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Seismic-resistant self-centering rocking core system

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ABSTRACT

Conventional braced frame systems exhibit limited drift capacity before brace buckling and associated damage leads to strength and stiffness degradation. A self-centering rocking core (SC-RC) system is being developed to provide significant drift capacity while limiting damage and residual drift.

The SC-RC system consists of beams, columns, and braces branching off a central column. Friction at lateral-load bearings that transfer inertia forces from the floor diaphragms to the SC-RC is used to dissipate energy to reduce the overall seismic response of the SC-RC system. Vertically oriented post-tensioning bars provide additional overturning moment resistance and help to reduce residual drift.

The paper introduces a preliminary design approach for SC-RC systems. Several SC-RC systems are designed, and pushover and dynamic nonlinear analysis results are presented. Dynamic analysis results confirm the expected drift capacity and behavior of the system.

1. Introduction

Buildings with conventional lateral force resisting systems are designed to ensure the safety of the occupants during an earthquake. Structural damage due to an earthquake is allowed [1], but collapse is not permitted. The allowable damage is anticipated to be repairable, but the repairs may or may not be economical.

The steel concentrically-braced frame (CBF) system is a commonly used lateral force resisting system. 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. Conventional CBFs are also susceptible to inter-story drift concentration and soft-story failure during earthquakes [2]. CBFs systems can be retrofitted with stiff rocking cores (e.g., [2,3]) to prevent structural failure of CBFs due to brace buckling and inter-story drift concentration. Alternatively, the CBF system's ductility capacity can be increased while maintaining stiffness through the use of buckling-restrained braces; however, buckling-restrained braced frame (BRBF) systems may exhibit significant residual drift after an earthquake [4].

Self-centering rocking braced frame systems that have large drift capacity and minimal residual drift relative to the conventional CBF under seismic loading have recently been developed and studied (e.g., [5–7]). One such system is the self-centering concentrically braced frame (SC-CBF) system [5], which is shown schematically in Fig. 1. The SC-CBF is designed to decompress at the base at a specific level of lateral loading, initiating a rigid-body rotation (rocking) on its base, as shown in Fig. 1(b). The SC-CBF system incorporates an extra set of columns so that the rocking frame is separated from the gravity loading, permitting the rocking behavior without damaging the floor slabs. Friction at lateral-load bearings between the gravity system and SC-CBF at each floor level (rather than member yielding) dissipates energy in the system. PT bars that run vertically over the SC-CBF's height provide a restoring force to return the frame to its foundation (i.e., self-centering the system).

However, the column uplift response of such systems, which causes one column to uplift from the foundation, and the resulting rocking behavior amplify the response of the higher structural modes, increasing member force demands [8,9]; this effect is more pronounced for taller structures [10]. Results from ongoing studies also 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. A reduction in higher mode response can be achieved by permitting column uplift and subsequent rocking behavior to occur at multiple locations throughout the height of the structure [6]; however, this requires complicated detailing.

CBF systems suffer not only from low drift capacity before structural damage occurs, but also from a susceptibility to soft-story failures due to drift concentration. Pollino et al. [2] and

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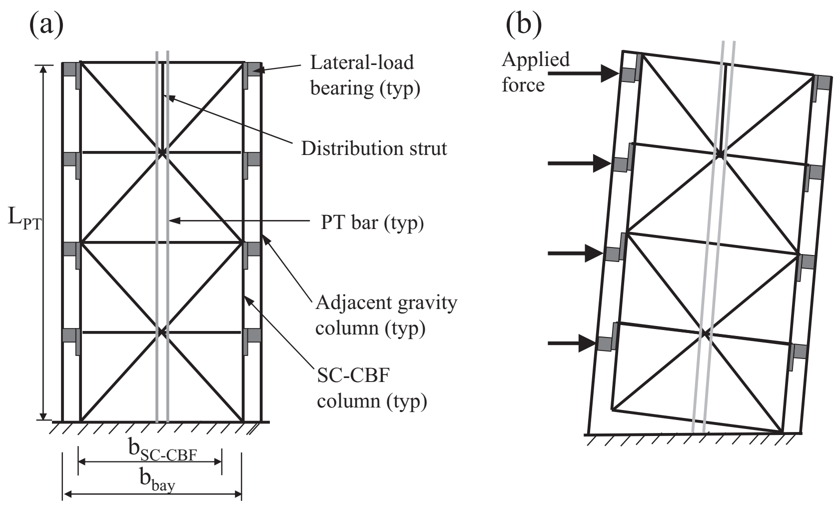

Fig. 1. Schematic of an SC-CBF system: (a) initial position; (b) "rocked" position.

