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EXPERIMENTAL AND NUMERICAL STUDY OF SPHERICAL SLIDING BEARING (SSB) PART 1: FULL-SCALE DYNAMIC TEST

Shinsuke Yamazaki(1), Kentaroh Minowa(2), Atsushi Watanabe(3), S. Kishiki (4), J. Li(5), S. Yamada(6)

(1) *Senior manager, Dr. Eng., Nippon Steel Engineering Co., Ltd. yamazaki.shinsuke.f5g@eng.nipponsteel.com*
(2) *Manager, Nippon Steel Engineering Co., Ltd. minowa.kentaroh.nf2@eng.nipponsteel.com*
(3) *Senior Manager, Nippon Steel Engineering Co., Ltd. watanabe.atsushi.8hx@eng.nipponsteel.com*
(4) *Associate Prof., Tokyo Institute of Technology, Dr. Eng. kishiki.s.aa@m.titech.ac.jp*
(5) *Graduate Student, Tokyo Institute of Technology. li.j.ax@m.titech.ac.jp*
(6) *Prof., Tokyo Institute of Technology, Dr. Eng. yamada.s.ad@m.titech.ac.jp*

Abstract

Friction Pendulum Bearing (FP), which is firstly developed in the United States, is widely used in earthquake-prone regions such as Italy, Turkey and United States. SSB is a type of double concave type Spherical Sliding Bearing developed in Japan, and its adoptions are gradually increasing in the base isolation building structure in Japan.

Compare with Rubber bearing, FP has several advantages. First, the ultimate displacement of FP can be directly determined by the diameter of both spherical stainless surface and the slider. However, rubber bearing has critical deformation because of the property of rubber and its shearing deformation configuration. Second, the period of FP is directly determined by the spherical radius, however, the period of rubber bearing is affected by the change of structure weight. Third, the damping performance of FP can be easily controlled by friction coefficient.

On the other hand, it is generally recognized that the coefficient of friction changes due to the increase of friction heat due to repeated loading, and loading speed and contact pressure also affect the friction coefficient. Therefore, it is necessary to know the dynamic behavior considering these influence factors under various conditions assumed in the base isolation structure, in order to evaluate the performance of the base isolation building to which the spherical friction sliding bearing is applied. Conventional unidirectional dynamic experiments using reduced size specimen are widely adopted due to the limitations of the capacity of the available test equipment. However, it is important to know the full scale size dynamic behavior to evaluate the performance of the base isolation structure appropriately. ASCE 7-16 Standard Item 17.8. requires the prototype test using the full scale size to evaluate the performance.

In this research, full scale dynamic loading test of this Spherical Sliding Bearing was conducted. Various parameters, such as vertical loading pressure, horizontal speed and amplitude were considered as a parameter of the test to evaluate the influence on the performance. In this part, outline of the test is reported.

Keywords: Seismic Isolation, Spherical Sliding Bearing, Full Scale, Dynamic Test

1. Introduction

FP is widely used in earthquake-prone regions such as Italy, Turkey and United States. Compare with Rubber bearing, FP has several advantages. First, the ultimate displacement of FP can be directly determined by the dimension of the spherical surface Φ and the diameter of the slider φ, however, rubber bearing has critical deformation because of the property of rubber. Second, the period of FP is directly determined by the spherical radius Rs, however, the period of rubber bearing is affected by the variation of rubber material and the change of structure weight. Third, the damping performance of FP can be easily controlled by friction coefficient μ.

Many unidirectional tests were held to investigate the properties of FP by using Single Concave Friction Pendulum Bearing (SCFP). And several friction models were proposed to simulate the behavior of FP under seismic excitation. V. Quaglini etc. (2011) proposed a procedure to pre-assess the behavior of FP that depends on pressure, velocity, external temperature and displacement by testing small scale SCFP under 1D dynamic loading [1]. G. Lomiento etc. (2013) proposed a friction model which take into account load, velocity and cycling effect by holding 1D prototype dynamic tests of SCFP [2]. V. Quaglini etc. (2014) proposed a 3D FEM of SCFP to estimate friction heating and the change of design properties due to friction heating is briefly estimated [3]. M. Kumar etc. (2015) proposed a friction model which take into account pressure, velocity and temperature at sliding surface by holding 2D prototype dynamic tests of SCFP [4].

