Development of Free Standing Steel Structure Using Kinematic Friction of Steel-Mortar

Ryuta Enokida, Michitaka Inami & Masayoshi Nakashima ,
Kyoto University, Japan

Takuya Nagae
E-Defense, Japan

Masahiro Ikenaga
Tohoku University, Japan

SUMMARY:
Free standing steel structures, whose columns bases are not fixed, contribute to decrease the damage of the buildings under large earthquakes. It is preferable to realize this system by steel and mortar, which are widely used in construction. The maximum static friction coefficient of steel and mortar is 0.8 and this value is too high for free standing steel structures designed by conventional design codes. To realize the free standing steel structure reasonably, reduction of the friction coefficient is necessary. We applied graphite well known as a solid lubrication to the interface of steel and mortar. Shaking table tests results show that the static friction coefficient of steel and mortar (0.8) is reduced to 0.2 only by using graphite. In the tests using a strong ground motion, the seismic responses of free standing steel structure lubricated by graphite becomes 1/8 of the base fixed structures.

Keywords: free standing steel structure, mortar, steel, shaking table test

1. INTRODUCTION

Under large earthquakes, the first floor columns tend to sustain severe damage, which may trigger collapse in the first floor. On the other hand, many pointed out that deformation of lower parts of structures such as the base or column base contributed to mitigate the seismic damage under large earthquakes (Hayashi et al., 1996, Kabeyazawa et al., 2008, Midorikawa et al., 2009). From this consideration, a free standing structure whose first floor columns are not anchored to the bases may be effective to mitigate the damage. Steel and mortar are preferable for the interface of this system, because they are widely used in construction. Experimental results on friction of steel and mortar reported that the friction coefficient is about 0.7 (McCormick J. et al. 2009). It was shown that the free standing structure with interface of steel-mortar gives benefit only for very large ground motion whose velocity reaches more than 1.0 m/s.
To make this system more practical, the friction coefficient has to be smaller. For this purpose, application of graphite to the surface of steel and mortar is a good choice because the graphite is well known as lubricant. This paper reports the shaking table test that examined the friction between steel-mortar with and without graphite.

2. SHAKING TABLE TESTS

2.1. Specimens

Shaking table tests on friction between steel-mortar and graphite were conducted. The specimen has two steel frames and rubber bearings in between the frames as shown in Figure 1. The upper steel frame and rubber bearings represent a superstructure of the free standing structure and the lower steel frame represents the sliding base. The weight of the upper steel frame is 3,350kg and that of the lower one is 1260kg. The total weight of the specimen is 4,600kg, the plan is 2.5m×2.5m with a height of

0.8m. To consider the influences from the supper structure to the sliding behaviour or friction coefficient, two types of specimen were prepared. One specimen, defined as the rigid specimen, had an H shaped beam for the layer of the rubber bearings. The other specimen, defined as the flexible specimen, did not have the beam. Figure 2 shows a photo of the specimen. The specimen was directly placed on the mortar bases. The natural frequency of the rigid specimen and the flexible specimen were 12.0Hz and 3.0 Hz by the system identification using random waves.
The specimen was supported by four steel boxes and they become the surface of sliding when it moves. The contact surface of each steel box and base mortar was 75mm×75mm and the contact pressure was 2.0 N/mm^2. Figure 3 (a) shows the base mortar and Figure 3(b) shows the base mortar with graphite. 3kg of graphite was scattered to each of the four base mortars. This corresponded to 0.07% of the specimen's weight.

