraskeva *et al.* 2006). Well agreement was found

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between MPA and nonlinear response hysteresis analysis (NLRHA) in these analyses. However, in terms of self-centering structures, very limited research placed focus on modal behavior. Roke *et al.* (2009) decomposed the modal behaviors for the self-centering rocking frames, and they found the effective accelerations in higher modes are underestimated by the current design spectrum. Wiebe L. *et al.* (2012) proposed two effective methods for the self-centering rocking frames, to mitigate the higher modes effects. Qiu and Zhu (2016) also noticed the high-modes effect of SCCBF.

Considering the need to understand the seismic responses of SCCBFs from the perspective of vibration modes. The aim of this study is to systematically analyze the higher modes contributions in the nonlinear seismic behaviors for the SCCBFs. To achieve this goal, the MPA method is briefly introduced and utilized in the analyses. With the purpose of a straightforward understanding of the seismic behavior of this new framing system, the BRBF systems are analyzed as well. Three key seismic response indices, including the interstory drift ratio, floor acceleration, and absorbed seismic energy, are examined, because they are closely related to the damage degree of structures. The current results are expected to promote the development of performance-based seismic design of SCCBFs.

2. Structural models

Three frame buildings with story number equals to 3, 6 and 16 are selected to represent typical low-, mid-, and high-rise buildings, respectively, as shown in Fig. 1. For the 3- and 6- story frames, the major structural components, including the columns, beams and braces, are directly obtained from the existing BRBFs, designed by Chen and Mahin (2012). Details of the 3- and 6- story frame dimensions, material properties and loads can be found in the corresponding report. However, except for the columns are continuous from bottom to up, all the connections are artificially transformed into nonmoment-resisting types. Such alternatives are made based on the following considerations: (1) the report (AISC/SEAOC 2001) recommended the braced frame to form a complete vertical truss mechanism, which can be achieved by allowing the utilization of hinged connections; (2) the advantages of hinged types over rigid types for the beam-to-column connections were experimentally validated by Fahnestock *et al.* (2007); (3) pinned column bases have been approved by previous investigators (Erochko *et al.* 2011). It is noted that these modifications may elongate the vibration periods of the structures, but still maintain the primary purposes of this investigation which aims to compare the modal behavior between SCCBFs and BRBFs. With the modifications of connections from rigid type to pinned one, the influence of moment-resisting frame is well isolated. This assures the lateral resisting capacity of the modified structures is purely provided by the bracing systems, and therefore, comparisons between BRBFs and SCCBFs become direct.

As mentioned in the report (Chen and Mahin 2012), the 16-story frame needs a second design to achieve a more favorable performance during the earthquakes. Therefore,

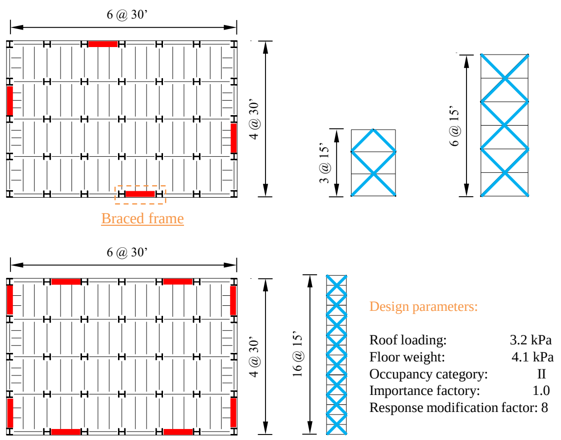


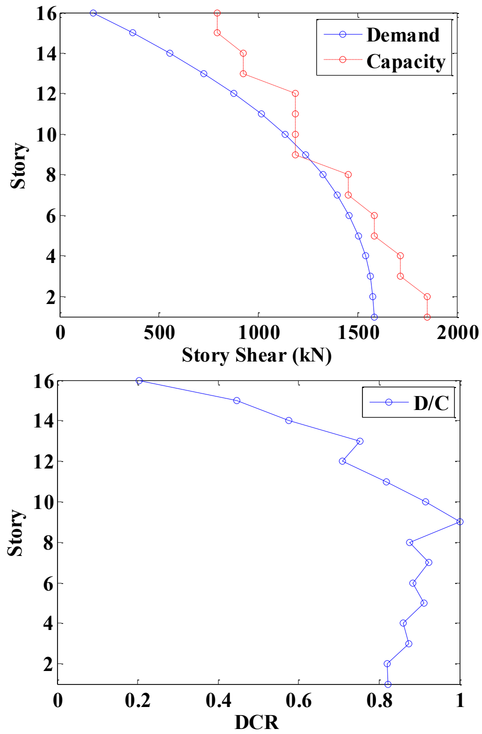
Fig. 1 Plan and elevation views of 3-, 6-, and 16- story braced frames

Table 1 $D_i \cdot V_y / C_i^2$, change of $D_i \cdot V_y / C_i^2$ in original and redesigned 16-story BRBF

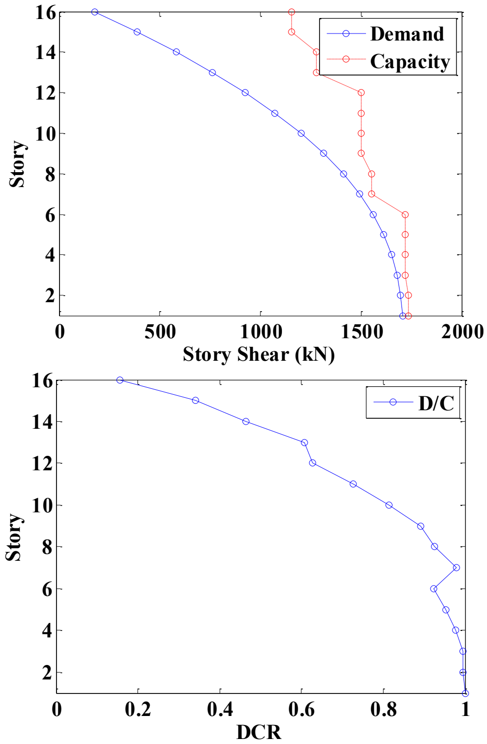
Floor/Story		Original		Redesigned	
		$D_i \cdot V_y / C_i^2$	change ratio of $D_i \cdot V_y / C_i^2$	$D_i \cdot V_y / C_i^2$	change ratio of $D_i \cdot V_y / C_i^2$
Roof	16	0.42	0.46	0.23	0.46
16	15	0.93	0.91	0.50	0.81
15	14	1.03	0.77	0.61	0.76
14	13	1.34	1.36	0.80	1.14
13	12	0.98	0.86	0.70	0.86
12	11	1.14	0.89	0.81	0.89
11	10	1.27	0.92	0.91	0.91
10	9	1.39	1.39	1.00	1.00
9	8	1.00	0.95	1.00	0.95
8	7	1.05	1.14	1.06	1.17
7	6	0.92	0.97	0.90	0.97
6	5	0.95	1.15	0.93	0.98
5	4	0.83	0.98	0.95	0.98
4	3	0.84	1.15	0.97	1.01
3	2	0.73	1.00	0.96	1.00
2	1	0.73	-	0.97	-

