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Drift Concentration of a Three-Story Special Concentrically Braced Frame with Strongback under Earthquake Loading

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Abstract. In conventional special concentrically braced frame (SCBF) structures, the buckling of the braces leads to severe reduction in system strength and stiffness. Therefore soft story mechanisms followed by large permanent deformation are commonly observed in SCBF structures. The strongback system using additional structural components along the height of the building to resist local deformation is able to improve the distribution of the drift. This research conducted case studies to investigate the effects of strength and stiffness of the strongback system on the behavior of typical three-story SCBF system. The primary variables to be investigated are stiffness factor α (strongback stiffness/SCBF stiffness) and strength factor β (strongback strength/SCBF strength). We conducted nonlinear dynamic analyses to evaluate the effectiveness of α and β on structural demand parameters including maximum drift ratio and drift concentration factor (DCF). Analyses results show that although strongback system with excessively high α and β will reduce maximum drift ratio and DCF of SCBF systems, it is noneconomic. On the other hand, strongback systems with low α and β ($\alpha<0.0048$ and $\beta<0.054$) have only little effects on improving structural behavior. The case studies suggested that $0.0096\leq\alpha\leq0.0168$ and $0.081\leq\beta\leq0.134$ accounting for both efficiency and economics can be used in the design of the selected SCBF systems.

Introduction

Special concentrically braced frame (SCBF) structural systems are widely used world-widely. It is efficient to provide lateral strength and stiffness to the structures. However, due to the buckling behavior of braces, the strength and stiffness reduced severely under large earthquake excitations. Moreover, it is not uncommon that soft-story mechanism occurs in SCBF structures leading to permanent damage or collapse of the structures. Canadian researchers [1, 2] used elastic truss structures incorporating with SCBF or buckling restrained braced frame (BRBF) to create uniformly deformed structures. In the meantime, Lai and Mahin [3] numerically investigated the behavior of hybrid strongback system which applied to a zipper-frame configuration [4-8]. The idea to keep half bay of the building to remain essential elastic and act as an elastic frame or a strongback has been applied to real practice [9]. Different from these elastic frame approaches, previous study [10] considered the contributions of gravity columns to lateral force resistance, and concluded that the gravity columns were able to reduce the deformation concentration. Ji et al. [11] investigated the effects of continuous gravity columns on braced frame structures and concluded that sufficient number of gravity columns reduce the deformation concentration effectively. More recently, Wada et al. [12] and Qu et al. [13] acknowledged the contributions of additional structures to change the energy dissipation mechanism of original structures and employed post-tensioned rocking walls and shear dampers to improve the mechanism of a moment resisting frame building. It was a successful application of strongback concept.

To quantify the design parameters of strongback system for its application to SCBF structures, we investigate how the strength and stiffness of strongback system affect the global behavior of SCBF frame in this study. Through nonlinear static and dynamic analyses, we looked into the demand parameters such as maximum drift ratio, permanent drift ratio, drift concentration factor (DCF) which was defined as DRmax/DRavg in literature [10].

Structural System Information

The model structure to be investigated is a three-story SCBF building with an additional strongback system. The original SCBF building is designed as per ASCE/SEI 7-05. We assume that the stiffness and strength of the beam-column connections and brace-to-framing connections adequate before the failure of brace, so they are not designed in detail. Following the recommendation from earlier research [14, 15], we conduct numerical simulations of SCBF system with OpenSees [16], which is capable of capturing nonlinear behavior of SCBF system and components, to identify the dynamic behavior of the system.

Design of Model Buildings. The SCBF was designed to represent a typical short-period braced frame system. Fig. 1 shows the layout of the model building. The braced bays were located at the perimeter of the structures. One bay of braced frame was used in each side of the perimeter. The SCBF was designed considering site condition of Site Class D and the resulting design lateral load was based on $S_s = 1.5g$ and $S_1 = 0.6g$. Member sizes are also shown in Fig. 1.

