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High-mode effects on seismic performance of multi-story self-centering braced steel frames

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ABSTRACT

Seismic-resisting, multi-story steel frames with self-centering braces (SCBs) are numerically investigated through pushover and incremental dynamic analyses. The seismic performance of self-centering braced frames (SC-BFs) is systematically compared with that of buckling-restrained braced frames (BRBFs), with emphasis on high-mode effect. The concentration of inter-story drift in the upper part of the buildings is more significant in SC-BFs than in BRBFs as a result of this effect. This high-mode effect strengthens with the increasing intensity of ground motions. Parametric studies indicate that increasing the post-yield stiffness ratio and/or energy dissipation capacity can successfully improve the seismic performance of SC-BFs, particularly in terms of limiting the high-mode effect. SC-BFs with enhanced post-yield stiffness and energy dissipation capacity exhibit relatively uniform inter-story drift ratios and reduced record-to-record variability in seismic performance.

1. Introduction

The substantial loss incurred after devastating earthquakes (e.g., Northridge and Kobe earthquakes) strongly motivates researchers and engineers to establish high-performance, seismic-resisting structures. Various energy dissipating devices, such as friction dampers [1], metallic yield dampers [2], and buckling-restrained braces (BRB) [3], have been developed to protect primary structures. Post-earthquake field reconnaissance revealed that many structures were demolished because of excessive permanent deformation, although structural collapse was avoided during earthquakes.

In light of these situations, a novel category of seismic-resisting structures with excellent self-centering capability was proposed to minimize the post-earthquake permanent deformation of structures, including post-tensioned structural systems and structures installed with various types of self-centering devices [4–9]. For instance, Ricles et al. [5] developed a self-centering beam-to-column connection with post-tensioned steel strands that are parallel to the beams and are anchored at the column flange. Another type of small memory alloy (SMA)-based beam-to-column connection with self-centering capability was developed by utilizing the superior properties of SMAs (e.g., [10–16]). Previous experimental and numerical investigations, including several large-scale experiments, validated the superior seismic performance of self-centering structures in terms of limited permanent deformation. The self-centering mechanism is often supplemented with additional energy dissipation to improve the structural seismic performance further. For instance, Ricles et al. [5] bolted the top and seat angles at beam-to-column connections; Christoupolos et al. [6] added energy-dissipating bars to beam flanges on beam-to-column connections; and Wolski et al. [17] enhanced the energy dissipation of self-centering beam-to-column connections via friction.

Among the different self-centering devices, self-centering braces (SCBs) are a promising type of seismic-resisting bracing element that provides both self-centering and energy-dissipation capabilities [18–24]. Dolce et al. [19] tested SMA-based SCBs within a scaled reinforced concrete frame in which two groups of superelastic SMA wires pre-tensioned to different levels were used to facilitate self-centering and energy dissipation, respectively. Christopoulos et al. [21] developed an SCB with post-tensioned steel tendons that undergoes significant axial deformation without structural damage and exhibits stable energy dissipation capacity. By recognizing the benefits of enhanced energy dissipation and post-yield stiffness in self-centering structures (as highlighted by Christopoulos et al. [25]), researchers have implemented different improvement schemes in SCBs. For example, Zhu and Zhang [20] enhanced the energy dissipation and post-yield stiffness of SCB by combining pretensioned and un-pretensioned SMA wires in an appropriate ratio. Zhu and Zhang [22] employed superelastic SMA wires and friction damping in SCBs to achieve self-centering hysteresis with an adjustable energy dissipation capacity. The testing of the scaled SCB model successfully detected the flag-shaped (FS) hysteretic loops that were repeatable for many loading cycles without any degradation in strength. Erochko et al. [24] also adopted internal friction dampers for

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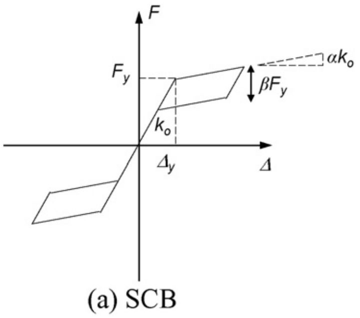


(a) SCB (b) BRB

Fig. 1. Simplified constitutive model of SCBs and BRB.

Table 1
Parameters of braces.