*Vy: the yielding capacity of the structure

examine and redesign of the bracing system was conducted for the 16-story frame before the formal analysis. To assess the capacity-demand relationship, the nonlinear pushover analysis was conducted by applying lateral force pattern compliant with the first vibration mode. The results are shown in Fig. 2, including the story shear along building height and the corresponding demand-to-capacity ratio (DCR). It can be seen that interstory drift and damage are concentrated in the 9th story in the original structure. This is due to the excessive difference in stiffness or strength at adjacent floors, which gives rise to a soft story/weak story mechanism. Thus, the proportion of the structural components in the archetype seems not appropriate. To reduce the drift concentration, the 16-story BRBF was redesigned, following the same design target as suggested



(a) Original braces



(b) Redesigned braces

Fig. 2 Story shear capacity and demand of first-mode pushover analysis and normalized demand-to-capacity ratio of BRBF

by Chen and Mahin (2012), i.e., the difference of in two adjacent levels was selected to be within 30% to reduce stiffness irregularity. Di and Ci refer to the demand and capacity at the ith story, respectively, and Vy is the yielding strength of the structure. Table 1 summarizes and the change ratio of for original and redesigned structures. It should be noted that only the brace sizes were changed; the size in beams and columns remained the same as the previous design. As shown in Fig. 2, the DCR along the building height becomes smoother in the redesigned structure than that in the original structure. The redesigned 16-story frame will be used in the following analysis.

3. Fundamentals of MPA

MPA was developed to evaluate the modal behavior for a multi-degree-of-freedom (MDOF) system, and the associated preliminary concept dates back to an early research (Sasaki *et al.* 1998), and was further developed by Chopra and Geol (2002). Since that, the MPA method gained wide attention and has been utilized to analyze various structural systems. For example, Chopra and Goel (2004) validated the MPA method on unsymmetrical-plan buildings; Chintanapakdee and Chopra (2004) extended this method to vertically irregular frames, including stiffness and/or strength irregular cases. Bobadilla and Chopra (2008) proved the applicability on reinforced concrete special moment resisting frame buildings. More studies based on the MPA method can be found elsewhere (Xiang *et al.* 2017, Mao *et al.* 2008, Jiang *et al.* 2010, Han *et al.* 2010).

The MPA method is essentially a static calculation process, thus only the static variables, such as the floor displacement and interstory drift ratio, can be readily extracted from the calculation database, but the dynamic variables, such as the floor accelerations, cannot be obtained directly from this static analysis. However, we adopted an alternative method to estimate the modal accelerations in the succeeding section. The modal concept plays an important role in the current study, and the procedure for MPA method (Chopra and Geol 2002) is briefly introduced and discussed as follows:

1) Determine natural frequencies, ωn and modal shapes, ϕn for the linear-elastic buildings. It should be noted that the dynamic characteristic changes if the structures are deformed into inelastic state.

2) For the nth mode, apply and maintain the gravity loads on the structure, and then carry out pushover analysis to develop the base shear-roof displacement, Vbn-urn, curve, as shown in Fig. 3(a). The lateral force pattern adopted during the nonlinear static analysis is given

$$\mathbf{s}_n^* = \mathbf{m}\phi_n \tag{1}$$

since ϕn is the eigenvalue vector of the elastic system, is invariant along the building height during the pushover analysis.

3) Convert the Vbn-urn pushover curve to the force-deformation, Fsn/Ln-Dn, as shown in Fig. 3(b), relationships for the nth-mode nonlinear SDOF system by utilizing

$$F_{sn} / L_n = V_{bn} / M_n^* \tag{2}$$

$$D_n = u_{rn} / \Gamma_n \phi_{rn} \tag{3}$$

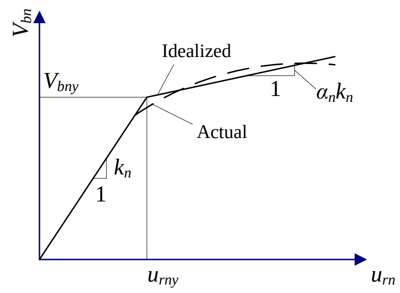


Fig. 3(a) An nth-mode pushover curve and its bilinear idealization

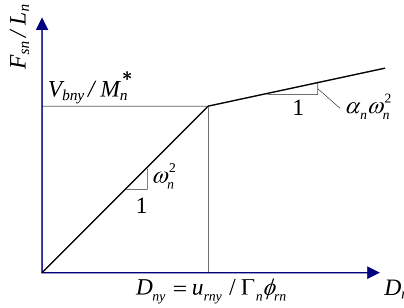


Fig. 3(b) force-deformation relation for the nth-mode inelastic SDOF system

Where is the effective modal mass, Dn is the peak deformation of the nth-mode SDOF system, it is worth noting that both of them are independent on the absolute value of ϕn.

4) Idealize the force-deformation relation for the nth-mode SDOF system. Generally, a bilinear assumption is accurate enough for the low-mode behavior, but a trilinear idealized curve may be needed in fitting the high-mode behavior.

5) Compute initial elastic vibration period of the nth mode inelastic SDOF system, Tn, and peak deformation of the nth mode inelastic SDOF system, Dn, through Eqs. (4) and (5) respectively for the corresponding SDOF system

$$T_n = 2\pi (L_n D_{ny} / F_{sny})^{1/2} \tag{4}$$

$$\ddot{D}_n + 2\zeta_n \omega_n \dot{D}_n + F_{sn} / L_n = -\ddot{u}_g(t) \tag{5}$$

where r represents building roof.

6) Calculate the peak roof displacement, urn, of the multi-story frame from the associated nth-mode inelastic SDOF system

$$u_{rn} = \Gamma_n \phi_{rn} D_n \tag{6}$$

7) From the pushover results generated in step 2, extract desired responses, rn+g, due to the joint effects of lateral and gravity loads at roof displacement equal to urn given by Eq. (6).

8) Repeat steps 3 to 6 to consider as many modes as required for sufficient accuracy. Then predict the total dynamic response by combining the peak modal responses using an appropriate modal combination rule, such as SRSS, CQC, ABSSUM, *et al.*; the SRSS rule is adopted for estimating structural deformations in the current study, because the structural systems are symmetric in the direction of earthquake attack.