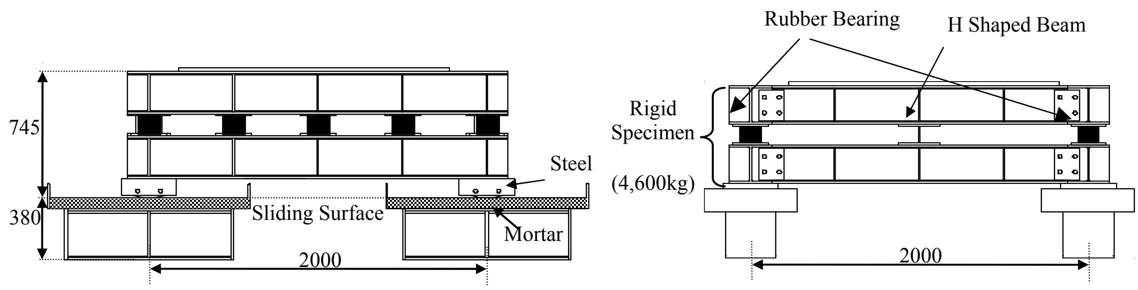


Figure 1. Experimental System

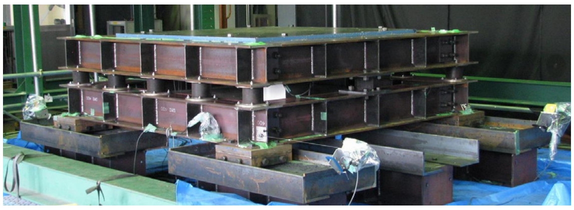
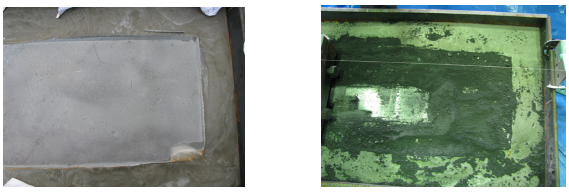


Figure 2. Overview of Experimental



(a) Mortar (b) Mortar with Graphite

Figure 3. Base Mortar

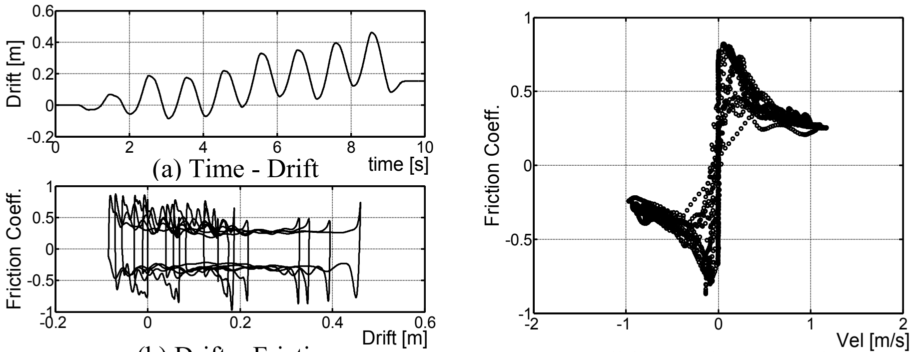
3. TEST RESULTS WITHOUT GRAPHITE

A series of shaking table tests were conducted and major test results are shown below. The friction coefficient shown in the results was estimated by the shear force obtained from the accelerometers and the total weight.

3.1. Rigid Specimen

A shaking table test was conducted by 1 Hz sinusoidal wave whose amplitude was 11.5 m/s^2. In Figure 4(a), the specimen begins moving at 0.5 s and the residual displacement reaches 0.18 m. The shape of the time history is similar with the sinusoidal wave used as the input, which implies the smooth movement.
Figure 4(b) shows the relation between the friction coefficient and sliding displacement. Although kinematic friction is often considered to be constant, the friction shown in the figure decreases drastically once it moves.

Figure 4(c) shows the relation between the sliding velocity and friction coefficient. The maximum static friction coefficient between steel and mortar is 0.8. Kinematic friction gradually decreases as the sliding velocity is made larger, and it is reduced to about 0.3 when the velocity was 1m/s. The friction follows the same path for the both the increasing or decreasing branches.

