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Experimental Study on Full-Scale Steel Moment–Resisting Frame Subjected to Multiple Earthquakes

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Abstract— **In this study, a cyclic loading test of full-scale steel moment-resisting frames was conducted. The specimen represents one-floor one-span of an intermediate story of the mid- or low-rise building. In addition, the nonstructural component was also attached to the steel frames. The loading protocol used in the test simulates the occurrence of multiple earthquakes with various intensities. From the test result, the seismic performance and building functionality continuity under multiple earthquakes are evaluated.**

I. Introduction

Generally, buildings are designed not to collapse against the severe earthquake which is expected to occur once during the lifetime. Thus, the seismic performance and functionality of buildings subjected to multiple severe earthquakes continuously remain unclear. This problem has become a growing concern recently following the occurrence of the 2016 Kumamoto Earthquake, in which several strong earthquakes occurred in a short period of time.

In this study, a cyclic-loading test of a steel frame with nonstructural components was conducted to evaluate the damage, the residual seismic performance, and the ability to maintain the functionality of a steel building when subjected to multiple strong earthquakes continuously.

II. Experimental Program

In this experiment, two full-scale SMRF specimens were tested. Fig.1 shows the setup and geometry of the specimen. The specimen represents one-story one-span of an intermediate story of the mid- or low-rise steel building. In this test, the main focus of the experiment is the steel frames on the NS direction (6 m × 3.5 m); thus, two oil jacks were attached at the top corner in the NS direction. The oil jacks were connected to the strong wall, while the specimen was connected to the strong floor using the pin joint.

Both of the specimens have the same detail of structural components. In the EW direction, in addition to the main beam, secondary beams were attached every 1.5 m to provide lateral support to the main beams in NS direction. At the upper and lower floor, reinforced concrete slabs were cast on the deck plate. As shown in Fig.1, within one specimen, there are two typical steel frames in the NS direction, i.e., E-plane and W-plane. The main difference between these two steel frames is the detail of the beam-to-column connection. The beam end connections of E-plane have a weld access hole that conforms to JASS 6 [1], while those of W-plane have no weld access hole.

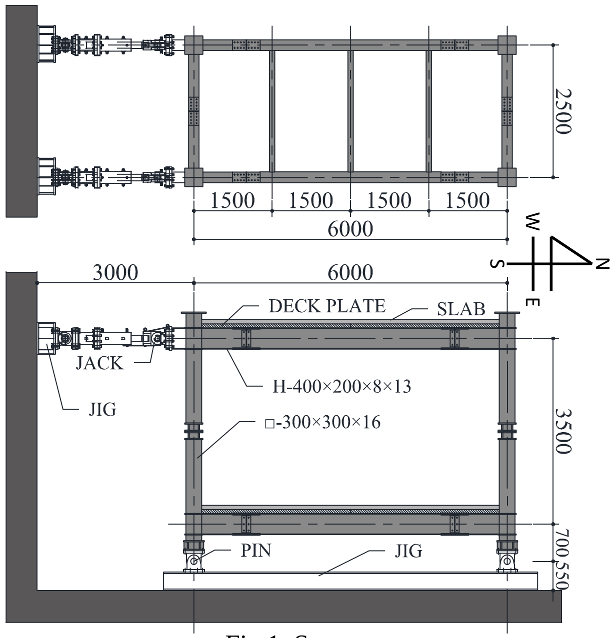


Fig.1. Setup

While the structural component of both specimens is the same, the nonstructural component attached to the 1st and 2nd specimens is different. For the 1st specimen, the light gauge steel (LGS) partition wall type was installed on the steel frames. The LGS partition wall mainly composes of two layers of gypsum boards and the LGS foundation frame to support the boards. Meanwhile, in the 2nd specimen, the autoclaved lightweight concrete (ALC) wall type was attached to the steel frames. The ALC wall mainly composes of the ALC panel and supporting angles that were attached around openings to support the panels.

To simulate the occurrence of multiple earthquakes, a special type of loading history was created from an inelastic time history response analysis result. The 3-story model of SMRF used by Tenderan et al. [2] to evaluate the seismic