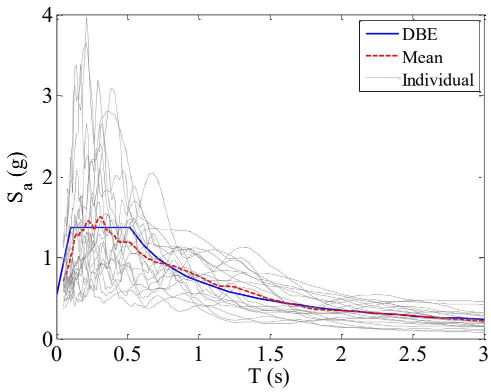


Fig. 4 Comparison of the mean acceleration spectrum of the selected 20 ground motions with the 5% damping design spectrum

4. Ground motions

Somerville (1997) developed a suite of ground motions containing a total of 20 earthquake records, designated as LA01-LA20. These 20 earthquake vibration records were generated for Los Angeles, having probabilities of exceedence of 10% in 50 years. The 20 records were derived from ten historical records with frequency domain adjusted and amplitude scaled, and their soil types were modified to soil type SD. Fig. 4 shows the 5%-damped elastic response spectra of considered ground motions. It is seen that the mean response spectrum of the selected ground motions well matches the design spectrum corresponding to the design basis earthquake seismic hazard level, although large dispersion is noticed between each single ground motion record.

5. Numerical model

The numerical models of multi-story SCCBFs were built in the earthquake simulation platform OpenSees (McKenna *et al.* 2000). For all the frames, only one bay was modeled by neglecting the torsional effect. The considered seismic weight equals to the total building weight divided by the number of frames. The main frame were made from ASTM A992 steel and modeled by force-based beam-column elements (Neuenhofer and Filippou 1997). Pin connections are introduced by releasing rotation restraints between different components. The deterioration of steel due to local buckling or low cycle fatigue was not considered. One single element is built to model the braces. The BRBs and SCBs were properly sized over the building height, and they were designated with identical stiffness and strength in each story for comparison purpose. The post-yield stiffness ratio is assumed to be 0.02, which is consistent with the report (Chen and Mahin 2012). BRBs and SCBs were defined by the Steel02 and SelfCentering

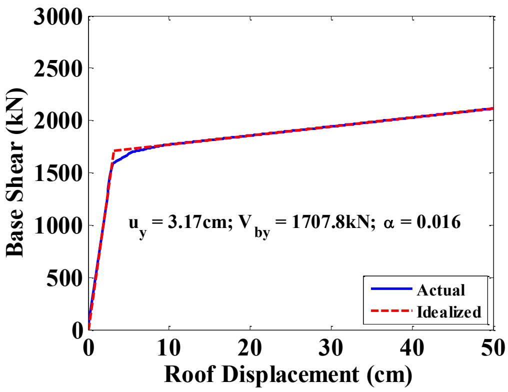


Fig. 5(a) 1st-mode pushover curve

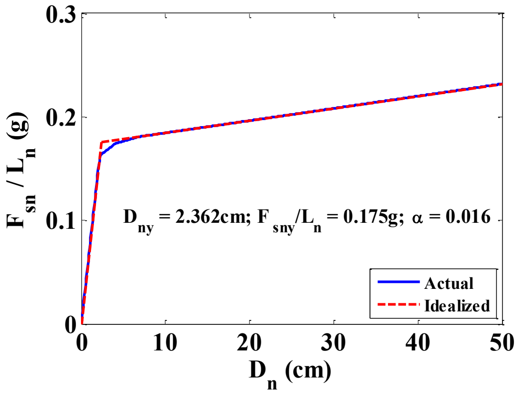


Fig. 5(b) force-deformation relationship for the 1st-mode inelastic SDOF system in 3-story frame

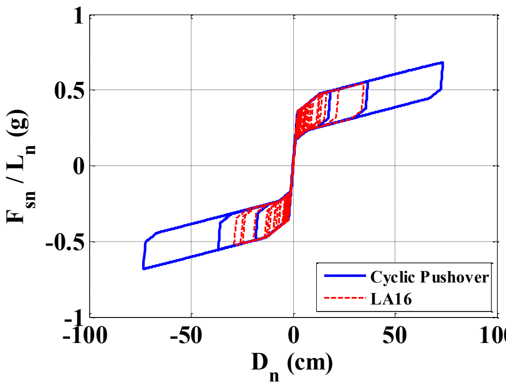


Fig. 6 Force-deformation relationship of the 2nd-mode SDOF system for the 6-story SCCBF

material, respectively, and were an assembly of uniaxial fibers at each integration point. The key hysteresis parameters of SCBs, including the post-yield stiffness and energy dissipation factor (Christopoulos *et al.* 2002), are currently set to be 0.02 and 0.5, respectively.

A leaning column was added adjacent to the braced frame to sustain the gravity loads. Pins were modeled between adjacent stories, contributing zero lateral stiffness or strength to the entire structure. Gravity loads are gradually applied to the leaning column before the transient analysis, and the P-Delta effects are considered during the seismic response. Thus the seismic loads were generated by the leaning column, whereas entirely sustained by the braced frame. Rayleigh damping is assumed to be 5% for the first two elastic modes. Sufficient duration time was added after the time history of ground motion records, to make sure the vibrations of building were damped out and thus to accurately capture the residual deformations after earthquakes.

6. Analysis of results

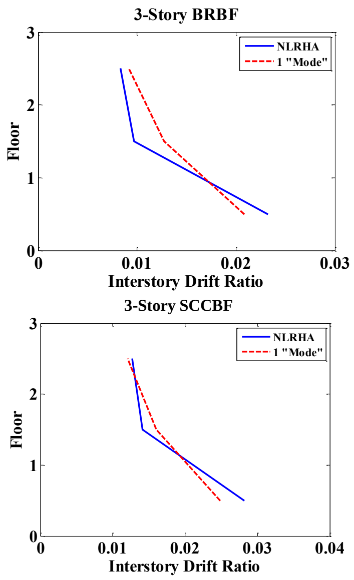
6.1 Force-deformation relationship for modal SDOF systems

The force-deformation relationship for inelastic modal SDOF system is determined from the nth-mode pushover curve by applying the lateral force distribution defined by Eq. (1), mainly depending on the material properties of structural members and the specified modes. The idealization of force-deformation is critical to the accuracy of MPA results. For the steel structures, a bilinear elasto-plastic constitutive model is sufficient (Chopra and Geol 2002), while reinforce concrete structures requires the peak-oriented model (Bobadilla and Chopra 2008). In terms of the modal role, bilinear curve always fits the actual curve well for low-mode, but a trilinear curve would be more appropriate, since it records the multi-yielding process. In the current study, the force-deformation shape is only affected by the modes.

