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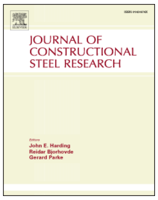

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Probabilistic seismic performance assessment of ribbed bracing systems

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ABSTRACT

This article evaluates the seismic performance of structures equipped with a ribbed bracing system (RBS). RBS uses ribbed faces that freely slide under compression, however, interlock under tensile forces. Two RBS mechanisms; Completely-closed RBS (CC-RBS) and Improved-centering RBS (IC-RBS), were proposed and successfully tested for eliminating compressive buckling of braces. CC-RBS and IC-RBS provide high energy dissipation capacity and small residual story drifts, respectively. Here, these mechanisms were employed for design and modeling of three structures with varying heights. The models were then subjected to incremental dynamic analysis (IDA), and their seismic performance was probabilistically evaluated at different levels of intensity. Based on the results, in the low to moderate lateral deformations, structural performance benefitted more from the energy dissipation capacity provided by CC-RBS. Nevertheless, CC-RBS demands were increased due to the accumulation of plastic deformations by surpassing height-dependent deformation thresholds. The governing thresholds were also observed to decrease with increasing buildings height as a result of the elevated significance of p-delta effects in tall structures.

1. Introduction

Compressive buckling of bracing members causes significant deteriorations to the performance of lateral force-resisting systems. The large inelastic deformation undergone by a buckled brace makes it prone to low-cycle fatigue. This type of fatigue is as a result of microscopic tears that yield in localized damage of a member [1]. From a macroscopic point of view, low-cycle fatigue leads to gradual reduction of strength and stiffness of the member. This reduction is known as “cyclic deterioration” [2] and affects the characteristics of the skeleton curve which define member's force-deformation behavior. A continual loss of strength and stiffness is thus experienced by a buckling member during a seismic event. Modeling of this gradual deterioration is significant in predicting lateral collapse capacity of a system. A laterally loaded structure usually collapses due to the secondary moments imposed by the gravity loading. On the other hand, the secondary moments become crucial when a softened local mechanism is triggered, e.g., in a story, by the softened behavior of some key load-resisting elements. Thus, buckling of braces can pose serious detrimental effects on collapse capacity of structures.

A number of solutions have been proposed by recent researchers to address the problems caused by compressive buckling of braces and can be categorized into two groups. Group (I) prevented buckling by strengthening the brace member, and group (II) eliminated compressive resistance of the member by using special mechanics for it. Buckling restrained braces (BRBs) [3] can be placed in the first group. The second group consists of innovative systems such as ribbed bracing system (RBS) [4] and a bevel-wedge brace connection [5]. RBS uses a ribbed interaction between two faces (known as the shaft and the jaws) that interlock in tension and freely slide under compression. The bevel-wedge connection detail, on the other hand, provides a tension-only interaction between the brace and the enclosing members. The RBS which is the focus of this paper uses fabrication details that lead to two various force-deformation mechanisms. These variants of RBS are called improved-centering RBS (IC-RBS) and completely-closed RBS (CC-RBS). The configuration and force-deformation details of these mechanisms are presented in the next section.

Before conducting experimental studies on RBS system, its efficiency in improving the performance of frame structures was assessed by Tabeshpour et al. [6, 7]. They used the theoretical force-deformation behavior of RBS mechanisms to model RBS-equipped multi-story frames. The established nonlinear models were analyzed under a bin of ground motions scaled to specific intensities. The results confirmed the efficiency of RBS in reducing the story drifts undergone by the structures. Golafshani et al. [8] conducted an experimental study on the axial behavior of RBS specimens and the theoretical behavior of the system was established and validated. Arzeytoon et al. [9] performed numerical and experimental studies on assemblies of a pair of RBS devices carrying lateral forces imposed on a moment frame. The experimental results verified the theoretically derived behavior and were used for calibrating a numerical model.

Arzeytoon et al. [9] also employed the calibrated model for comparing the behavior of RBS against those of concentric and buckling-restrained braces. The selected BRB configuration was composed of one

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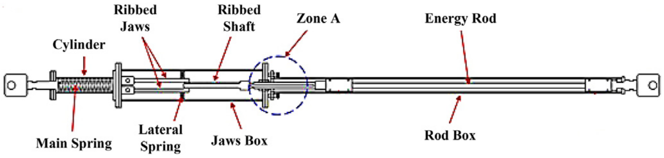


Fig. 1. General configuration of an RBS specimen [9].

diagonal brace and provided smaller stiffness and energy absorption capacity than CC-RBS braces used in a pair [9]. Although IC-RBS assembly provided a stiffness equal to that of the BRB, its energy absorption capacity was found to be about half of the BRB. This observation was attributed to the pinched hysteresis experienced by the IC-RBS assembly. During this hysteresis, every cycle of plastic loading re-centered to the origin before entering the loading cycle in the opposite direction. However, an ideal re-centering was observed for the IC-RBS assembly which distinguished it from other bracing systems [9, 10].