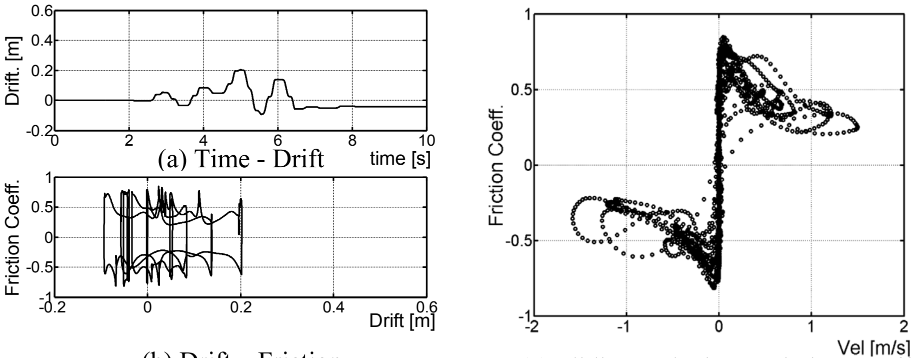


(a) Time - Drift
(b) Drift – Friction
(c) Sliding Velocity – Friction

Figure 4. Test Results of Rigid Specimen

3.2. Flexible Specimen

The shaking table test for the flexible specimen was conducted by 1 Hz sinusoidal wave whose amplitude was 8.5 m/s^2. The specimen moved at around 2 s in Figure 5(a). The shape of the time history is not as smooth as that of the rigid specimen in Figure 4(a). Much research reveals that stick-slip phenomenon is caused by the flexibility of sliding objects (Antoniou et al. 1976, Banerjee, 1968, Van de Velde et al. 1997). In addition, kinematic friction is also influenced by stick-slip and the relation of sliding velocity and friction coefficient forms a clockwise loop. The hysteresis of Figure 5(c) differs from that of Figure 4(c). These characteristic suggest that the stick-slip occurred at the flexible specimen.



(a) Time - Drift
(b) Drift – Friction
(c) Sliding Velocity – Friction Coeff.

Figure 5. Test Results of Flexible Specimen

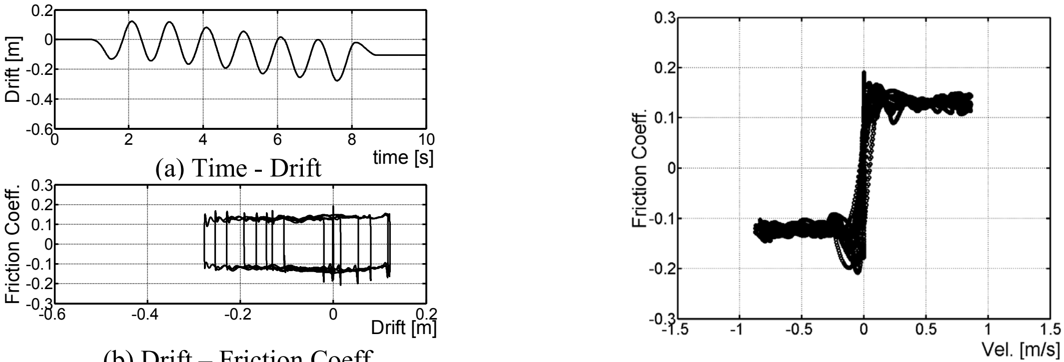
4. TEST REUSLTS WITH GRAPHITE

Through the shaking table tests on friction of steel-mortar, it was found that the maximum static friction coefficient was around 0.8 and the kinematic friction coefficient gradually decreases to 0.3 and the stick-slip occurred depending on the rigidity of structures. The maximum static friction coefficient was regarded too large for structures conventionally designed. Therefore, application of graphite to the interface was considered to reduce the friction coefficient of steel-mortar.

Graphite is well known as lubricant in mechanics, and it is materially stable, high pressure resistant and inexpensive. We investigate the performance of graphite lubrication by using the base mortar with graphite shown in Figure 3 (b) for shaking table tests.