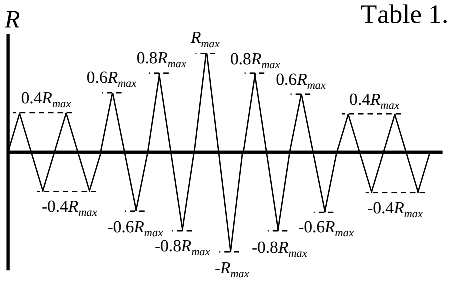


Fig.2. Typical one set of loading history

Table 1. R_{max} of each set

Set No.	R_{max}
1	1/400
2	1/200
3	1/100
4	1/200
5	1/75
6	1/100
7	1/50
8	1/75
9	1/33

performance of SMRF under multiple strong earthquakes was adopted. From the response analysis, the story drift angle (R) time history response at the 2nd story was extracted, and the rainflow counting algorithm [3] was performed to obtain the number of cycles of each amplitude. Then, each amplitude was grouped into several groups based on the ratio to its maximum amplitude (R_{max}). The typical one set of loading history is shown in Fig.2. This one set of loading history is considered to correspond to one earthquake. During the test, multiple sets of loadings were performed to simulate the occurrence of multiple earthquakes. The magnitude of the loading set was adjusted by adjusting the R_{max} as shown in Table 1. In total, nine sets of loading were planned to be conducted for each specimen.

III. Experimental Result

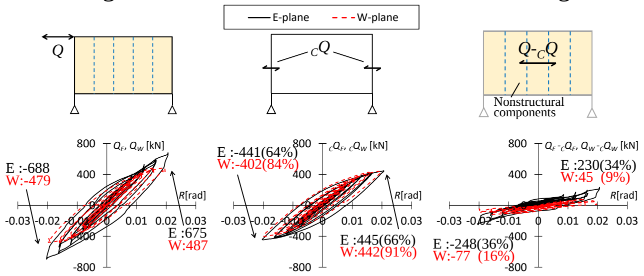
The seismic performance of the structure is evaluated by comparing the structural performance of the steel frame in E-plane (with weld access hole detail) and W-plane (with no weld access hole detail). Fig.3 shows the condition of the beam end of the 1st specimen at the final loading. At E-plane, the lower flange section was fully fractured, and the cracks at the web progressed until most of the cross-section was fractured. Meanwhile, in W-plane, even though the crack at the weld toe of the lower flange was initiated at set no. 9, the crack hardly progressed even after finishing ten and a half cycles of constant amplitude cyclic loading with R = 1/33. This comparison shows that the connection detail without the weld access hole performs better under the excitation of multiple big earthquakes (R_{max} 1/100×2 + 1/75×1 + 1/50×1).

Moreover, the building functionality continuity after an earthquake event is evaluated by comparing the nonstructural performance of the LGS wall and ALC wall. In the LGS wall, the crack in the gypsum board around the opening part was generated at set no. 2, and a part of the foundation frame was detached at set no. 5. Meanwhile, in the ALC wall, a visible crack was observed around the opening of the ALC panel at set no. 7. However, the ALC wall in the E-plane (without opening) was almost undamaged until the end of the loading. Based on that comparison, it could be concluded that the functionality continuity of buildings excited by multiple earthquakes might be determined by the damage of the LGS wall (interior wall) rather than the ALC wall (exterior wall) because the ALC wall performs better than the LGS wall.

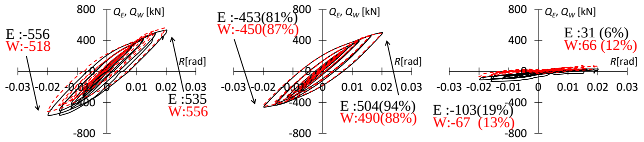
Fig.4 shows the load-deformation relationship of both specimens under set no. 7 (R_{max}=1/50). In the figure, three types of load-deformation relationship are shown, i.e., whole specimen, structural component only, and nonstructural component only. In addition, in every graph, the shear force and the percentage resisted by the structural and nonstructural components at the R_{max} are also shown. It could be seen that the strength of the steel frame on both specimens

(a) with weld access hole (b) without weld access hole

Fig.3. Beam end condition at the final loading



(a) 1st specimen (LGS Frame)



(b) 2nd specimen (ALC Frame)

Fig.4. Load-deformation relationship at set no. 7

is almost the same. However, in terms of the strength of the whole specimen, the maximum strength is varied depending on the type and the configuration (with or without opening) of the nonstructural component. On average, the shear force acting on the LGS wall is around 33% and 20% in the plane without and with openings, respectively. On the other hand, the shear force resisted by the ALC wall on average is 17% and 8% for the plane without and with openings, respectively.

IV. Conclusion

In this study, a cyclic loading test of steel moment-resisting frames considering multiple earthquakes was conducted. Two specimens were tested with the variation in the structural and nonstructural systems. The seismic performance and building functionality continuity of SMRFs under multiple earthquakes are evaluated by comparing the damage progression. In addition, the contribution of the nonstructural component to the whole specimen is also evaluated.

Acknowledgment

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