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Seismic lateral displacement analysis and design of an earthquake-resilient dual wall-frame system

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ABSTRACT

Traditional reinforced concrete shear walls are both prone to damage during earthquakes and difficult to repair after an earthquake. Accordingly, two replaceable buckling-restrained braces (BRBs) are installed at the base of a hinged wall (HW) to form an earthquake-resilient shear wall (HW with BRBs at the base, HWBB). This paper focuses on the seismic analysis and the design of a dual system with an HWBB and a moment-resisting frame (HWBBF). An elastic lateral displacement analysis is conducted for the HWBBFs based on an equivalent continuous model, which consists of a flexural beam with a rotational spring at the base and a shear beam. The strength and stiffness demand formulas of the HW when the frame enters the inelastic stage are approximated based on the results of the elastic analysis. Based on the provided inelastic formulas, an elastic displacement spectrum-based design procedure is presented for HWBBFs to directly determine the sectional area of the BRBs, the required strength and stiffness of the HW. As an example, a 6-story HWBBF is designed using the proposed procedure, and a series of nonlinear response history analyses (NRHAs) are used to validate the procedure and inelastic formulas. The example effectively illustrates the errors associated with the target roof displacement and the formulaic HW demands compared to the corresponding NRHA results, respectively.

1. Introduction

Reinforced concrete shear walls (RCSWs) with substantial stiffness and strength are currently considered as an efficient lateral resistance system and are widely used in earthquake engineering. However, the failure mode of the base of an RCSW is difficult to control and prone to shear failure; therefore, the strength of an RCSW significantly decreases during a major earthquake. Although ideal flexural failure can occur and an ideal plastic hinge can be formed at the base of an RCSW through reasonable structural design, the ductility capacity of this plastic hinge is poor, and its energy dissipation capacity is limited because of the brittleness of the concrete material. Therefore, traditional RCSWs that exhibit poor ductility are both prone to damage during earthquakes and difficult to repair after an earthquake. Lew et al. [1] studied the dynamic behavior of tall buildings in the 2010 Chile earthquake with a moment magnitude of 8.8 and noted that this earthquake caused serious damage to RCSWs. The damage to some wall bases greatly exceeded the scope of repair.

Many related studies have been conducted by scholars to avoid shear failure in RCSW bases and improve the deformation capacity of such walls. Sittipunt et al. [2] and Shaingchin et al. [3] enhanced the shear strength and energy dissipation capacity of an RCSW by changing the reinforcement forms of the RCSW where diagonal web reinforcement was used. Moreover, various composite steel-concrete shear walls with vertical steel-encased profiles [4], steel plates [5] and steel trusses [6] were proposed and tested, and their hysteretic performance and failure mechanism were investigated. Dazio et al. [7] used a hybrid fiber concrete instead of ordinary concrete in the RCSW potential plastic hinge area (RCSW base) to improve the rotational ability of the plastic hinge. Mohamed et al. [8] studied the performance of glass fiber-reinforced RCSWs. The results showed that glass fiber-reinforced RCSWs exhibited both high strength and a sufficient deformation capacity. Liu and Jiang [9] installed four steel components at the two bottom corners of RCSWs to improve the energy dissipation capacity.

A rocking wall is formed by releasing the RCSW base constraint, which can effectively prevent damage to the RCSW base and is another valuable way to improve the seismic performance of RCSWs. Housner [10] reported some cases from the 1960 Chile earthquake in which buildings were damage free because the structures experienced an overall rocking phenomenon. This study noted that rocking structures exhibited more stable characteristics than other structures, and these findings marked the beginning of research on rocking structures

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[11,12]. During the movement of rocking walls, only elastic deformation occurs, and little seismic energy is dissipated; therefore, some studies have attempted to establish various dampers on rocking walls [13–16]. In [13–16], a prestressed reinforcement was used to reduce the residual deformation of the studied structures.

The body of a rocking wall rotates around one of the toes when in motion. In comparison to this type of motion, another rocking structure is a hinged wall (HW), which rotates around a fixed hinge at the base of the wall. Some scholars have investigated the positive features of HWs. Alavi and Krawinkler [17] applied HWs to reinforce frame structures and effectively control the vibration mode, thereby avoiding concentrated story drift and decreasing the magnitude of story drift. Similarly, Wada et al. [18] proposed the concept that HWs can be used to enhance the integrity of structures and applied this concept in the retrofit of the G3 teaching building at Tokyo Industrial University. This structure survived the 2011 Miyagi earthquake.

Buckling-restrained braces (BRBs) that serve the dual function of resisting lateral forces during small earthquakes and dissipating seismic energy during major earthquakes are widely used in earthquake engineering [19]. As a displacement-type energy dissipation brace, BRBs are often arranged at locations that experience relative deformation. For an example, the inter-story displacement demand is utilized in buckling-restrained braced frames. Additionally, Kim and Seo [20] placed BRBs at the nodes of frames with pinned beam-column connections and utilized the rotational demand. Pekcan et al. [21], Wongpakdee et al. [22] and Takeuchi et al. [23] proposed various types of structures equipped with BRBs by replacing some members with BRBs in truss systems. In these systems, the structural deformation profiles were preset, and the BRBs yield first under earthquake actions to protect the structures from damage. Wang et al. [24] installed a steel truss with BRBs at the base of an RCSW to replace the damage-prone area of the RCSW. In this paper, two replaceable BRBs are vertically and symmetrically installed at the base of an HW to form an earthquake-resilient shear wall, which is called an HW with BRBs at the base (HWBB).