The gravity load only framing system is simplified as being a leaning column in the design. The P-delta effects are considered by applying gravity load on the leaning column, which is assumed to be axially rigid, but to have no lateral resisting capacity.

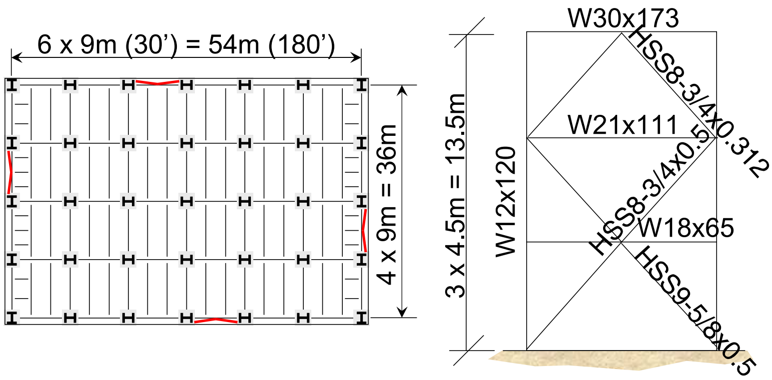


Fig. 1 Plan and elevation of 3-story braced frame archetypes.

Numerical Model. The structures are simulated using two-dimensional plane frame models with a leaning column as illustrated in Fig. 2. The columns are assumed continuous and are fixed to the base for all the nonlinear models. The beams are rigidly connected to the columns. At connections with gusset plates, the behavior is very nearly fixed, even if such connections are not detailed as being fully restrained. We also use a continuous column as a strongback; the sectional properties are selected to be the primary investigated parameters in this study. Also, the sections are the same along the height of the building. An empirical cycle counting method is used to simulate rupture due to low-cycle fatigue [15]. The material properties are set based on previous study [15]. In OpenSees models, Steel02, which is Menegotto-Pinto model with isotropic strain hardening, is used for all steel components. Fiber sections are adopted for the columns, beams, braces and gusset plates. Structural members including beams, columns and braces are modeled by using forced-based nonlinear beam-column elements. To simulate the dynamic behavior of the structures, damping ratio is an important parameter; Rayleigh damping, based on the mass and tangent stiffness proportional damping, is used in the analyses with 4% damping ratio at the first-mode period (T_1) and $0.2T_1$.

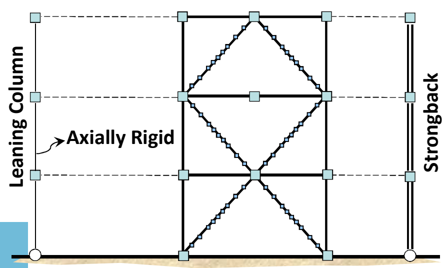


Fig. 2 Sketch of basic OpenSees model.

We calibrate the parameters of the numerical models by comparing to the experimental results of previous study [14, 15]. Fig. 3 shows that the strength, stiffness as well as the occurance of rupture of a two-story SCBF specimen can be satisfactorily simulated.

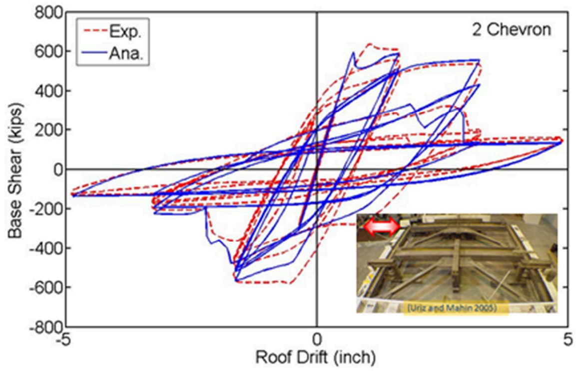


Fig. 3 Comparison of analytical and experimental responses of two-story chevron braced frame.

