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Aseismic behaviors of steel moment resisting frames with opening in beam web

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ABSTRACT

Opening in beam web short away clear of beam-to-column connection is an effective method to improve the aseismic behaviors of steel moment resisting frames (MRFs). The pseudo-dynamic (PSD) test and the quasi-static test on the aseismic behaviors of full-size steel MRFs with opening in beam web are carried out. The PSD test shows that the tested frame can satisfy the design requirement and its stiffness isn't weakened by the web opening. It can be judged from the strain distribution around the beam-to-column connection that the seismic energy is dissipated by local deformation in the weakened area of the beam due to the opening in the case of severe earthquake action, and the expected failure mode of a ductile frame ('strong column but weak beam' and 'strong connection but weak component') is reached. In the quasi-static test, the failure mode of the tested frame is in conformity with the judgement, i.e., Vierendeel mechanism is formed in weakened areas due to web opening and brittle weld fracture is avoided, which results in an improvement of the aseismic behaviors of steel MRF. Based on numerical analysis, the non-linear analysis model of steel MRF with opening in beam web is provided. Some experimental tests are numerically re-analyzed by applying the proposed model and the numerical results are in conformity with the test results, which verify the validity of the model. A 17-story steel MRF building, damaged during the Northridge earthquake and measured in detail after the earthquake, is selected as the studied case. Push-over analysis shows that the ultimate displacement of the modified building with web openings increases a lot due to the opening and the building's ductility is improved greatly. Plastic hinge distribution in time-history analysis indicates that brittle weld fracture can be avoided in the frame including connection with opening and the maximum plastic zone moves to the weakened areas. It can be concluded that the aseismic behaviors of steel MRF are improved due to the opening in beam web.

1. Introduction

Damage investigations after the Northridge earthquake in 1994 and the Kobe earthquake in 1995 showed that there were many brittle fractures in the beam-to-column connections of steel moment resisting frames (MRFs) subjected to the severe seismic action before their components yield [1,2]. In the case of horizontal seismic action, bending moment diagram of a frame is shown in Fig. 1a, which is similar to the cantilever beam with concentrated load acting on its end Fig. 1b, c. The diagrams show that the rotation capacity of the beam-to-column connection is important to the ductility of steel MRFs. However, the damage experience showed that the conventional beam-to-column connection cannot satisfy such requirements, and many methods have been proposed to improve the ductility of steel MRFs over the past ten years.

According to the principle of the aseismic design, i.e., 'strong column but weak beam' and 'strong connection but weak component' [3,4], one of the effective methods to improve the ductility of steel MRFs is to weaken the beam clear of connection and make the weakened area yield first (the failure mode is shown in Fig. 2), which is in conformity with the concept of the ductile steel MRFs suggested by SAC [5].

Based on the mechanism mentioned above, reducing the bending moment resisting capacity of the beam is an effective method to improve the aseismic behaviors of steel MRFs. As the bending moment resistant capacity of the popularly applied I-beams is approximately offered by the flanges and the beam height, reducing beam flanges (Fig. 3, [6]) or beam height (Fig. 4, [7]) is a rational approach.

An opening in beam web short-way clear of beam-to-column connection may be another effective method to improve the ductility of steel MRF. Web opening may result in the forming of Vierendeel hinges (Fig. 5) at the perforated sections by the interaction of the bending moment and shear force [8]. As the Vierendeel mechanism failure is a ductile mode, it is believed that opening in beam web short-way clear of beam-to-column connection may dissipate seismic energy and improve the ductility of steel MRFs. Moreover, piping and ductwork can go through the opening, which will decrease the story height and make the space be used effectively. In addition, perforating is easy work for fabrication, which makes its application much easier.

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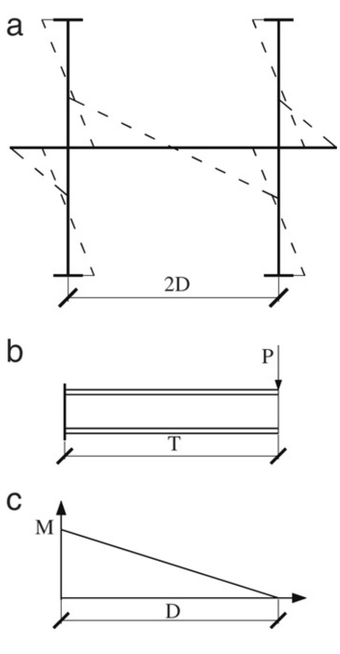

Fig. 1. Bending moment diagram.