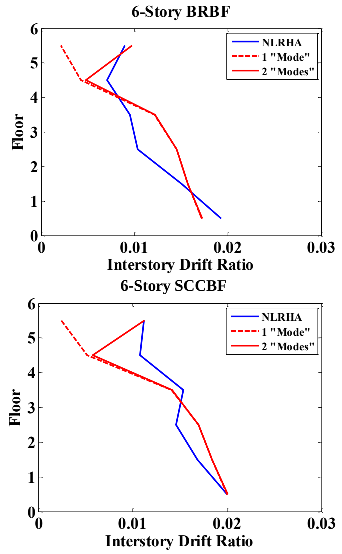
Fig. 5 illustrates how to transfer the pushover curve to the force-deformation for the 1st-mode SDOF system in the 3-story frame. It is seen that the bilinear idealized curve fits the actual results very well. The post-yield stiffness of the first-mode pushover curve is slightly less than that of the braces because of P- effects. The 2nd-mode case also uses the bilinear curve, and thus not presented. Fig. 6 shows the 2nd-mode force-deformation relationship for the 6-story SCCBF. It is seen the post-yield branch of the 2nd mode exhibits trilinear behavior. Therefore, the idealization of the 2nd modal behavior requires a trilinear constitutive model, which can be achieved by paralleling two simple material models. In this work, two flag-shape models are paralleled to generate the final model. To validate that the constructed model is able to accurately predict the behavior associated with the 2nd mode, Fig. 6 contains the curves generated by cyclic pushover analysis and nonlinear time history analysis. Ground motion LA16 is artificially selected to demonstrate the dynamic behavior. It is seen that the constructed model successfully fits the constitutive model of the 2nd-mode SDOF system for the SCCBFs. The same idealization rule is adopted for the other frames, and not presented due to space limitation.

6.2 Interstory drift ratio demand

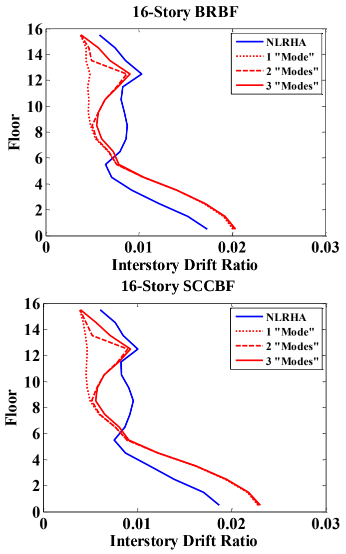
Interstory drift ratio, max, is a critical index in the seismic performance evaluation, because it is closely related to the damage degree of structural and nonstructural components. Fig. 7 compares the results by NLRHA and MPA for low- to high-rise BRBFs and SCCBFs. The NLRHA results are based on mean value. Globally, it is seen that the first mode alone is inadequate in estimating



(a) 3-story frame



(b) 6-story frame



(c) 16-story frame

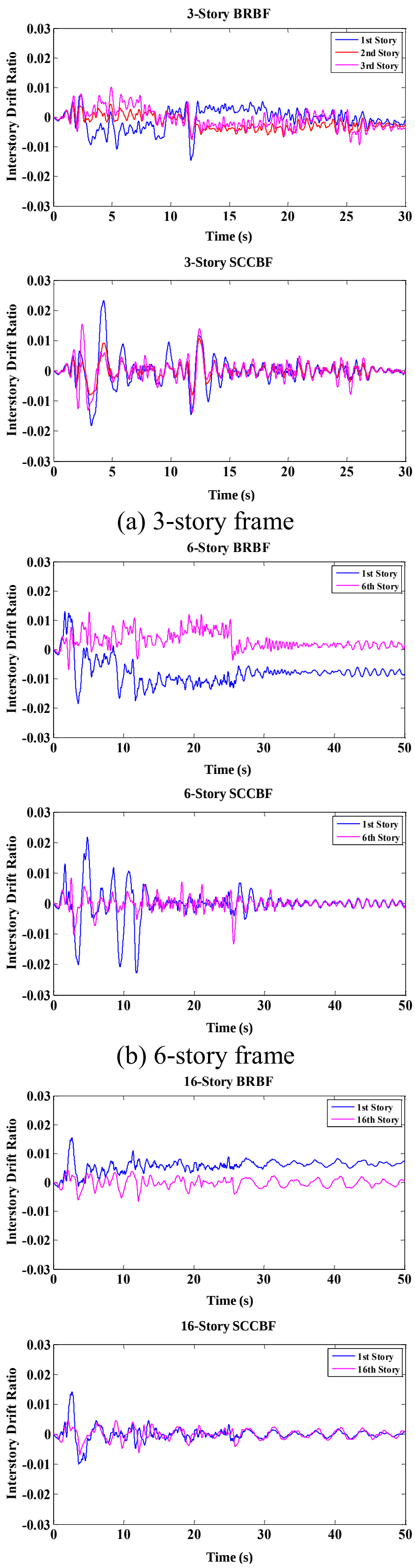
Fig. 7 Maximum interstory drift ratio demands in multi-story frame buildings

interstory drift ratios to a certain degree, but with higher modes included, interstory drift ratios estimated by MPA are well improved, especially in the upper stories. The discrepancy of 1st-mode prediction tends to increase with the building height, because the higher-mode contributions are known to be usually more significant for high-rise buildings (Chopra and Geol 2002).

When predicting the structural deformation demand, the high modes contribution varies as the story height/number changes. As shown in Fig. 7(a), the results of the 3-story buildings show that the 1st-mode MPA result accurately predicts the NLRHA result in both BRBF and SCCBF, although mild discrepancy is found over the building height. In terms of the 6-story structures, as shown in Fig. 7(b), the 1st-mode alone prediction by MPA is reasonably accurate along the building height, except for the top story, in which the prediction is approximately 80% smaller. However, the combined modes result improves the prediction remarkably in the top story, producing a well-matched result. As far as the 16-story building is concerned, a similar trend like that of the 6-story building is observed. The 1st-mode result is only accurate from the low to middle stories, but the combined modes result in good agreement with the NLRHA outcome. It is interesting to note that the responses of BRBF and SCCBF are close to each other, which is mainly attributed to the equal displacement rule for long-period structures. In this high-rise building, it should be noted that the P-Δ effect due to gravity is more significant than that in lower-story buildings, leading to noticeably larger deformation in the lower stories in the MPA, compared with the NLRHA results. Excluding the P-Δ effect (Chopra and Geol 2002, Chintanapakdee and Chopra 2004) may improve the prediction in this case.