According to the presented review, the cyclic behavior of CC– and IC-RBS mechanisms has been approved and shown to provide promising features. The numerical methods that can represent this behavior have also been established and validated. Although a few preliminary studies [6, 7] have validated the efficiency of RBS system in mitigating seismic demand of structures, but more detailed studies are still required for this purpose. First of all, state of the art knowledge should be incorporated for nonlinear modeling of RBS behavior. Then, the established models have to be used for estimating system's performance at different levels of behavior nonlinearity. Finally, these analyses should account for uncertainty associated with ground motion hazard.

To meet all these requirements systematically, incremental dynamic analysis (IDA) [11] can be employed. In recent years, this methodology has been employed by many researchers for a variety of structural systems. Jalali et al. ([12, 13]) used IDA to evaluate the effect of beam-to-column connection on the seismic collapse of steel moment-resisting frames. Uriz and Mahin [14] comparatively evaluated the performance of concentrically braced steel frame structures. Tafakori et al. [15] used an IDA-based seismic loss estimation (following FEMA p58 [16]) to optimize retrofit of steel structures using friction dampers. Jalali and Banazadeh [17] performed IDA on steel plate shear wall systems in which various levels of behavior deterioration were incorporated.

2. Scope and objective

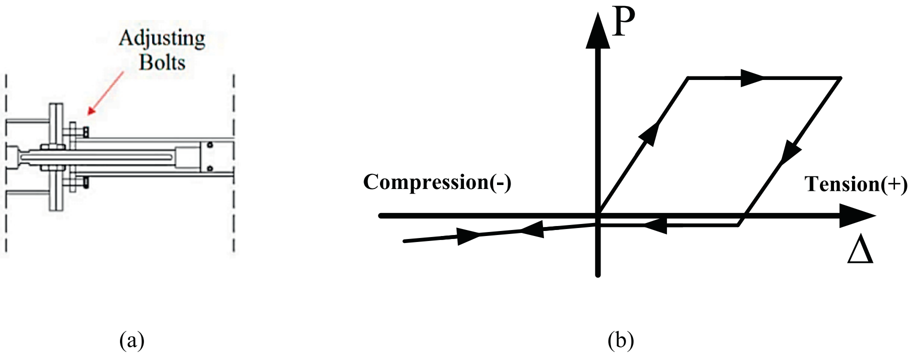
In this research, the calibrated numerical model is used to study the seismic performance of multi-story frames equipped with RBS. Initially, a number of 3-, 7-, and 15-story braced frames were designed and modeled in OpenSees [18] software. The frames are then subjected to static pushover analyses for the verification of the models in the nonlinear range of behavior. Incremental dynamic analysis (IDA) is then applied to the models using 44 ground motion records for evaluating the seismic performance of the structures. IDA results are used to extract probabilistic curves that express collapse capacity of different structures in terms of the endurable ground motion intensity. The seismic performances provided by CC– and IC-RBS mechanisms are finally compared considering different response metrics at different levels of intensity. Ground motion uncertainties are incorporated in deriving these conclusions by employing IDA results.

3. Force-carrying mechanism of RBS

The force transmission mechanisms provided by alternative RBS detailing have to be elaborated before involving it in the design and modeling of RBS equipped frames. Generally, the philosophy behind the development of RBS is to sacrifice the brace elements to shield frame members from serious damage. Therefore serving as a structural fuse, construction of RBS should follow methods that allow replacement of the member after an earthquake. To obey this philosophy, two different fabrication details have been proposed and tested for RBS [9, 10]. These mechanisms were designed to maximize either the self-centering capability (IC-RBS) or the energy dissipation of the system (CC-RBS).

General configuration of a RBS specimen is illustrated in Fig. 1. In an experimental configuration, a straight rod (called energy rod) plays the role of an actual brace member in absorbing the energy via inelastic deformation. A lock provides accessible connection of the rod to a ribbed shaft. Whether a rod plays the bracing role or an actual steel section, the brace is surrounded by a covering box. The energy rod is connected to a ribbed shaft that slides between two ribbed jaws inside the box of RBS device. An axial spring (main spring) intervenes the RBS box and the rest of the brace member. In an experimental configuration, the second end of RBS box is connected to an actuator. When the energy rod is subjected to tension, the ribbed shaft is locked in the jaws and prevents free sliding between the ribbed parts. Note, RBS acts differently under compression.

The behavior of the system in withstanding an axial compression is dependent on the details of the connection between the covering box and the RBS device. This detail is marked with "zone-A" in Fig. 1. In an IC-RBS, the length of the covering box is adjusted using two bolts to equal the full length of the rod accurately. Therefore, the covering box remain in contact with the RBS device before the start of the loading as illustrated in Fig. 2a. When a cycle of plastic loading-unloading is applied in tension, plastic deformation of the rod leads to a gap between the covering box and the RBS device. By reversing the loading to compression, the ribbed shaft freely slides into the jaws until the gap is neutralized and the specimen is re-centered to its initial length. At this stage, the covering box comes again in contact with the RBS device. Thus, further compressing of the rod leads to simultaneous movement of the shaft and the RBS device. Due to this concurrent movement, no sliding can occur between the shaft and the jaws and the applied compressional force results in shortening of the main spring. The elastic



(a) (b)

Fig. 2. The "zone-A" detail and the force-deformation hysteresis of an IC-RBS.