



# Elastic displacement spectrum-based design of damage-controlling BRBFs with rocking walls

Yulong Feng<sup>a,\*</sup>, Zhi Zhang<sup>b</sup>, Xun Chong<sup>a</sup>, Jing Wu<sup>c</sup>, Shaoping Meng<sup>c</sup>

<sup>a</sup> School of Civil Engineering, Hefei University of Technology, Anhui Province 230009, China

<sup>b</sup> Department of Civil Engineering and Engineering Mechanics, University of Arizona, Tucson, AZ 85721, USA

<sup>c</sup> Key Laboratory of Concrete and Prestressed Concrete Structures, Ministry of Education, Southeast University, Sipailou 2, Nanjing 210096, China

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## ABSTRACT

This paper investigates the seismic design and performance of buckling-restrained braced frames with rocking walls (BRBF-RWs) for the purpose of using rocking walls (RWs) to mitigate the drift concentration issue of buckling-restrained braced frames (BRBFs). Formulas for calculating the elastic structural lateral displacement and RW internal force under typical lateral loads are derived and validated; then, the stiffness and strength demand of the RW are approximately determined based on the elastic formulas when the BRBF-RW enters the inelastic stage. Combined with the proposed inelastic demand, an elastic displacement spectrum-based design procedure is presented, which can directly determine the sectional area of the buckling-restrained braces (BRBs) and the required stiffness and strength of the RW. A 6-story steel BRBF-RW is designed using the proposed procedure as an example, and a series of nonlinear pushover analyses (NPAs) and nonlinear response history analyses (NRHAs) are performed to validate the design. The example shows that the designed target displacement and the NRHA result are close and that the deviations between the drift concentration factor, RW maximum moment and shear force obtained using formulas and using NPAs and NRHAs are small. Lastly, a brief comparative analysis is performed to illustrate the enhanced seismic performance of the designed BRBF-RW via NPAs and NRHAs.

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## 1. Introduction

Buckling-restrained braces (BRBs) can yield without buckling under compression force, showing excellent ductility and stable hysteretic performance in comparison to conventional braces [1]. Frames using such braces form a new generation of braced systems and are known as buckling-restrained braced frames (BRBFs). Previous studies showed that BRBs were effective in dissipating earthquake energy and controlling inter-story drift of BRBFs [2, 3]. BRBFs are currently widely used in earthquake engineering [4].

However, BRBFs are prone to large permanent drift and damage concentration at certain stories of the structure due to the low post-yield stiffness of BRBs [5]. The BRBs at all stories cannot simultaneously enter the yield stage under an earthquake, and the yield of the BRBs at one story or certain stories will cause a story stiffness mutation among stories in BRBFs, resulting in the drift concentration issue. Fahnstock et al. [6, 7] performed a series of nonlinear response history analyses (NRHAs) and a hybrid test on a 4-story BRBF. The observed large residual drifts in the test indicated one potential drawback of the BRBF system: the large residual drifts may cause

significant challenges when seeking to put the structural system back into service after a major seismic event. Erochko et al. [8] compared residual drift responses of special moment-resisting frames (SMRFs) and BRBFs in steel buildings and noted that the SMRFs and BRBFs showed similar peak drifts, while the BRBFs underwent larger residual drifts than the SMRFs.

At present, approximately three approaches have been explored by researchers to mitigate the damage concentration effect and reduce the residual displacement of structures equipped with BRBs: (1) The use of dual systems, where a moment-resisting frame (MRF) is used in addition to the BRBF. Kiggins and Uang [9] suggested a dual system design in which the added MRF served as a restoring force mechanism to reduce the residual inter-story drift. Ariyaratana and Fahnstock [10] noted that switching pin connections to moment-resisting connections within the BRBF and/or adding a SMRF in parallel with the BRBF can both reduce the residual displacement and the possibility of forming the soft-story mechanism in the BRBFs. (2) The use of self-centering BRBs [11, 12], which applies the self-centering concept to traditional BRBs to reduce the structural residual deformation. Tremblay et al. [13] and Choi et al. [14] noted that steel frames with self-centering BRBs generally experienced smaller peak story drifts, less damage concentration over the building height, and smaller residual lateral deformations compared to BRBFs. (3) The use of strongback spine systems,

\* Corresponding author.

E-mail address: feng\_yulong@126.com (Y. Feng).

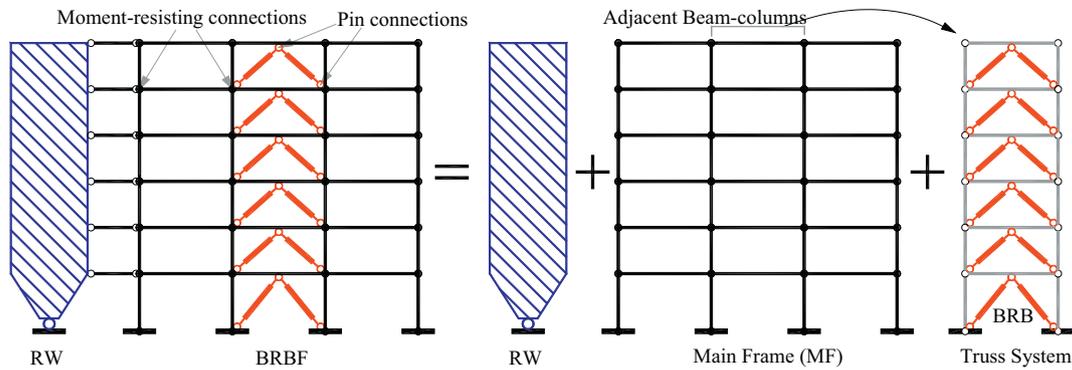


Fig. 1. Illustration of the BRBF-RW System.

which combine aspects of a traditional concentric braced frame (CBF) with a mast to form a hybrid system. Lai and Mahin [15] investigated and compared the seismic performance of several different strongback spine configurations with conventional braces or BRBs. The results showed that the spine systems can effectively reduce the concentration of deformations in braced frames.