4.1. Rigid Specimen

A shaking table test for the rigid specimen was conducted by 1 Hz sinusoidal wave whose amplitude was 6.8 m/s^2. In Figure 6(a) the specimen slides smoothly because the shape of the response time history is the same as the sinusoidal input. Figure 6(b) shows the hysteresis of friction coefficient and sliding displacement. The maximum static friction coefficient is 0.2, which is one fourth of the friction coefficient of steel-mortar. The kinematic friction coefficient does not change as much as that of steel-mortar. It can be expressed by one constant value (e.g. 0.15). Figure 6 (c) shows the relation of the friction coefficient and sliding velocity. The friction coefficient sharply decreases to 0.15 from 0.2 after its movement and the coefficient remains constant at the range of over 0.2 m/s.



(a) Time - Drift

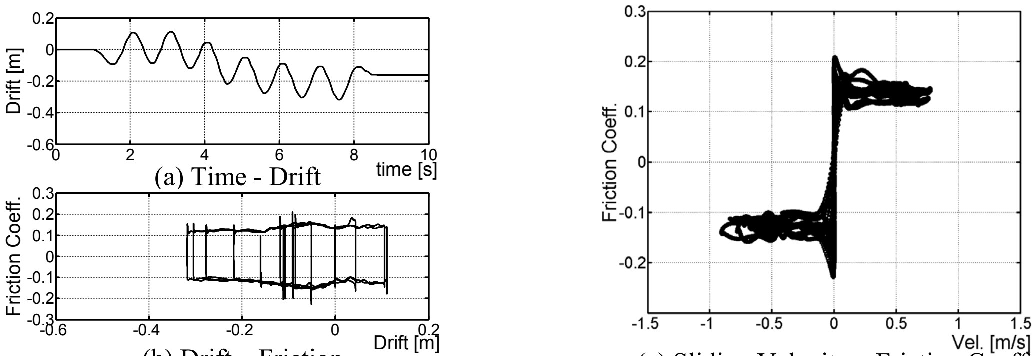
(b) Drift – Friction Coeff.

(c) Sliding Velocity – Friction Coeff.

Figure 6. Test Results of Rigid Specimen

4.2. Flexible Specimen

The shaking table test for the flexible specimen was conducted by 1 Hz sinusoidal wave whose amplitude was 5.5 m/s^2.The graphite contributed to make the sliding behaviour smooth even for the flexible specimen, because the shape of time history in Figure 7(a) is very similar with the input sinusoidal wave. The Figure 7(b) and Figure 7(c) show very similar results with the Figure 6(b) and Figure 6(c), respectively. These results lead to a conclusion that graphite decreases the friction coefficient to 0.2 and this contribute to prevent occurrence of stick-slips.



(a) Time - Drift

(b) Drift – Friction

(c) Sliding Velocity – Friction Coeff.

Figure 7. Test Results of Flexible Specimen

5. TEST RUSULTS WITH GRAPHITE UNDER GROUND MOTION

The shaking table tests using 1Hz sinusoidal wave were conducted to examine the basic characteristics of the friction. Here, a shaking table test conducted by a recorded ground motion to study the response of the free standing steel structure is shown. In this test, a recorded ground motion JMA Kobe EW at

1995 Kobe earthquake was used for the flexible specimen. The obtained results are shown in Figure 8. In Figure 8 (a), the displacement increased gradually after the large movement and the residual displacement became 0.45m. Graphite greatly contributes to the reduction of the friction coefficient, but it simultaneously made the sliding displacement larger. From Figure 8(b) and 7(c), the friction obtained by sinusoidal wave and the ground motion are similar. The friction obtained by sinusoidal wave can be used for free standing structures under ground motions.

The acceleration response spectrum of the ground motion becomes 3.2g at the period of the flexible specimen (0.33 s). This corresponds to the maximum acceleration response of the flexible specimen if its base is fixed. In this test, the maximum base shear coefficient of the superstructure of the flexible specimen lubricated by graphite became 0.4. This means that base shear coefficient of the free standing steel structure becomes around 1/8 of the based fixed structure.

