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Seismic-resistant self-centering rocking core system with buckling restrained columns

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ABSTRACT

Conventional concentrically braced frame (CBF) systems have limited drift capacity prior to brace buckling, and related damage leads to deterioration in strength and stiffness. CBFs are also susceptible to soft-story failure. A pin-supported self-centering rocking core system with buckling-restrained columns (SCRC-BRC) is being developed to provide significant drift capacity while limiting damage due to residual drift and soft-story mechanisms.

The SCRC-BRC system consists of beams, columns, and braces branching off a central column, with buckling restrained columns (BRCs) incorporated into the system at the first story external column positions. The BRCs and friction generated at lateral-load bearings at each floor level are used to dissipate energy to reduce the overall seismic response of the SCRC-BRC system. Vertically-aligned post-tensioning bars provide additional overturning moment resistance and aid in self-centering the system to eliminate residual drift. The pin support condition at the base of the central column and the lateral stiffness of the system enable it to exhibit a nearly uniform inter-story drift distribution.

In this study, the suite of 44 DBE-level ground motions used in FEMA P695 is numerically applied to several SCRC- BRCs to demonstrate the seismic performance of the system. The results show that the SCRC-BRC system has a nearly uniform inter-story drift response, high ductility, and a high energy dissipation capacity, and is an effective seismic-resistant system.

1. Introduction

Steel concentrically-braced frames (CBFs) and moment resisting frames (MRFs) are commonly used lateral force resisting systems for seismic design. CBF systems are economical and have significant strength and stiffness. However, CBFs suffer from limited system ductility capacity prior to brace buckling and related structural damage. Under the design basis earthquake (DBE), CBFs are expected to undergo drift demands that will yield or buckle the brace members, which may result in residual lateral drift after the earthquake. MRFs have high ductility capacity but, like CBFs, they are susceptible to residual drifts and soft-story failures (e.g., [1,2]). Many structural collapses have occurred during earthquakes as a result of soft-story mechanisms, which may cause upper floor collapse of many buildings under seismic loading [3].

For sustainability of CBF systems, then, structural damage must be mitigated under seismic loading. The use of buckling-restrained braces can reduce the non-recoverable structural damage in CBFs; however, buckling-restrained braced frame (BRBF) systems may exhibit significant residual drift after an earthquake [4]. Self-centering concentrically-braced frame (SC-CBF) structural systems have been developed to offer the enhanced drift capacity of BRBF systems while reducing (or eliminating) residual drift (e.g., [5,6]). However, results from previous studies show that local member yielding may occur at the base of the SC-CBF first story external columns due to the concentrated vertical force acting on a single SC-CBF column during rocking [7,8].

Recent research shows that soft-story failure in existing multi-story buildings originally designed with CBFs or MRFs can be prevented by incorporating stiff pin-supported systems into the structure (e.g., [1,2]). Pollino et al. [9] and Qu et al. [10] mitigated soft-story mechanisms in sub-standard buildings using a stiff rocking core (RC), which may be a steel truss or prestressed concrete wall. The RC is pin-supported and has high stiffness over the height of the structure to create a more uniform ductility demand and story drift profile. Nonlinear numerical analysis results show that increasing the stiffness of the RC decreases the inter-story drift concentration in the building [10]. Qu et al. [11] experimentally implemented a pin-supported wall frame system to retrofit an eleven–story steel reinforced concrete frame structure that was originally designed with moment-resisting frames. Similar to the stiff RC discussed earlier, the stiffness of the wall is essential to controlling the drift pattern of the structure.

Blebo and Roke [12] introduced a self-centering rocking core (SC-RC), a modification of an SC-CBF that provides significant nonlinear drift capacity (without column uplift and pounding) while limiting structural damage and residual drift. Fig. 1 shows a schematic of the SC-RC system. The system comprises a single column at the middle of the

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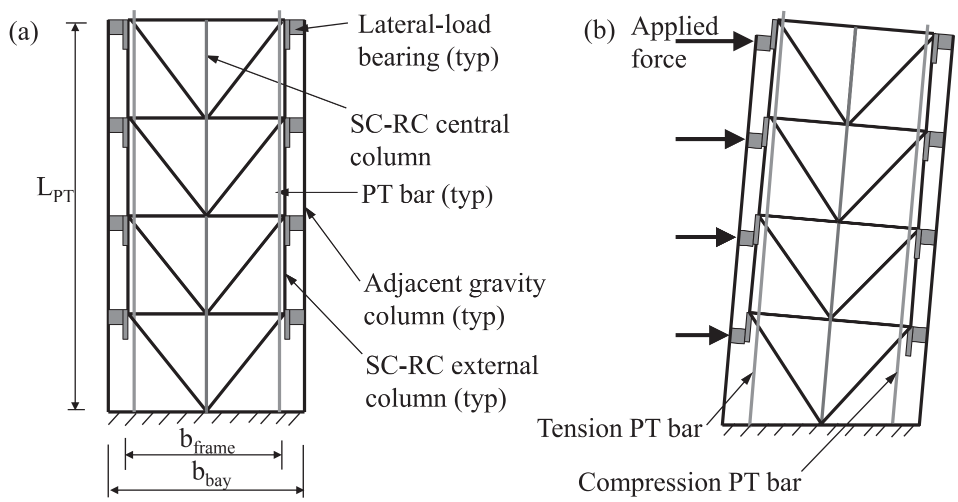