Particularly, the dual system is also a valuable design solution to mitigate the concentration of drifts and residual displacements for other braced frames. The Chinese seismic design code [16] recommends to use the brace and moment-resisting frame as the first and second seismic protection systems in designing a braced frame, which essentially is a dual system. Costanzo et al. [17] examined the beneficial use of moment-resisting connections in chevron CBFs and noted that the moment-resisting connection can increase the structural redundancy, ensuring the distribution of plastic deformations along the structural height. Ioan et al. [18] proposed a dual system that composed of a deformable MRF and an eccentrically braced frame (EBF) with removable links. The possibility to reduce the drift and restore the building is guaranteed by the proposed dual system.

In addition, rocking systems have frequently been used in both structural retrofitting and new building design to control structural deformation and damage distribution. Alavi and Krawinkler [19] investigated the seismic performance of rocking wall frames (RWFs) and demonstrated that the rocking wall (RW) hinged at the base can cause a uniform distribution of story drifts over the height of MRFs. Ji et al. [20] discussed the role that continuous hinged columns play in decreasing the story drift concentration in CBFs. Wada et al. [21, 22] applied the hinged wall to retrofit the G3 teaching building in Tokyo Industrial University. Deierlein et al. [23] proposed a rocking steel frame system with overturning resistance provided by high-strength steel post-tensioning tendons and energy dissipating fuses. Qu et al. [24] investigated the adequacy of a seismic rehabilitation technology through the implementation of sufficiently stiff and strong rocking cores to reduce inter-story drift concentration and the risk of forming soft-story failures in low-rise and mid-rise steel CBFs. The use of an RW has proven to be an effective way to control the

MRF or braced MRF lateral deformation and mitigate the inter-story drift concentration.

Based on the concept of dual systems and rocking systems, a dual system composed of an RW and an BRBF with moment-resisting connections (BRBF-RW) is proposed for the purpose of mitigating the drift concentration of the BRBF. This paper focuses on the seismic design and performance of the BRBF-RW through theoretical and numerical investigation. First, the damage-controlling BRBF-RW system is stated. Afterward, an elastic lateral displacement analysis is conducted for the BRBF-RW based on an equivalent continuum model to estimate the seismic inelastic demand of the RW. Then, a seismic design procedure based on the RW demand is proposed for the BRBF-RW. A 6-story steel BRBF-RW is designed using the proposed procedure, and the accuracy of the design procedure and the RW demand is investigated by nonlinear pushover analyses (NPAs) and NRHAs. Finally, a BRBF, an RW and a MRF are used as reference structures to illustrate the enhanced seismic performance of the BRBF-RW via NPAs and NRHAs.

## 2. Damage-controlling BRBF-RW system

Fig. 1 shows the BRBF-RW system, which is composed of an RW and a BRBF. The BRBF in the BRBF-RW for lateral load resistance consists of a main frame (MF) with moment-resisting connections and a truss system formed by the BRBs and their adjacent beam-column members. The RW is used as the member controlling the BRBF lateral deformation.

Fig. 2a shows the expected curve of the base force  $V_b$  and roof displacement  $u_r$  ( $V_b$ - $u_r$ ) for the BRBF-RW. The BRB is designed to remain in an elastic range under small earthquakes. The truss system works together with the MF to provide lateral stiffness for the structure. The RW cannot provide additional lateral stiffness to the system. The lateral stiffness of the structure will be reduced due to the yield of the BRBs and the MF when subjected to moderate and major earthquakes, respectively. The BRBs are expected to dissipate all the seismic energy, and the RW with a large self-stiffness is expected to control the distribution of deformation to each story along the structural height under moderate and

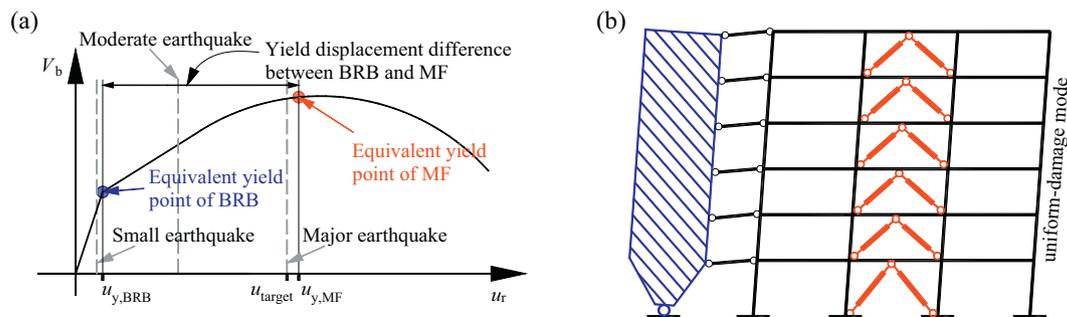


Fig. 2. Expected seismic performance of a BRBF-RW: (a) Expected curve of the base shear force and roof displacement; (b) Expected structural deformation mode.

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