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Preliminary dynamic response characterization Tests-III: South NCREE Multi-directional shake table test for the seismic performance evaluation of the freestanding structures

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Abstract

Structures with movable base had been applied for reducing the seismic force. Recent years, a movable base system using cast iron and mortar as the bearing materials has been proposed and tested to evaluate the seismic performance. A full scale, 10-story R.C. frame using the movable base system was tested in E-Defense. The shaking table test showed that the graphite layer was developed at the interfaces and the friction coefficient was an almost constant value of 0.2 during sliding. The structural deformation was notably reduced comparing with the specimen with fixed base. Uplifts of the base and rotation of the specimen were also observed in the test. In 2018, a full scale two-story, one-span, and one-bay steel moment resist frame equipped with the cast iron-mortar movable base was tested in the south laboratory of NCREE to exam the dynamic behaviors under series seismic shakings. The friction coefficient reached about 0.4, and the rocking, rocking-sliding responses were significant under the intensive shakings. The variation of the value might be caused by the different contents of the mortars used in the two tests. This study conducted shaking table tests on the same two-story, one-span, and one-bay freestanding steel frame but using higher strength and lower fineness modulus of the mortar bases to evaluate the influences on the friction coefficient. Two directional and three directional seismic inputs were applied to exam the effects of the vertical excitations. After the shakings, the graphite layer was observed on the mortar surfaces. For the JMA Kobe 50% shaking, sliding dominated the responses and reached a distance of about 240mm. The vertical excitation did not cause notable difference in dynamic responses. For the 100% intensity shakings, the maximum base sliding distance reached about 500mm. The friction coefficient was ranged about from 0.2 to 0.25. The mortar with higher strength and smaller fineness modulus exhibited smaller friction coefficient, and lead to larger sliding distances than that of the previous test. The maximum relative deformation of the steel frame was similar with the previous freestanding specimen but smaller than that of the specimen with fixed base. Damages on the mortar surfaces due to the concentration and collisions with the cast iron under the rocking was observed. The unsmooth surface would affect the dynamic responses of the freestanding frame.

Keywords: movable base system, cast iron, mortar, friction coefficient

1. Introduction

In the earthquake events, middle-to-low rise buildings tend to sustain most serious damage. Most of the buildings are residential buildings and houses. Among the damaged cases, many low story failures are observed [1, 2]. Base isolation system has been proved to be an effective alternative to reduce seismic damages by elongating the natural period of the structure and applying additional damping. Rubber bearing system or the sliding-type system, such as friction pendulum systems, have been adopted in many cases. Due to their high cost and maintenance demands, the base isolation systems are mostly applied to important building such the hospitals or museums.

A movable base system had been proposed to develop a simple sliding mechanism on the base. A stable and appropriated friction coefficient would be the key to enhance the seismic performance and reduce the repair

costs. The simple system demand very limited maintenance requirement which might be more cost efficient for the residential buildings and houses. Enokida evaluated the slide behaviors between various materials by conducting shaking table tests on a free-standing structure [3]. The results showed that the maximum coefficients of ductile iron to mortar, gray iron to mortar, and an interface with a graphite layer were about 0.28, 0.3, and 0.22, respectively. The kinematic friction coefficients of the ductile iron–mortar, gray iron–mortar, and graphite layer interfaces were found to have an almost constant value of 0.2 under various velocities. The graphite would be developed from the iron under the sliding and the graphite layer was found to be effective to reduce the friction coefficient in the interfaces. In 2015, a full-scale, free-standing 10-story reinforced concrete building equipped with a gray iron–mortar movable base were tested in E-Defense [4]. The measured friction coefficient between iron and mortar was approximately 0.2. The maximum drift angle was only 0.6% under 100% JMA Kobe wave intensity shaking. The counterpart specimen with a fixed-base reached a drift angle of 3%. The reduction of the deformation is notable, however, the base uplift due to the rocking and the rotation were also observed. In 2018, a free-standing two-story steel moment frame equipped with a cast iron-mortar sliding base was tested in NCREE of Taiwan to evaluate the dynamic responses of the system while sustained continuous shakings [5]. The results indicated that the measured friction coefficient was about 0.35. The differences in strength and contents of the mortar might be the reasons to cause the variation between the two tests. Rocking, sliding, and rocking-sliding responses were observed and the friction coefficient varied significantly under intensive shaking. In addition, significant rocking caused impacts and stress concentration on the mortar surface and lead to surface crushes in several locations. The unsmooth surface condition might contribute to the variation of friction coefficient and affect the dynamic responses. The first-story interstory drift in the free-standing specimen was approximately 0.25%, which declined to around 30% compared with that of the fixed-base specimen.
To evaluate the resaon to cause the variation of the friction coefficient and exam how it affects the dynamic responses, full scale shaking table tests were conducted in the study. The two-story freestanding steel frame specimen used in the previous test [5] was adopted and tested by two-horizontal and three-dimension seismic shakings to estimate the effects of the vertical excitations. The strength and contents of the base mortar were changed to exam the influence to the friction coefficient. The major observations and results are summarized in the paper.