This paper focuses on the seismic lateral displacement analysis and the design of a dual system composed of an HWBB and a moment-resisting frame (MRF), which is deemed an HWBBF. First, the HWBB and the HWBBF are described. Elastic formulas for the structural lateral displacement and internal forces of the HW are obtained through a lateral displacement analysis. Second, inelastic formulas for the stiffness and strength demands of the HW are approximated based on the elastic formulas and an internal force superposition method. Third, a seismic design procedure is presented for the HWBBF. Fourth, a 6-story HWBBF is designed using the proposed procedure to illustrate and validate the procedure and inelastic formulas.

2. Descriptions of the HWBB and HWBBF

2.1. HWBB and its equivalent calculation model

Fig. 1a describes the proposed HWBB, which consists of an HW, a hinged support and two BRBs at the base. The HW in the HWBB rotates within a certain range around the base hinge during an earthquake to coordinate the deformation of the entire structure. Thus, two BRBs at the base can produce cyclic tension and compression deformation, as shown in Fig. 1b. The HWBB design concept is that the BRBs and the hinged support are considered as flexural and shear elements, respectively, by decoupling the flexural-shear effect at the base of the shear wall. In other words, the shear force generated by the seismic action is transformed by the hinged support, and the corresponding flexural moment is balanced by a coupled moment provided by the BRBs. Additionally, the weight of the HWs is borne by the hinged support. Fig. 1c presents a structural repair method in which a jack is used as the external restoring force to adjust the HW position in the rotational direction after the damaged BRBs are removed. Fig. 1d–f shows the connection details of the HWBB, for which the hysteresis performance will be further experimentally studied. The HWBB only restrains the horizontal displacement of the floor system through a roller bar that is set in slots on the connecting plates. The pin connections between the HW and BRB (or foundation) are formed by combining a pin bar and circular holes. These connection forces are transmitted to the HW and foundation through high-strength bolts, end plates and anchor bars. Some similar connection forms can be found in [24–26].

For simplicity, a flexural beam with a rotational spring at the base is used as the equivalent model of the HWBB, as shown in Fig. 2c. The relationship between the axial force and the deformation of the BRB is assumed bilinear, as shown in Fig. 2b. Based on the geometric relationship shown in Fig. 2a, the yield moment, rotational stiffness and yield rotation of the spring ($M_{y,s}$, k_s and $\theta_{y,s}$), as shown in Fig. 2d, can be obtained based on Eqs. (1)–(3), respectively.

$$M_{y,s} = f_{y,BRB} A_{BRB} B \tag{1}$$

$$k_s = \frac{E_s A_{BRB} B^2}{2H_1} \tag{2}$$

$$\theta_{y,s} = \frac{2H_1 f_{y,BRB}}{BE_s} \tag{3}$$

where $f_{y,BRB}$, A_{BRB} and E_s are the yield strength, sectional area and elastic modulus of the BRBs, respectively; B is the distance between the two BRBs at the base; and H_1 and H are the heights of the BRB and HW, respectively. Eqs. (1)–(3) show that the spring parameters are related to the BRB parameters and geometric parameters (B and H_1). The post-yield stiffness ratio of the bilinear curve in Fig. 2d equals that of the curve in Fig. 2b. Notably, the BRB parameters, such as the sectional area and the length of the elastic segment, are not considered in detail in this paper.

2.2. HWBBF and its expected seismic performance

Fig. 3a describes the HWBBF, which consists of an HWBB, an MRF and some rigid links. The HW and MRF are connected with the horizontal rigid links in each floor level. According to Fig. 1, the rigid links transmit only the horizontal axial force between the HW and the MRF. Similar to Fig. 1b and c, Fig. 3b and c show the lateral deformation of the HWBBF during earthquakes and its seismic resilience after earthquakes, respectively. The MRF can be regarded as the internal restoring force if the performance target of the MRF is basically elastic.

Based on Fig. 3, Fig. 4a shows a schematic diagram summarizing the functional division and performance targets of the HWBBF. In the HWBBF system, the MRF is primarily used to bear the vertical load and to provide partial lateral stiffness; BRBs at the base are designed to provide the main lateral stiffness during small earthquakes and to dissipate the energy during moderate and major earthquakes. The HW, which is characterized by a high moment-resisting stiffness, transfers inter-story stiffness between stories and controls structural deformation. The HWBB composed of the BRBs and HW can be regarded as a shear wall that provides large lateral stiffness during small earthquakes. The MRF can be designed as basically elastic, and the beam-column members of the MRF incur only minor damage throughout the earthquake process. The structural functions of the HWBBF can be quickly restored by replacing the damaged BRBs after an earthquake.

Fig. 4b shows the expected curve of the base shear force and roof displacement for the HWBBFs. $u_{y,BRB}$ and $u_{y,f}$ are the HWBBF roof displacements when the BRBs and MRF yield, respectively, and u_{target} is a given target roof displacement for the HWBBF in the displacement-based design, as shown in Section 5.

Notably, the excellent seismic performance and resilience of the HWBBF require further numerical and experimental studies, and this paper focuses on the seismic analysis and design of the HWBBF as follows.

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