Brace type	Frame name	Parameters of braces	
		α	β
BRB	BRBF	0.01	–
SCB	SC-BF-I	0.01	0.5
	SC-BF-II	0.20	0.5
	SC-BF-III	0.01	1.0

SCBs to produce a full FS hysteresis. Shaking table tests were conducted on SCBs within a scaled steel frame model, and the SCBs successfully withstood consecutive strong earthquakes without damage while maintaining a stable friction-damping capacity.

The seismic performance of self-centering braced frames (SC-BFs) has been numerically evaluated through frequent comparisons with other types of seismic-resisting braced frames, such as steel braced frames and buckling-restrained braced frames (BRBFs) [19,22,23,26,27]. However, these comparisons result in ambiguous conclusions because of the different devices or comparison bases considered in various studies. For example, Dolce et al. [19] reported that the seismic performance of SMA-based SC-BFs was comparable to that of conventional steel braced frames. Zhu and Zhang [22] determined that SC-BFs without and with additional coulomb damping showed an inferior seismic performance to and a comparable seismic performance with that of BRBF, respectively, in terms of peak inter-story drift control. McCormick et al. [26] revealed the superiority of SMA-based braces over steel braces with respect to limiting inter-story and residual drifts. Tremblay et al. [27] numerically compared the seismic performance of SC-BFs and BRBFs and observed that the former was superior to the latter because of the smaller peak story drifts, less damage concentration along the height and smaller residual lateral deformation observed in properly designed SC-BFs.

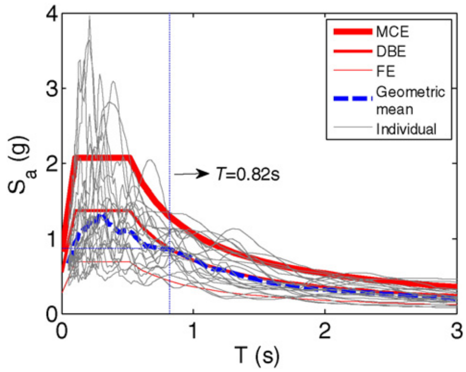
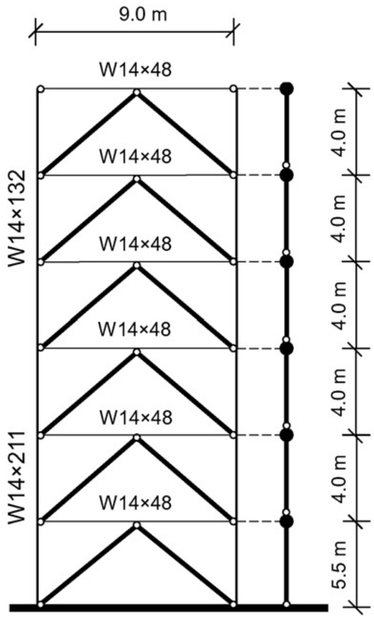


Fig. 3. Elastic response spectra of the selected ground motion records.

The current study systematically compares the seismic performance of SC-BFs and BRBFs. It conducts single-degree-of-freedom (SDOF), pushover, and incremental dynamic analyses (IDA) on multi-story steel braced frames with SCBs or BRBs. The comparison results indicate that SC-BFs are subject to higher deformation demand under strong earthquakes when SC-BFs and BRBFs are designed with the same parameters. This deficiency of SC-BF is mainly caused by reduced energy dissipation and additional high-mode contribution, the latter of which tends to induce the significant concentration of inter-story drift ratios in the top stories of buildings. The effects of increasing energy dissipation or the post-yield stiffness of SCBs are specifically investigated through a parametric study of multi-story frames, as inspired by the SDOF analysis conducted by Christopoulos et al. [25]. The results indicate that increasing either post-yield stiffness or energy dissipation can effectively reduce the seismic deformation demand on SC-BFs by compensating the aforementioned deficiency. In particular, increasing the post-yield stiffness of SC-BFs can facilitate a seismic performance that is comparable to that of BRBFs in terms of peak deformation



Properties of braces:

Story	Yield Strength (kN)	Initial Stiffness (kN/m)
6	394	0.734E+05
5	711	1.326E+05
4	961	1.793E+05
3	1161	2.165E+05
2	1306	2.435E+05
1	1704	2.878E+05

Fig. 2. Modeling of the prototype frame in OpenSees.