Qu et al. [3] developed an approach to mitigate structural damage due to inter-story drift concentration in CBFs through the use of a stiff rocking core (RC), which may be a steel truss or prestressed concrete wall, as shown in Fig. 2. 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. Energy dissipating elements are placed between the RC and the existing frame to minimize the overall system drift. Numerical analysis was performed to investigate the behavior and performance of RC retrofits with existing sub-standard moment-resisting frame and braced frame multi-story buildings. The results show that the inter-story drift concentration decreases with increasing stiffness of the RC relative to the existing lateral force resisting system.

This study seeks to develop a self-centering frame system that does not require column uplift response (mitigating the amplification of the higher mode response and structural damage). A self-centering rocking core (SC-RC) system is an adaptation of SC-CBF and RC systems that is being developed to provide significant nonlinear drift capacity without column uplift response and resistance to drift concentration, while limiting damage and residual drift. This paper presents a preliminary discussion of the SC-RC system and demonstrates its seismic response to DBE-level ground motions.

2. System behavior

The SC-RC system is illustrated schematically in Fig. 3. The system comprises a single column at the middle of the bracing bay, with beams, braces, and columns branching off the central column. The arrangement of the structural members is similar to 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. As lateral forces are applied to the SC-RC, the displacement of the frame causes a reduction in the initial tensile stress in the "compression" PT bar (the bar that is compressed due to the applied forces, as indicated in Fig. 3(b)), and causes an increase in the initial tensile stress in the "tension" PT bar (the bar that is in tension due to the applied forces). Therefore, applied lateral force increases tension in the tension PT bar and reduces tension in the compression PT bar.

The SC-RC system is isolated from the floor diaphragms to permit relative vertical displacement between the ends of the SC-RC beams and the gravity system. Friction is generated at each floor level where lateral-load bearings transfer inertia forces from the floor diaphragms to the SC-RC. This friction is used to dissipate energy to reduce the overall seismic response of the SC-RC system. This behavior has been adapted from SC-CBF systems with friction bearings (e.g., [11]). The friction at the lateral-load bearings has been shown to provide reliable energy dissipation that is not dependent on member yielding or structural damage [12].

Overturning moment from applied lateral loads causes rotation about the base of the SC-RC column. This rotation can be idealized as a rigid-body rotation, as shown in Fig. 3(b). The behavior is similar to that of the concrete pin-supported wall-frame systems [13]; however, the post tensioned tendon in the wall-frame system is intended to prevent cracking and the resulting degradation of the wall stiffness, not to self-center the system.

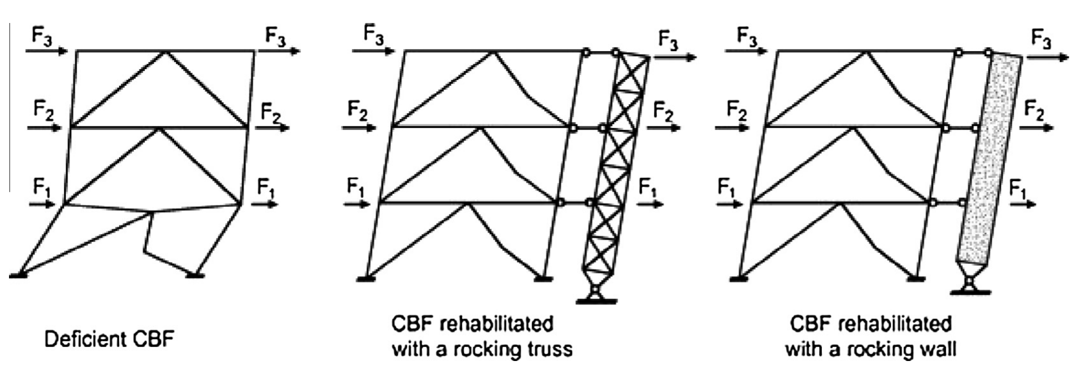

Fig. 2. Schematic of sub-standard braced frame and stiff rocking core (Qu et al. [3]).