2. Shaking table tests

The tests were conducted using the new shaking table facility in the south laboratory of the National Center of Research on Earthquake Engineering (NCREE, Taiwan) in 2019. A two-story, one-span, and one-bay steel moment-resisting frame used in the previous test [5] was adopted as the specimen. As shown in Fig. 1(a), the specimen has a 3.5-m span in two plane directions, and the height of each story is approximately 3 m. In a base slab, which consisted of girders and beams and was topped with a 21-mm-thick steel plate, was bolted to the column bases. An FC250 iron bearing block was designed as round section cylinder to reduce the stress concentration. It was bolted to the bottom flanges of the foundational girders at each column location by applying a transfer plate. The diameter of the bearing block was 150 mm. The bottom boundaries of the blocks were grinded to round edges, resulting in an effective bearing area of the surface of 140mm in diameter. The specimen was placed on four mortar bases that were mounted on the table. The mortar specimen has a measured strength of about 650 kg/cm^2 and fineness modulus of 2.2. For the previous shaking table test [5], the strength and fineness modulus are 350 kg/cm^2 and 2.9, respectively. A 5-ton reinforced concrete mass was mounted on each story, making the weight of the specimen 34.5 ton. The compression stress on the iron bearing surface was approximately 5.2 MPa, which is the same with the previous test [5]. The specifications of the members are listed in Table 1. Fig. 1(b) shows overall views of the freestanding specimen. Fig. 1(c) shows the counterpart, fixed-base specimen in the previous test [5]. The column bases were fixed on the table.

The ground motion observed at JMA’s Kobe Marine Meteorological Observatory during the Southern Hyogo Prefecture Earthquake (hereinafter referred to as JMA Kobe) was used for the input wave. The maximum acceleration of the seismic motion was 8.18 m/s^2 in the north-south (NS) direction, 6.17 m/s^2 in the east-west (EW) direction, and 3.32 m/s^2 in the up-down (UD) direction, as shown in Fig. 2 (a).

The pseudo acceleration response spectra of the ground motions are presented in Fig. 2(b). The JMA Kobe wave exhibited a strong response at approximately 0.36 s and 0.75 s. The test sequence is shown in Table 2, The specimen was loaded with gradually increasing amplitude of vibration. Two direction and three-dimensional inputs were applied to evaluate the influence of the vertical excitation. White-noise inputs with an RMS of 0.6 m/s^2, duration of 70 s, and frequency bandwidth of 0.1–50 Hz were applied prior to each main test. The first model periods of the freestanding specimen were about 0.3 s.