Stiffness Factor and Strength Factor. This study uses stiffness factor (α) and strength factor (β) to represent the relationship between strongback and concentrically braced frame. α is defined as the ratio of the lateral stiffness of strongback to the horizontal stiffness of braces at the first story, and is expressed in equation (1). β is defined as the ratio of the lateral strength of strongback to the horizontal strength contribution of braces at the first story and is expressed in Eq. (2).

$$\alpha = \frac{(EI/h^3)_{strongback}}{K_{h,brace}} \tag{1}$$

$$\beta = \frac{M_{PS}/h}{(R_y P_y + 0.3P_{cr})\cos\varphi} \tag{2}$$

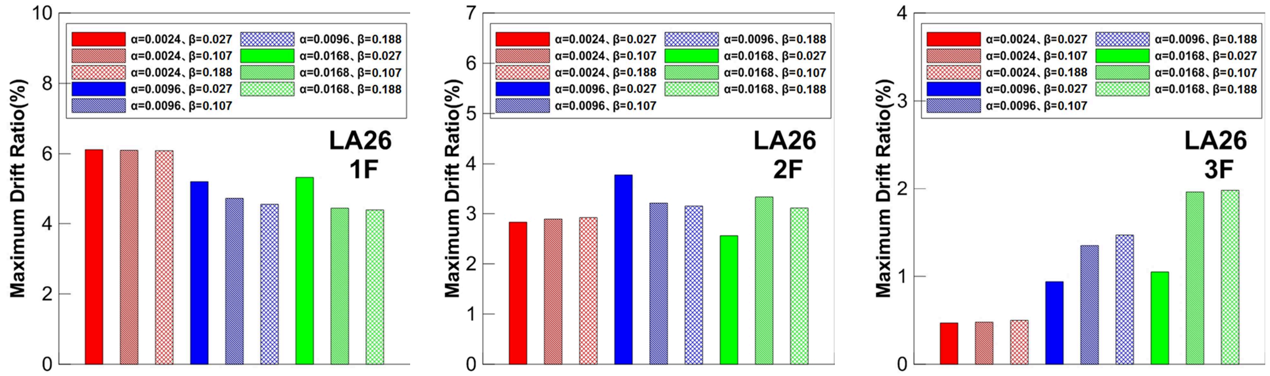
where, E is Young's modulus of steel, I is the moment of inertia of a strongback, h is the story height, $K_{h,brace}$ is the total horizontal stiffness of braces in a story, M_{PS} is the moment capacity of a strongback, R_y is overstrength factor of steel [17], P_y is the tension capacity of a brace, P_{cr} is the compression capacity of a brace and φ is the incline angle of the brace with respect to horizon in the frame.

One of the cases is adopting one column in the braced bay as the strongback; the corresponding α factor is 0.0024 and β is 0.027.

Nonlinear Analysis of Three-Story SCBF

Nonlinear dynamic analyses were conducted to investigate the performance of 3-story SCBF with different strength and stiffness of strongbacks. We applied 60 ground motions [18] to the structure representing design-level earthquakes (10% probability of exceedance in 50 years), MCE-level earthquakes (2% probability of exceedance in 50 years), and service-level earthquakes (50% probability of exceedance in 50 years). The structural responses under only design-level and MCE-level earthquakes are discussed here.

Maximum Drift Ratio. Because strongbacks are most efficient to improve structural behavior under MCE-level earthquakes, we investigated the maximum drift ratios of SCBF in response to one of the MCE-level earthquakes. Fig. 4 shows the maximum drift ratios at each story corresponding to various combinations of (α, β). The maximum drift ratios are indices approximately proportional to the nonlinearity of hysteretic behavior at each story. From the distribution of the maximum drift ratios in Fig. 4, we can observe the trend that increasing both α and β reduces the maximum drift ratio in the first story and redistribute the nonlinear behavior to other stories. It is more obvious in the third story that the maximum drift ratio increases as the strongbacks become stiffer and stronger. The results demonstrate that strongbacks are effective to change the mechanism of SCBF and result in a more uniformly distributed deformation of the structure. Most import, more structural elements in more stories participate in nonlinear behavior to dissipate more input energy from earthquakes.