Through the above comparisons, it is concluded that the nonlinear seismic performance for this two braced frames share two same features: 1) the 1st-mode deformation demand dominates the total demand in the low-rise buildings, and accounts for a large percentage among all the modal demands in the higher-rise buildings, but the deformation demand of SCCBFs are always greater than that of BRBFs; 2) the higher modes, i.e. the 2nd and 3rd modes, are central in predicting the top story deformations, irrespective of the frame types. Due to lower energy dissipating capacity, the SCCBFs tend to sustain a larger deformation demand than BRBFs, but recent research results show properly designed SCCBFs (Zhu and Zhang 2008, Christopoulos *et al.* 2002, Tremblay *et al.* 2008) exhibit comparable deformation as the BRBFs. Parenthetically, the yield strengths of BRBFs and SCCBFs are designated to be exactly the same in this analytical study, in other words, a same response modification coefficient (ASCE 2010) is assumed for both systems. Therefore, the significant disparity in seismic responses implies that the seismic design of SCCBFs should use specially developed design parameters which differ from that of BRBFs, provided if these two systems are expected to meet same performance targets defined by seismic provisions.

Fig. 8 presents the response time history of interstory drift ratio at selected stories for all buildings upon ground motion record LA01. This specific ground motion record is selected, with the aim to observe the time histories of



(a) 3-story frame

(b) 6-story frame

(c) 16-story frame

Fig. 8 Response time history of interstory drift ratio in the 3-, 6- and 16-story frames upon ground motion LA01

interstory drift ratio and transient modal periods. For the 3-story frames, the maximum interstory drift ratio tends to concentrate at the first story, but occurs at different moments, which are approximately 10s and 4s in BRBF and SCCBF, respectively. This implies the maximum response is delayed in BRBF, compared with the SCCBF. Another important feature of SCCBF can be found at the first inelastic excursion, which leads to a remarkable deformation at the top story. But this behavior is not evident in the BRBF, which implies that the higher modes contribution seems more likely to be excited in the SCCBFs, similar trend can be found in the time history responses of the 6- and 16-story buildings. However, the 6- and 16-story buildings show mild time delay of peak response, attributed to the smaller drift concentration degree (Qiu *et al.* 2018), which equals to the ratio of maximum interstory drift over maximum roof drift, representing an index describing the uniformity of the peak deformation demand along the vertical direction of the building.

6.3 Floor acceleration demand

A large portion of non-structural components and building contents are damaged primarily as a result of being subjected to large floor acceleration demands. An estimation of floor acceleration in each mode is important when estimating the seismic performance of critical facilities that are expected to maintain in operation during and after earthquakes. However, as aforementioned, the modal acceleration cannot be extracted directly from the MPA database. Therefore, the total floor accelerations at any floor are approximated using classical modal analysis by considering the contribution of only the first m modes of vibration computed as follows (Singh and Sharma 1985, Miranda and Taghavi 2005)

$$\ddot{u}^t = \ddot{u}_g + \sum_{i=1}^{m} \Gamma_i \phi_i \ddot{D}_i \qquad (7)$$

where and represent the total floor acceleration and ground motion acceleration, respectively; the other parameters are the same as those defined in previous equations. It should be noted that Eq. (7) is only theoretically valid for the elastic systems, and gives exact solution by including all modes. Considering the current buildings deformed well into inelastic stages, this equation would be no longer accurate (Kunnath 2004).

Although this combination rule, i.e., Eq. (7), may be lack of accuracy for the seriously inelastic deformed structures, the main purpose of this investigation is to study the higher modes contributions in SCCBFs. It is expected that the accuracy of this combination rule would decrease as the structures experiencing frequent modal change during seismic response. To facilitate a better understanding of the variation of modal shapes, eigenvalue solutions were obtained at several discrete steps throughout the time-history analysis for the 3-story buildings. To generate Fig. 9, an eigenvalue analysis was carried out at an interval of 0.1 second providing snapshots of the modal period shifts at 150 discrete points. The spikes in the modal periods represent plastic behavior at relatively large deformations, and imply the modal change as well. It is clear that, compared with the BRBF, the SCCBF suffers more frequent modal shape changing.

Fig. 10 compares the modal acceleration prediction by MPA and the exact NLRHA results. The NLRHA results are

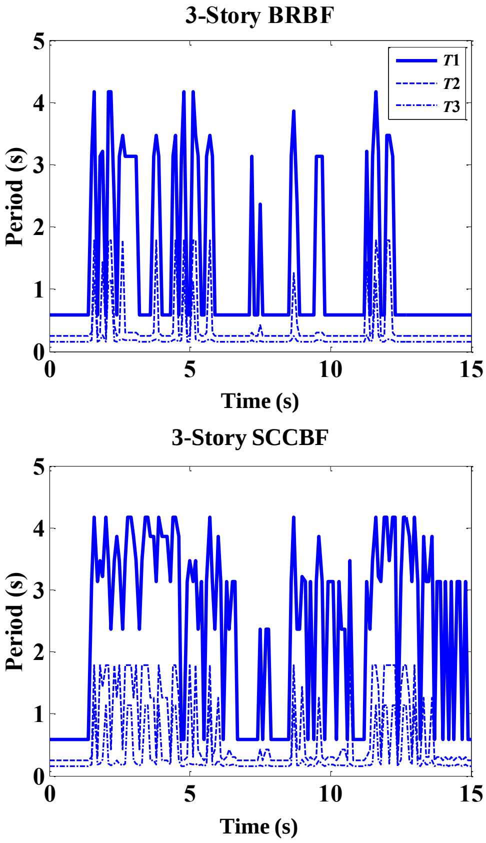


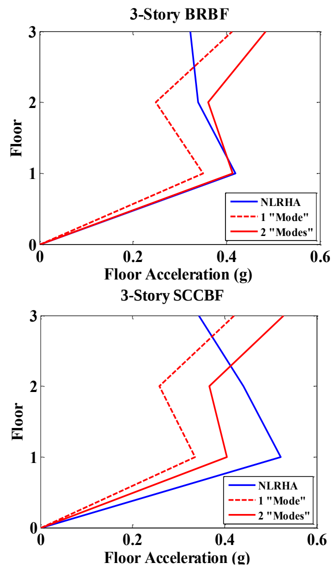
Fig. 9 Transient modal periods of the 3-story frames upon ground motion LA01

based on the mean values of 20 ground motion records. It is seen that the acceleration prediction is not as good as the interstory drift ratio prediction in both structural systems, but we can still observe some trends from this investigation. The top story accelerations are overestimated, but the low- to mid-stories are underestimated. By considering higher modes contributions, an acceptable accuracy can be found in the BRBFs, but there is still noticeable error in the SCCBFs. Therefore, due to the more frequent modal change, the errors in SCCBFs are noticeably larger than BRBFs, particularly in the low stories. However, current seismic design practice assumes the same response modification factor for all modes, even though there is strong evidence that inelasticity affects higher modes of vibration unequally. Thus, an appropriate estimation method of modal accelerations in higher modes is particularly important for the SCCBFs.