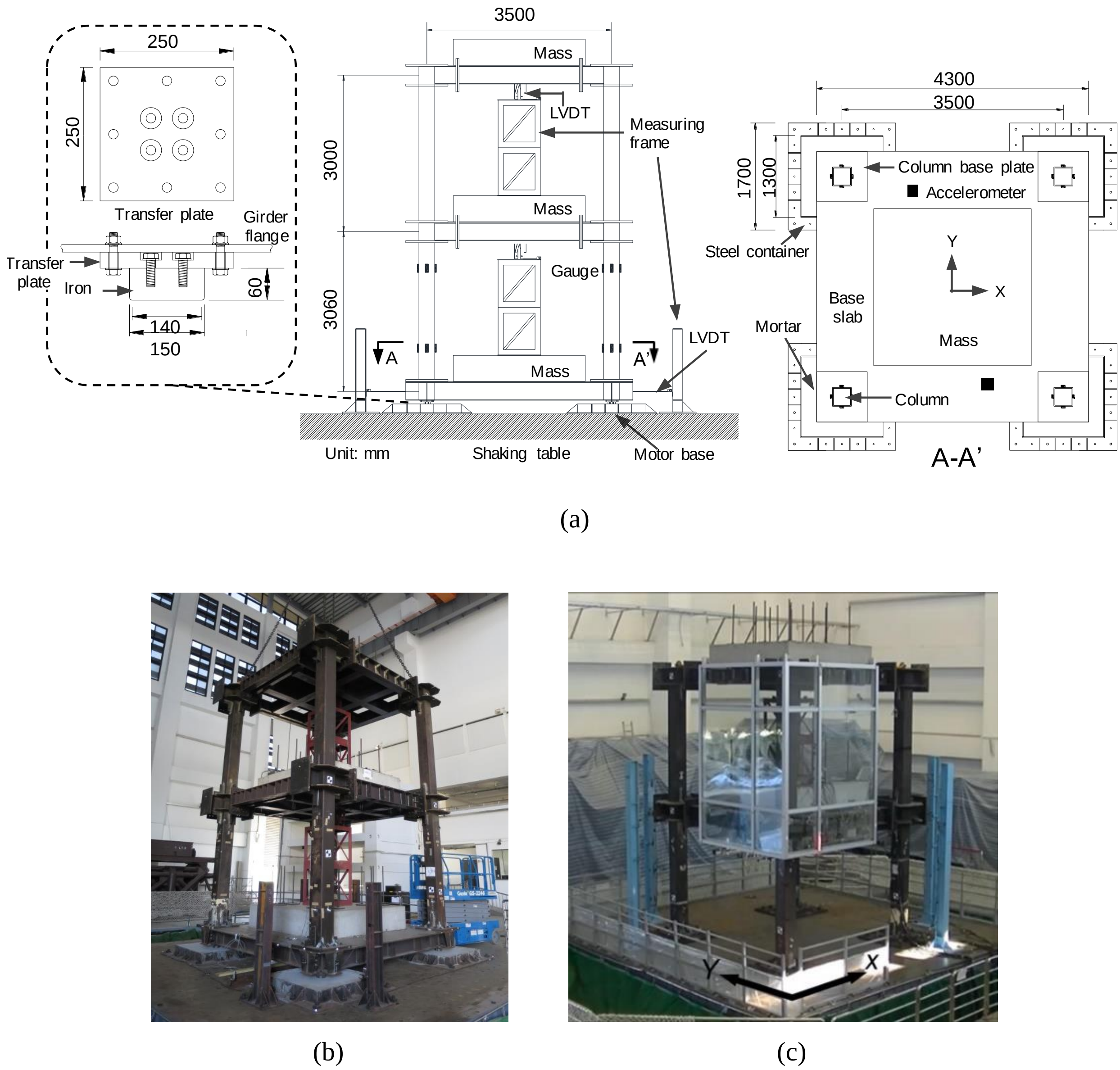


Fig. 1 –Specimen design: (a) Two-story test frame and measurements; (b) Freestanding specimen (c) Base fixed specimen [5]