(a) (b) (c)

Fig. 4 Maximum drift ratio of three-story SCBF with various strongbacks under ground motion record LA26 (a)1F (b)2F (c)3F.

Drift Concentration. Table 1 and Table 2 listed the normalized DCF with combinations of α and β factors at three hazard levels. We obtained the DCF values based on the maximum drift ratios at different stories during earthquake excitations. The listed normalized DCF values are median responses to a suite of earthquakes. Under design-level earthquakes, SCBF undergoes minor to moderate nonlinear behavior. Under design-level earthquakes, a strongback with low stiffness does not help reduce DCF even if the strongback has high strength. The strongback takes effect when its stiffness is sufficient. Under MCE-level earthquakes, we can observe similar and more obvious trend. A strongback with low stiffness cannot reduce DCF effectively (i.e. $\alpha = 0.0024$, larger β factor cannot help reduce DCF). However, as long as the strongbacks are stiff and strong enough ($\alpha \geq 0.0096$, and $\beta \geq 0.081$), DCF is reduced more than 19% (normalized DCF≤0.81). We can design a strongback with sufficient stiffness and strength without overly design it. From the case study, we suggested that α is in the range of $0.0096 \leq \alpha \leq 0.0168$ and β is in the range of $0.081 \leq \beta \leq 0.134$.

Table 1 Normalized DCF of 3-story SCBF with various strongbacks under design-level earthquakes.

α \ β	**0.027**	**0.054**	**0.081**	**0.107**	**0.134**	**0.161**	**0.188**
0.0024	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.0048	0.97	0.96	0.96	0.96	0.96	0.96	0.96
0.0072	0.95	0.93	0.93	0.93	0.93	0.93	0.93
0.0096	0.94	0.89	**0.89**	**0.89**	**0.89**	0.89	0.89
0.012	0.92	0.86	**0.86**	**0.86**	**0.86**	0.86	0.86
0.0144	0.91	0.87	**0.86**	**0.86**	**0.86**	0.86	0.86
0.0168	0.90	0.86	**0.84**	**0.84**	**0.84**	0.84	0.84

Table 2 Normalized DCF of 3-story SCBF with various strongbacks under MCE-level earthquakes.

α \ β	**0.027**	**0.054**	**0.081**	**0.107**	**0.134**	**0.161**	**0.188**
0.0024	1.00	0.99	0.99	0.98	0.98	0.98	0.98
0.0048	0.97	0.89	0.90	0.89	0.89	0.89	0.89
0.0072	0.94	0.88	0.86	0.84	0.83	0.83	0.83
0.0096	0.94	0.86	**0.81**	**0.81**	**0.79**	0.78	0.78
0.012	0.94	0.83	**0.77**	**0.78**	**0.75**	0.75	0.75
0.0144	0.94	0.83	**0.75**	**0.75**	**0.73**	0.72	0.72
0.0168	0.94	0.82	**0.73**	**0.73**	**0.72**	0.71	0.71

Conclusions

SCBF is likely to concentrate deformation in one story. Taking the advantage of strongbacks, we can improve the seismic performance of SCBF. Strongbacks effectively redistribute the deformation of structure uniformly along the height.

Case study of SCBF with strongbacks under dynamic excitations shows an obvious trend that strongbacks are able to reduce the maximum drift ratio. The statistics of DCF shows that strongbacks are most effective for the SCBF under MCE-level earthquakes and less efficient for design-level earthquakes. To consider both effectiveness and cost, we suggested stiffness and strength ratios in the range of $0.0096 \le \alpha \le 0.0168$ and $0.081 \le \beta \le 0.134$ are reasonable values to design strongbacks.

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