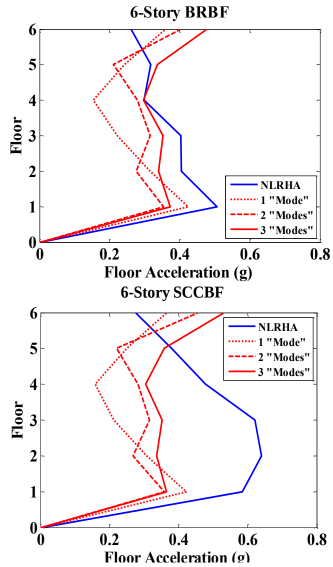
6.4 Energy demand

Besides with the interstory drift ratio, seismic energy absorbed by the hysteretic behaviors of structures during an earthquake is another key factor to evaluate the structural damage degree. The energy balance equation (Uang and Bertero 1990) for a multi-story building subjected to an earthquake ground motion is given as follows

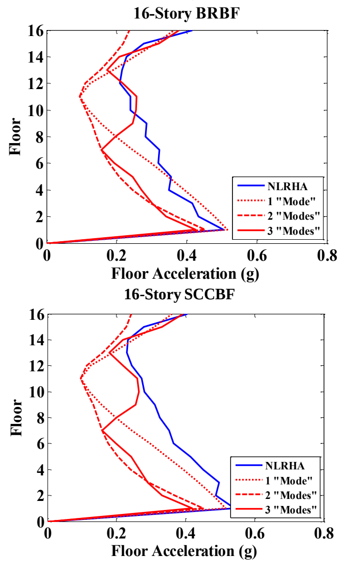
$$\frac{1}{2}\dot{\mathbf{v}}_t^T\mathbf{m}\dot{\mathbf{v}} + \int \dot{\mathbf{v}}^T\mathbf{c}d\mathbf{v} + \int \mathbf{f}_s^T d\mathbf{v} = \int (\sum_{i=1}^{N} m_i \ddot{v}_{ti}) dv_g \tag{8}$$



(a) 3-story frame

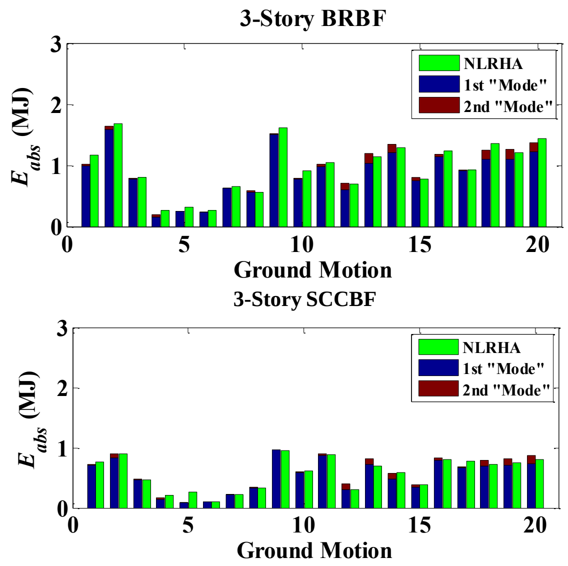


(b) 6-story frame

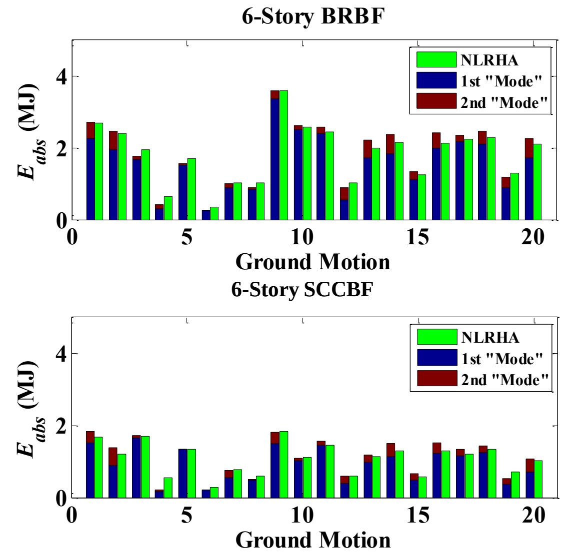


(c) 16-story frame

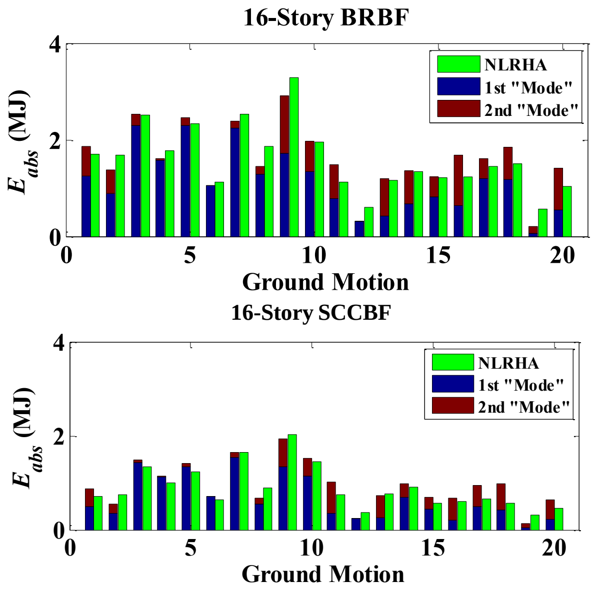
Fig. 10 Maximum floor acceleration demands in multi-story frame buildings