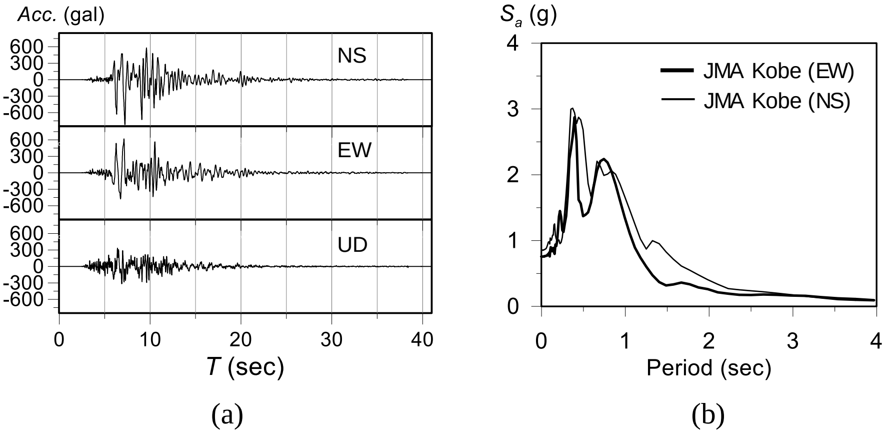


Fig. 2 –Input waves: (a) Time history of JMA Kobe; (b) Response spectra

Table 1 –Specification of specimen

Member	Specification	Material
Column	Box 300×9	STKR400
Girder	H340×250×9×14	SN400B
Mass	5 (t)	RC
1st floor weight	11.17	-
2nd floor weight	12.16	-
Roof floor weight	11.17	-
Total weight	34.5	-

Table 2 –Test program

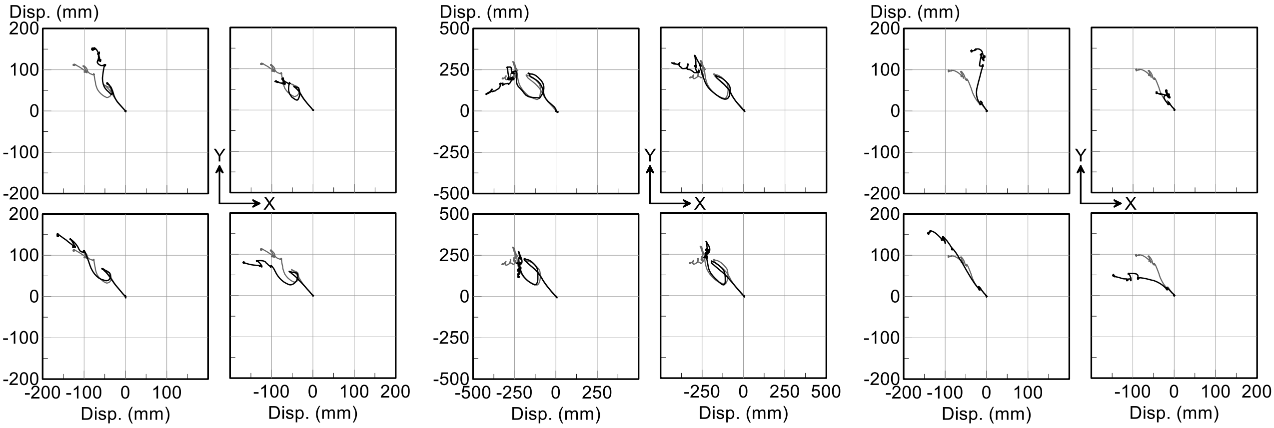
Input	Intensity
JMA Kobe_2D	25%
JMA Kobe_2D	50%
JMA Kobe_2D	100%
JMA Kobe_3D	25%
JMA Kobe_3D	50%

3. Test results

3.1 Observations

The base started to slide while under the JMA Kobe 50% shaking. No sliding or rocking response of the specimen was observed in JMA Kobe25% shaking. Fig. 3 shows the horizontal moving tracks of the four iron bearing blocks under the shakings. The locations of the four foundations are illustrated in Fig. 1(a). The gray line represents the movement of the mass center of the base slab obtained by averaging the displacements of the four bearing blocks. The 50% intensity shaking caused the base sliding up to about 240mm (Fig. 3(a)). For the 100% intensity shaking, the maximum displacement of the single base reached about 500mm (Fig. 3(b)). When the specimen sustained 3-directional shaking, the moving tracks and the maximum displacement are similar with that of the 2-directional shaking. Slight rotations were observed in the two shakings. Vertical excitation seems not cause notable difference in the response.