Fig. 1. Schematic of an SC-RC system: (a) initial position; (b) rotation about the base of the SC-RC central column [12].

bracing bay, with beams, braces, and columns branching off the central column. The arrangement of the structural members is like that of a conventional CBF system; however, vertical post-tensioning (PT) bars are located at the ends of the SC-RC beams to provide additional stiffness and self-centering behavior. Nonlinear dynamic analysis results show that the SC-RC system may exhibit high inter-story drifts under DBE level ground motions [12,13]. There is, therefore, a need to increase the energy dissipating capacity of the system to reduce the drift response of the system under the DBE level ground motion.

In this study, the energy dissipation capacity of a braced frame system is increased by incorporating buckling-restrained braces (BRBs) into the system. Unlike ordinary braces, BRBs exhibit symmetric hysteric behavior in compression yielding and tension yielding, as shown schematically in Fig. 2 [14], and they dissipate energy through stable tension-compression hysteric behavior [15]. As shown in Fig. 3, BRBs consist of the following components: (i) a steel core, made up of a short middle section called the yielding zone and larger (non-yielding) end sections, that resists axial force; (ii) the surrounding concrete-filled hollow structural steel (HSS) member that prevents buckling in the steel core by providing lateral restraint along the entire length of the brace; (iii) the bond-preventing layer that separates the steel core from the surrounding buckling-restraining unit so that the axial loads are resisted only by the steel core; and (iv) the connection unit that extends beyond the casing and connects the brace to the frame [16–18].

The BRBs used in this study were assumed to be manufactured by Star Seismic, LLC, due to the availability of test results on different configurations of Star Seismic's BRBs (e.g., [19]). Merritt [19] performed subassemblage testing of eight full-scale buckling-restrained braces manufactured by Star Seismic. Expressions were developed for calculating the adjusted tension strength factor, ω, and the adjusted compression strength factor, β, from the test results. Additional experimental studies (e.g., [4]) have also utilized BRBs manufactured by Star Seismic, LLC, further validating the numerical models of the behavior of the Star Seismic BRBs.

In this study, BRBs are incorporated into an SC-RC system to increase the system's energy dissipation capacity, thereby reducing its peak drift response to ground motions. The BRBs are located at the first story external column position in the SC-RC, and are therefore referred to as buckling-restrained columns (BRCs) in this study. The resulting SCRC-BRC system is a stiff self-centering system with a pin-supported base that is intended to prevent soft-story failure and reduce residual drift under earthquake loading. The objective of this study is to analytically investigate the effect of design parameters on the behavior and seismic response of the self-centering SCRC-BRC system and to establish it as an effective lateral force resisting system. To achieve this objective, several SCRC-BRC frames are designed, and nonlinear static and

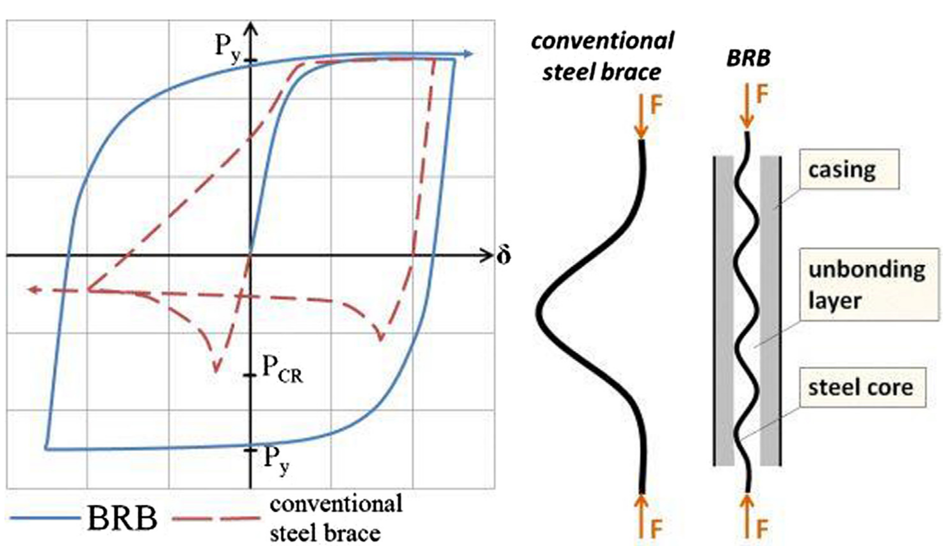

Fig. 2. Comparison of cyclic behavior of conventional steel braces and buckling-restrained braces [14].