(a) 3-story frame



(b) 6-story frame



(c) 16-story frame

Fig. 11 Energy demands in multi-story frame buildings

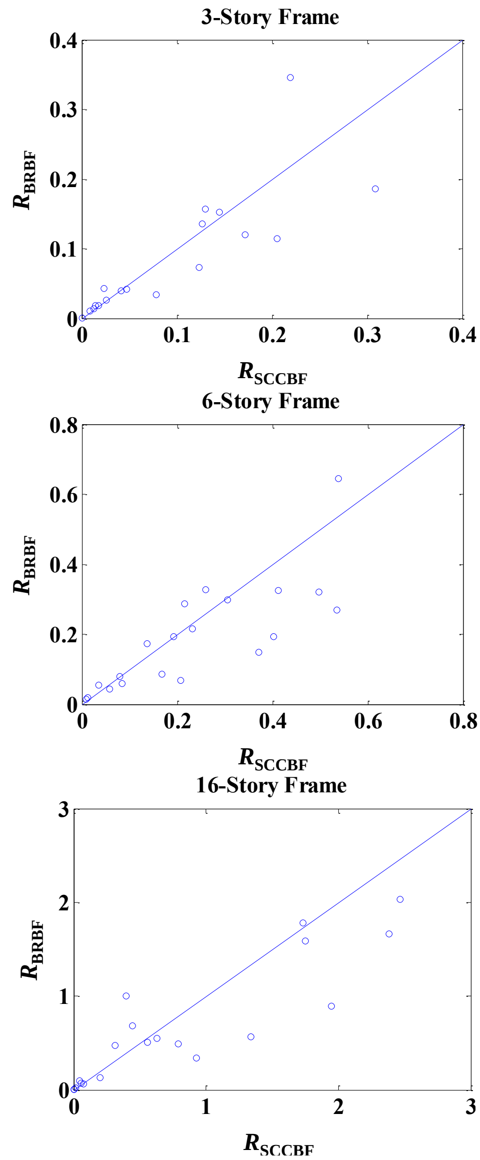


Fig. 12 Scatter plots comparing R_{BRBF} and R_{SCCBF}

where m, c, and v are the mass matrix, viscous damping matrix and relative displacement vector respectively. mi is the lumped mass associated with the ith floor, is the absolute acceleration at the ith floor. The third term is the absorbed energy (Eabs), and the right-hand-side term is the input seismic energy (Ei). Recalling the floor accelerations are larger in SCCBF than in BRBF, more energy will tend to be input into the SCCBFs. The current focus, however, is on the absorbed energy.

Based on the MPA concept, some investigators (Chou and Uang 2003, Prasanth *et al.* 2008) studied the distribution of Eabs in different vibration modes, they concluded that the total absorbed energy, Et, in a multi-story frame can be approximately estimated by summing the absorbed energies of the first two modes. Therefore, Et can be divided as

$$E_t = E_1 + E_2 \tag{9}$$

Fig. 11 compares the energy demands by MPA and NLRHA for a total of 20 ground motion records. For the 3-

and 6-story buildings, it is seen that the first-mode result approximately accounts for the total energy, but the second-mode result contributes slightly. However, in the 16-story buildings, the second-mode contribution becomes significant, which can be clearly observed from the case associated with ground motion record LA09. Furthermore, E2 could even contribute more than E1 in the total absorbed energy, as illustrated by the case of ground motion record LA13. To quantify the energy weight among different modes, a comparative index, R = E2/E1, is introduced in the current study. Comparisons are made between these two structural systems with various stories for all analysis results, as shown in Fig. 12. It is evident that R increases greatly as the story number increases, regardless of building types. Furthermore, the second-mode energy exhibits higher contribution in the SCCBFs than the BRBFs, which is particularly evident in Fig. 12(c).

7. Conclusions

The seismic performance of multi-story SCCBFs is interpreted by analyzing the dynamic response of single mode. The SDOF systems are obtained by decomposing the multi-story frames, as defined in the MPA method. Through direct comparisons with comparable BRBFs, the seismic response characteristics of SCCBFs are highlighted. Damage indices, including interstory drift ratio, floor acceleration, and absorbed energy, were evaluated. Major findings and conclusions are summarized as follows:

• The modal behavior is similar in determining the interstory drift ratio for both the BRBFs and the comparable SCCBFs. The first-mode alone result well predicts the accurate response of the 3-story frames. But for the 6- and 16-story frames, the higher modes are significant in predicting the top story deformation. Because of relatively low energy dissipation capacity, the SCCBFs always exhibit higher displacement demand than BRBFs, which implies the seismic design parameters for SCCBFs may differ from that of BRBFs.

• The floor acceleration cannot be obtained directly from the MPA database, but is obtained from a method which is only valid for the elastic systems. For this reason, noticeable bias is found in the comparisons between the estimated accelerations and exact results. Due to their mode shape changes more frequently, the current estimation method for floor accelerations is not as effective in SCCBFs as that in BRBFs. Thus, an appropriate estimation method of modal accelerations in higher modes is particularly important for the SCCBFs.

• The absorbed energy demand is assessed by using the MPA-based method. For both frame systems, the summation of 1st- and 2nd-modal absorbed energy is found approximately equal to the total absorbed energy. Nearly total energy is absorbed by the 1st-mode response in the 3-story frames. As the number of story increases, more energy will shift to the higher modes response. The energy distribution depends on the frame type, and it is seen that more energy tends to shift to the higher modes in SCCBFs, compared to BRBFs.

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References

American Society of Civil Engineers (ASCE), *Minimum Design Loads for Buildings and Other Structures*, Reston, VA 2010.

Bobadilla, H. and Chopra, A.K. (2008), "Evaluation of the MPA procedure for estimating seismic demands: RC-SMRF buildings", *Earthq. Spectr.*, **24**(4), 827-845.

Chen, C.H. and Mahin, S.A. (2012), *Performance-Based Seismic Demand Assessment of Concentrically Braced Steel Frame Buildings*, PEER Report, Pacific Earthquake Engineering Research Center, Headquarters at University of California, Berkeley, California, U.S.A.

Chintanapakdee, C. and Chopra, A.K. (2004), "Seismic response of vertically irregular frames: Response history and modal pushover analyses", *J. Struct. Eng.*, **130**(8), 1177-1185.

Chopra, A.K. and Geol, R.K. (2002), "A modal pushover analysis procedure for estimating seismic demands for buildings", *Earthq. Eng. Struct. D*, **31**, 561-582.

Chopra, A.K. and Geol, R.K. (2004), "A modal pushover analysis procedure to estimate seismic demands for unsymmeric-plan buildings", *Earthq. Eng. Struct. D*, **33**, 903-927.

Chou, C.C. and Uang, C.M. (2003), "A procedure for evaluating seismic energy demand of framed structures", *Earthq. Eng. Struct. D*, **32**, 229-244.

Chou, C.C., Chen, Y.C., Pham, D.H. and Truong, V.M. (2014), "Steel braced frames with dual-core SCBs and sandwiched BRBs: Mechanics, modeling and seismic demands", *Eng. Struct.*, **72**, 26-40.

Christopoulos, C., Filiatrault, A. and Folz, B. (2002), "Seismic response of self-centring hysteretic SDOF systems", *Earthq. Eng. Struct. D*, **31**(5), 1131-1150.

Erochko, J., Christopoulos, C., Tremblay, R. and Choi, H. (2011), "Residual drift response of SMRFs and BRB frames in steel buildings designed according to ASCE 7-05", *J. Struct. Eng.*, **137**(5), 589-599.

Fahnestock, L.A., Ricles, J.M. and Sause, R. (2007), "Experimental evaluation of a large-scale buckling-restrained braced frame", *J. Struct. Eng.*, **133**(9), 1205-1214.

Fang, C., Wang, W., He, C. and Chen, Y.Y. (2017), "Self-centring behaviour of steel and steel-concrete composite connections equipped with NiTi SMA bolts", *Eng. Struct.*, **150**, 390-408.