Fig. 4 presents the surface conditions of the mortar bases. The shakings developed few graphite layers on the surface. JMA Kobe 100% shaking exhibited large sliding in the beginning part of the shaking, then rocking and rocking-sliding responses became notable. The shaking resulted in large residual displacement. Intensive impact on the mortar during the rocking response caused the surface crushes and this might be the reason to cause the notable rocking response in the later part of the JMA Kobe 100% shaking.



(a) (b) (c)

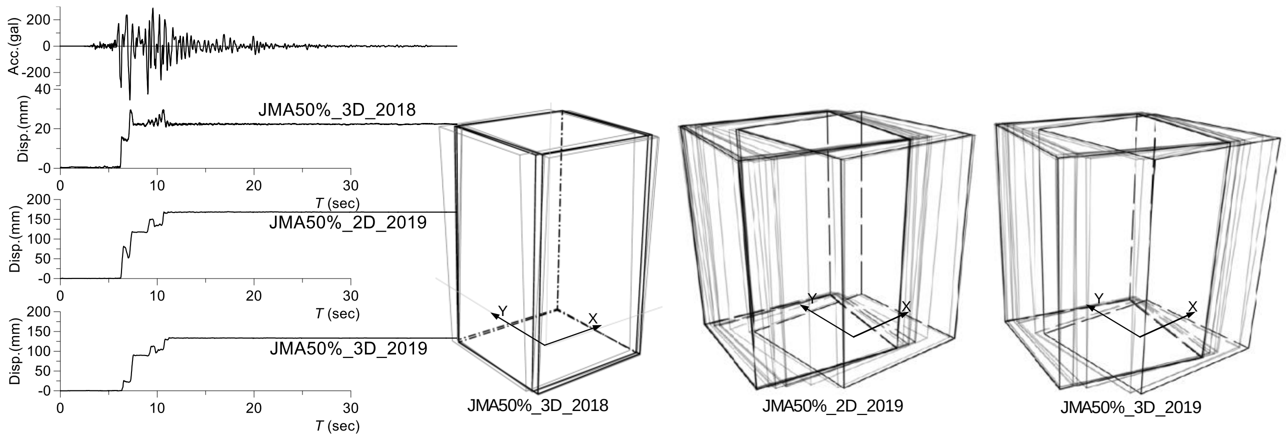
Fig. 3 –Movement of the specimen: (a) JMA Kobe 2D_50%; (b) JMA Kobe 2D_100%; (c) JMA Kobe 3D_50%

(a) (b)

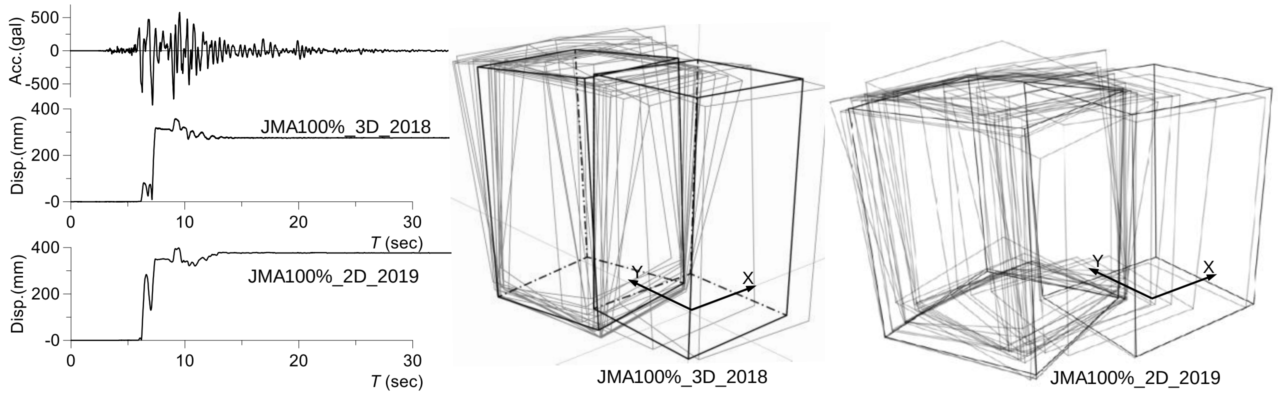
Fig. 4 –Observation of the motor base surfaces: (a) after JMA Kobe 50%_2D shaking; (b) after JMA Kobe 100%_2D shaking