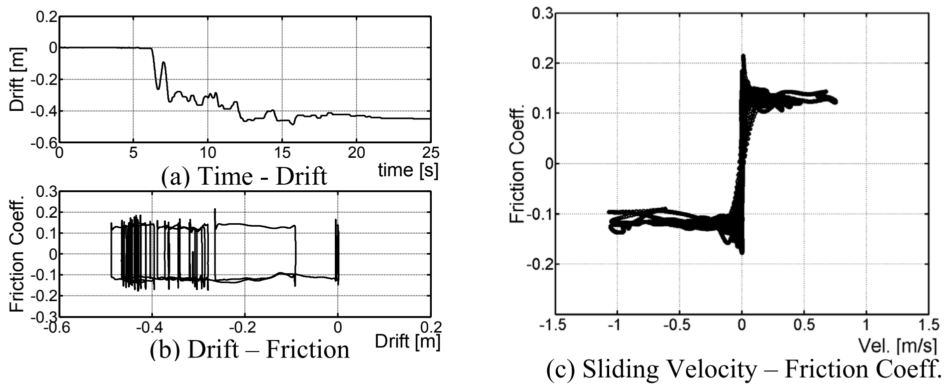


Figure 8. Test Results of Flexible Specimen under JMA Kobe

5. CONCLUSION AND FUTURE WORK

A series of shaking table tests was conducted to study the friction behaviour of steel-mortar and performance of graphite lubrication. The conclusions obtained from the tests are shown as below.

(1) The maximum static friction of steel-mortar was about 0.8. Kinematic friction gradually decreases and reduced to about 0.3 at 1m/s.
(2) For the interface of steel-mortar, stick-slip was induced, because of the flexibility of the superstructure. Stick-slip changed the sliding behaviour and kinematic friction.
(3) The maximum static friction coefficient of steel-mortar with graphite was about 0.2. As for the kinematic friction coefficient, it suddenly decreases to 0.15 from 0.2 after the movement, and it remained the same while sliding. Graphite contributed to prevent the stick slip phenomenon.
(4) A free standing structure on the interface of steel-mortar with graphite contributed to mitigate the seismic damage and the response was reduced to around 1/8 of the base fixed structure.

As a sacrifice of the mitigation, the sliding displacement tends to become large when graphite is used. Therefore a method to keep the functionality of mitigation by sliding and restrain the sliding displacement in some range is required for a future work.

REFERENCES

Antoniou S.S., Cameron A., Gentle C.R., (1976), 'The friction speed relation from Stick-Slip data,' *Wear*, 36 (2), 235–254.

Banerjee A.K., (1968), 'Influence of kinetic friction on the critical velocity of Stick-Slip motion,' *Wear*, 12 (2) 107-116.

Hayashi Y., (1996), 'Damage Reduction Effect Due to Basement Uplift of Buildings,' *Journal of structural and construction engineering Transactions of AIJ* (485), 53-62, (in Japanese)

Kabeyazawa T., Kabeyazawa T., Matsumori T., Kabeyazawa T., Kim Y., (2008), 'Shake Table Test On Full-Scale Three-Story Reinforced Concrete Building Structure,' *Journal of structural and construction engineering. Transactions of AIJ* 73 (632), 1833-1840. (in Japanese)

McCormick J., Nagae T., Ikenaga M., Zhang P.C., Katsuo M. Nakashima M., (2009), 'Investigation of the sliding behavior steel and mortar for seismic applications in structures,' *Earthquake Engineering And Structual Dynamics*, 38, 1401-1419.

Midorikawa M., Sudo T., Asari T., Azuhata T., Ishihara T., (2009), 'Three-Dimensional Seimic Response Of Ten-Story Steel Frame Frames With Yieding Base Plates Allowed To Uplift' *Journal of structural and construction engineering. Transactions of AIJ* 74 (637), 495-502. (in Japanese)

Van de Velde F., De Baets P., (1997), 'Comparison of Two Stick-Slip Testers and Recommendations for Repeatable and Significant Stick-Slip Testing,' *Tribotest* 3–4 3, 361–392.