Han, S.W., Moon, K.H. and Chopra, A.K. (2010), "Application of MPA to estimate probability of collapse of structures", *Earthq. Eng. Struct. D*, **39**(11), 1259-1278.

Hou, H.T., Li, H., Qiu, C.X. and Zhang, Y.C. (2017), "Effect of hysteretic properties of SMAs on seismic behavior of self-centering concentrically braced frames", *Struct. Contr. Health Monitor*.

Jiang, Y., Li, G. and Yang, D. (2010), "A modified approach of energy balance concept based multimode pushover analysis to estimate seismic demands for buildings", *Eng. Struct.*, **32**(5), 1272-1283.

Karavasilis, T.L. and Seo, C.Y. (2011), "Seismic structural and non-structural performance evaluation of highly damped self-centering and conventional systems", *Eng. Struct.*, **33**(8), 2248-2258.

Kunnath, S.K. (2004), "Identification of modal combinations for nonlinear static analysis of building structures", *Comput-Aid. Civil Inf.*, **19**, 246-259.

Mao, J., Zhai, C. and Xie, L. (2008), "An improved modal pushover analysis procedure for estimating seismic demands of structures", *Earthq. Eng. Eng. Vibr.*, **7**(1), 25-31.

McCormick, J., Aburano, H., Ikenaga, M. and Nakashima, M. (2008), "Permissible residual deformation levels for building structures considering both safety and human elements", *Proceedings of the 14th World Conference on Earthquake Engineering*, Beijing, China.

McCormick, J., DesRoches, R., Fugazza, D. and Auricchio, F. (2007), "Seismic assessment of concentrically braced steel frames with shape memory alloy braces", *J. Struct. Eng.*, **133**(6), 862-870.

McKenna, F., Fenves, G.L. and Scott, M.H. (2000), "Open system for earthquake engineering simulation", University of California, Berkeley, California, U.S.A.

Miranda, E. and Taghavi, S. (2005), "Approximate floor acceleration demands in multistory buildings. I: Formulation", *J. Struct. Eng.*, **131**(2), 203-211.

Neuenhofer, A. and Filippou, F.C. (1997), "Evaluation of nonlinear frame finite-element models", *J. Struct. Eng.*, **123**(7), 958-966.

Nguyen, A.H., Chintanapakdee, C. and Hayashikawa, T. (2010), "Assessment of current nonlinear static procedures for seismic evaluation of BRBF buildings", *J. Constr. Steel Res.*, **66**(8), 1118-1127.

Paraskeva, T.S., Kappos, A.J. and Sextos, A.G. (2006), "Extension of modal pushover analysis to seismic assessment of bridges", *Earthq. Eng. Struct. D*, **35**, 1269-1293.

Prasanth, T., Ghosh, S. and Collins, K.R. (2008), "Estimation of hysteretic energy demand using concepts of modal pushover analysis", *Earthq. Eng. Struct. D*, **37**, 975-990.

Qiu, C.X. and Zhu, S. (2016), "High-mode effects on seismic performance of multi-story self-centering braced steel frames", *J. Constr. Steel Res.*, **119**, 133-143.

Qiu, C.X. and Zhu, S. (2017a), "Shake table test and numerical study of self-centering steel frame with SMA braces", *Earthq. Eng. Struct. D*, **46**, 117-137.

Qiu, C.X. and Zhu, S. (2017b), "Performance-based seismic design of self-centering steel frames with SMA-based braces", *Eng. Struct.*, **130**, 67-82.

Qiu, C.X., Li, H., Ji, K.F., Hou, H.T. and Tian, L. (2017), "Performance-based plastic design approach for multi-story self-centering concentrically braced frames using SMA braces", *Eng. Struct.*, **153**, 628-638.

Qiu, C.X., Zhang, Y.C., Li, H., Qu, B., Hou, H.T., and Tian, L. (2018), "Seismic performance of concentrically braced frames with non-buckling braces: a comparative study", *Eng. Struct.*, **154**, 93-102.

Rahgozar, N., Moghadam, A.S. and Aziminejad, A. (2017), "Response of self-centering braced frame to near-field pulse-like ground motions", *Struct. Eng. Mech.*, **62**(4), 497-506.

Recommended Provisions for Buckling-Restrained Braced Frames (2001), *AISC/SEAOC Recommended Provisions for BRBF*.

Roke, D., Sause, R., Ricles, J.M. and Gonner, N. (2009), "Design concepts for damage-free seismic-resistant self-centering steel concentrically braced frames", *Proceedings of the Structures Congress: Don't Mess with Structural Engineers: Expanding Our Role*.

Sasaki, K.K., Freeman, S.A. and Paret, T.F. (1998), "Multi-mode pushover procedure (MMP)-a method to identify the effects of higher modes in a pushover analysis", *Proceedings of the 6th U.S. National Conference on Earthquake Engineering*.

Seo, C.Y. and Sause, R. (2005), "Ductility demands on self-centering systems under earthquake loading", *ACI Struct. J.*, **102**(2), 275.

Singh, M.P. and Sharma, A.M. (1985), "Seismic floor spectra by mode acceleration approach", *J. Struct. Eng.*, **111**(11), 1402-1419.

Somerville, P.G. (1997), *Development of Ground Motion Time Histories for Phase 2 of the FEMA/SAC Steel Project*, SAC Joint Venture.

Tremblay, R., Lacerte, M. and Christopoulos, C. (2008), "Seismic response of multistory buildings with self-centering energy dissipative steel braces", *J. Struct. Eng.*, **134**(1), 108-120.

Uang, C.M. and Bertero, V.V. (1990), "Evaluation of seismic energy in structures", *Earthq. Eng. Struct. D*, **19**, 77-90.

Vargas, R. and Bruneau, M. (2009), "Experimental response of buildings designed with metallic structural fuses. II", *J. Struct. Eng.*, **135**(4), 394-403.

Wiebe, L., Christopoulos, C., Tremblay, R. and Leclerc, M. (2012), "Mechanisms to limit higher mode effects in a controlled rocking steel frame. 1: Concept, modeling, and low-amplitude shake table testing". *Earthq. Eng. Struct. D*, **42**(7), 1053-1068.

Xiang, Y., Luo, Y.F. and Shen, Z.Y. (2017), "An extended modal pushover procedure for estimating the in-plane seismic responses of latticed arches", *Soil. Dyn. Earthq. Eng.*, **93**, 42-60.

Xie, Q., Zhou, Z., Li, C. and Meng, S. (2016), "Parametric analysis and direct displacement-based design method of self-centering energy-dissipative steel-braced frames", *J. Struct. Stab. Dyn.*, 1750087.

Zhu, S. and Zhang, Y. (2008), "Seismic analysis of concentrically braced frame systems with self-centering friction damping braces", *J. Struct. Eng.*, **134**(1), 121-131.

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