The three-dimensional movements of the freestanding specimen obtained using the visual movement measurement system are illustrated in Fig. 5. Black outlines represent the initial and final specimen positions. Gray outlines represent the instant movement of the specimen under the peak responses. The NS component of the input time history, and the root sum square of the vertical displacement and two horizontal displacements of the mass center of the base slab are also presented in the figure. The response of the freestanding specimen in the previoius test [5] is included. For the JMA Kobe 50% shaking, the preveious test exhibited rocking and slight sliding responses. The shaking excitation induced substantial slides during the first two intensive shakes. After reaching a maximum displacement of 30 mm, the specimen slightly slid back to 20 mm and kept rocking during the last part of the input time history. In the 2019 test, sliding dominates the respones. Sliding distance was increased from about 30mm to 160mm. The new mortar bases notably changed the dynamic responses. Two direction and three directional inputs did not shown significant difference.

When the input intensity of the JMA Kobe wave reached 100%, the intensive shakes induced significant rocking and sliding responses in the two tests (Fig. 5(c)). In the 2019 test, the shaking induced large slide in the beginning, and reached a distance of about 350mm. Mortar suface of one base sustained srerious crushes in the middle of the shaking. The rocking reponse became notable. The previous test showed shimiar response but with smaller moving distance. Some surface crushes of the mortar were also observed. The unsmooth surfaces might be the reason to make rocking become notable.



(a)



(b)

Fig. 5 –Three-dimensional movement of the specimen while subjected to(a) JMA Kobe 2D_50%; (b) JMA Kobe 2D_100%

3.2 Friction coefficient

Fig. 6(a)–(c) presents the friction coefficient and slide amount of the mass center of the base slab in both base slide directions while it was subjected to JMA Kobe 50%_2D, JMA Kobe 100%_2D, and JMA Kobe 50%_3D shakings. The friction coefficient of the base was estimated from the horizontal inertial force, which is obtained by obtaining the sum of the story weights and multiplying it by the acceleration generated at each story, and the weight, which considers the effect of vertical input acceleration. The equation is as follows.

$$\mu = \left(\sum_{Base}^{R} m_i \cdot \alpha_{Hi}\right) / (M \cdot g - M \cdot \alpha_Z) \quad (1)$$

m_i is the mass at each story, α_{Hi} is the horizontal acceleration at each story, M is the total mass of the specimen, g is the gravitational acceleration, and α_Z is the vertical acceleration at the shaking table. The friction coefficient under JMA Kobe 50%_2D and JMA Kobe 50%_3D shakings show similar responses. The coefficient of kinetic friction was approximately in the range of 0.2 while the base was slipping. The values smaller than that of the previous test, whose friction coefficients were 0.36 under the same compression of 5.2 MPa. For the JMA Kobe 100% excitation, as shown in Fig. 6(b), the friction coefficient fluctuated. The peak value notably increased and reached 0.8, and the kinetic friction coefficient was approximately 0.25. Rocking would cause vertical and horizontal acceleration plus responses on the freestanding frame. This would cause a large fluctuation basing on the eq. (1).