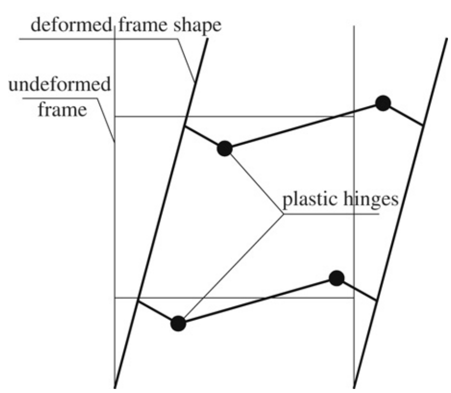

Fig. 2. Failure mode of ductile frame.

The feasibility of the beam-to-column connection with opening in beam web of steel MRFs has been studied [9–11] numerically and experimentally and it is shown [12] that Vierendeel hinge can be formed in the weakened area and the yielding load almost does not decrease. But the researches mentioned above were focused on the cyclic behaviors of beam-to-column connection, and the aseismic behaviors of steel MRFs with web openings are not included.

In the present investigation, experimental and numerical researches have been carried out to investigate the aseismic behaviors of steel MRFs with openings in beam webs. The pseudo-dynamic (PSD) test and the quasi-static test on a full-size steel MRF with openings in beam webs are carried out. The PSD test focuses on the seismic responses of the tested frame, and the quasi-static test focuses on its failure mode. Then, the non-linear analysis model of steel MRFs with openings in beam webs is provided and verified. A 17-story steel MRF building, damaged during the Northridge earthquake and measured in detail after the earthquake, is taken as a case to be investigated by Push-over and Time-history analysis.

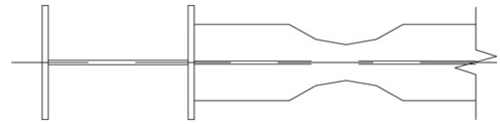

Fig. 3. Reducing beam flange.

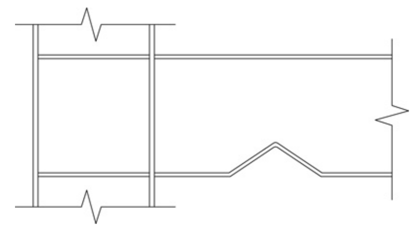

Fig. 4. Changing beam height.

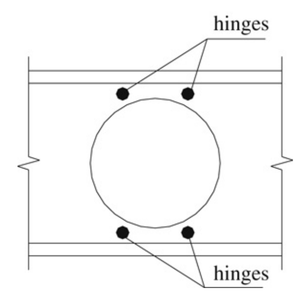

Fig. 5. Vierendeel mechanism.

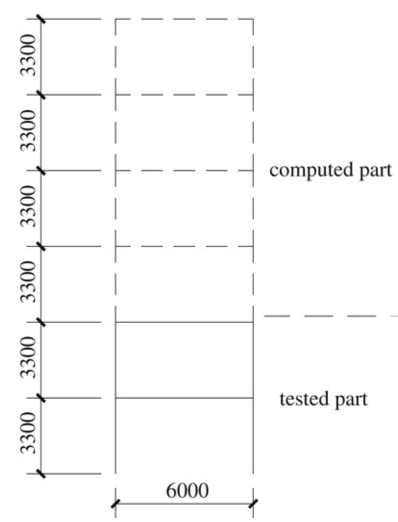

Fig. 6. Substructure model.

2. Experimental test

2.1. Tested frame

The specimen selected for the test is a full size 6-story 1-bay steel MRF (Fig. 6), with 6-m span and 3.3-m story height; the beam section is H300 × 200 × 8 × 12 (mm) and the column section is H400 × 300 × 12 × 18 (mm), the yield strength is 235 MPa.

The substructure technique is applied in the PSD test [13,19], in which the lower two stories are tested physically (Fig. 7) and the upper four stories are tested numerically (with story mass 37.8 T, story stiffness 20 kN/mm and damping ratio 0.035). To increase the lateral stability and stiffness, two frames with 1.5-m clearness are tested, in which there are six connections with opening and two