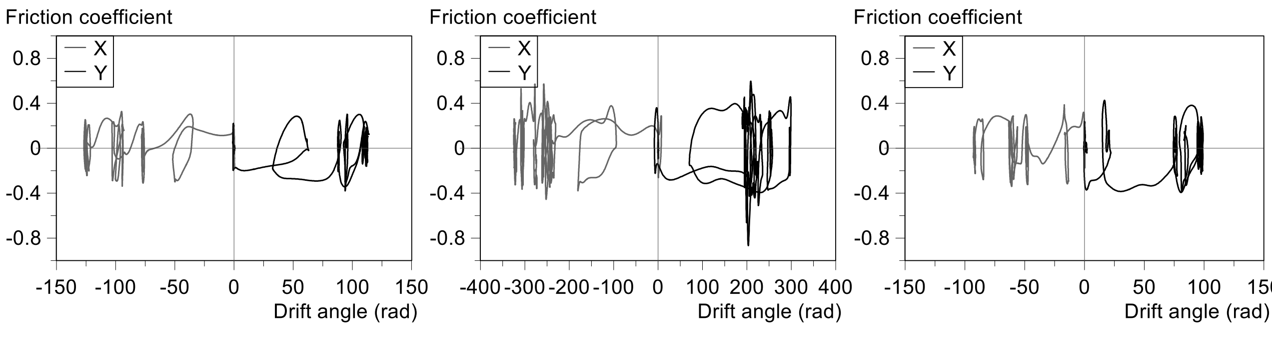


Fig. 6 –Friction coefficient: (a) JMA Kobe 50%_2D; (b) JMA Kobe 100%_2D; (c) JMA Kobe 50%_3D

3.3 Structural responses

Structural responses in terms of the maximum inter-story relative displacements are summarized in Fig. 7. The response at the base represents the maximum relative displacement between the base slab and the shaking table. Responses of the free-standing and fix-base specimens in the previous test are included in the figures. For the JMA Kobe 50% shaking, the maximum relative interstory displacements of the first story of the free-standing specimens were approximately 6.5 mm in both directions, with drift angles of approximately 0.24%. The values were similar to those for the fixed-base specimen. The 2019 test results show slightly smaller values. When the input intensity was increased to 100%, the maximum relative interstory displacements in the two directions of the first story of the fixed-base specimen were 12 and 13.4 mm, with relative drift angles of 0.44% and 0.5% in the two directions. The drift angles in the freestanding specimens were similar. They were smaller than that of the base-fixed specimen. Although the 2019 test exhibited smaller friction coefficient, the structural response might not be reduced notably when the rocking response occurred. The maximum deformation was reduced by approximately 10-30% in the frame with the movable base system.

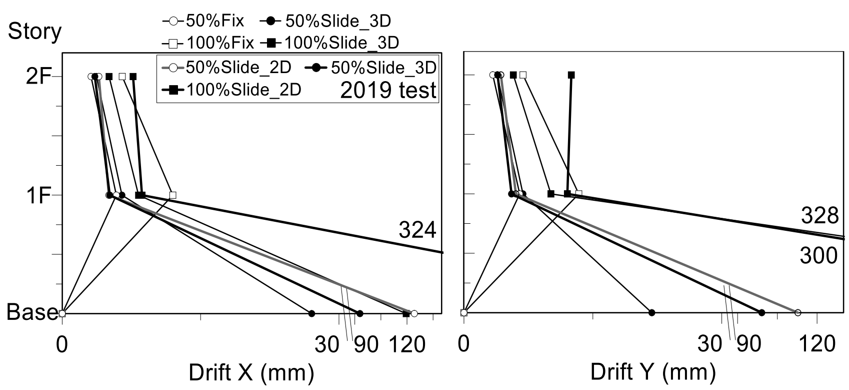


Fig. 7 –Relative displacement responses

4. Conclusions

A series of shaking table tests on a full-scale, two-story steel moment frame equipped with a mortar-iron slide base were conducted. The specimen adopted new mortar base with different contents to evaluate the influence on the friction coefficient and dynamic responses by comparing it with the previous tests, including the freestanding and base-fixed specimens. The major observations were as follows.

After the shakings, the graphite layer was observed on the mortar surfaces. For the JMA Kobe 50% shaking, sliding dominated the responses and reached a distance of about 240mm. The vertical excitation did not cause notable difference in dynamic responses. For the 100% intensity shakings, the maximum base sliding distance reached about 500mm. The friction coefficient was ranged about from 0.2 to 0.25. The mortar with higher strength and smaller fineness modulus exhibited smaller friction coefficient and lead to larger sliding distances than that of the previous test. The maximum relative deformation of the steel frame was similar with the previous freestanding specimen but smaller than that of the base fixed specimen. Damages on the mortar surfaces due to the concentration and collisions with the cast iron under the rocking was observed. The unsmooth surface would affect the dynamic responses of the freestanding frame and make rocking response become notable.

4. Acknowledgements

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