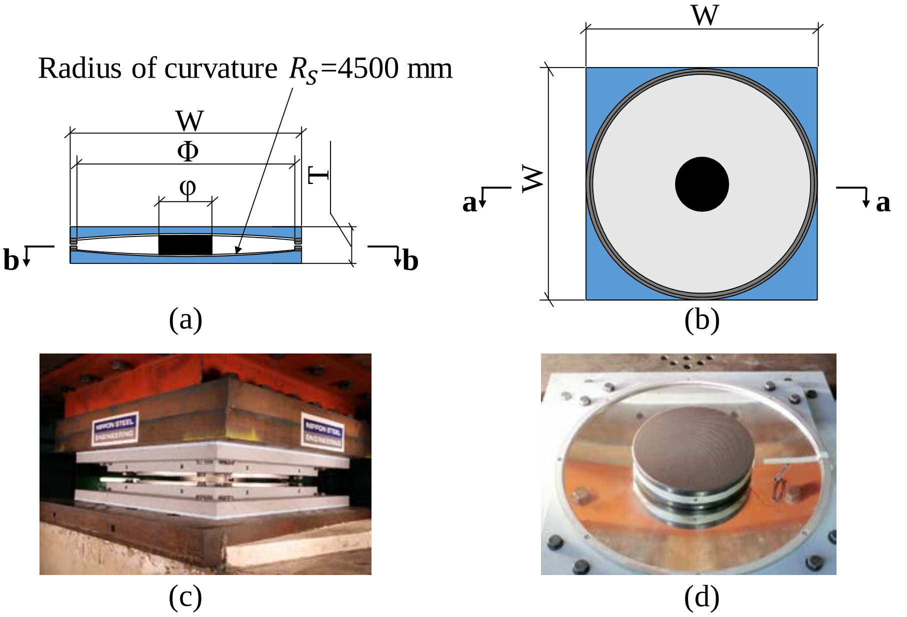
However, in most cases, the friction model was only checked under limited conditions, which cannot be considered representative of all the possible situations that FP will experience in their service life. Also, the variation of FP properties under different situations is still not clear.

To figure this, nearly one hundred full-scale dynamic tests on Double Concave Friction Pendulum (DCFP), which is considered to contain various conditions that DCFP can experience in their life, were conducted for 2 types of specimen based on standard ASCE [5]. Also, a friction property models were proposed and it was evaluated by comparing it with experimental data under various conditions. The model is expected to be available for estimating the change of DCFP properties due to different conditions and this change was discussed based on both experimental and analytical data.

This research (part 1, FULL-SCALE DYNAMIC TEST) summarizes the details of the specimens, test parameters, set up, measurement plan, loading protocol and test results. Later in part 2, FRICTION MODELS, a friction property models considering various dependency were proposed and those were evaluated by comparing it with the experiment results. And in last part 3, SEISMIC RESPONSE, seismic response analysis using above models were carried out to evaluate the performance of the isolated structure using the DCFP.

2. Specimens

Two types of DCFPBs provided by Nippon Steel Engineering were tested. The dimensions of these specimens are shown in figure 1 and table 1, where φ is the diameter of the slider, Φ is the diameter of the spherical surface, W is the width of the concave plate and T is the thickness of the specimen. The sliding material on the upper and lower surface of slider is composite PTFE material and the material of the sliding plate on the two concave plate is stainless steel. The nominal friction coefficient μ_n is 0.043 (±0.01), which represent for the friction coefficient under nominal condition, 60MPa, 400mm/s and 20˚C [6].



(a) (b)

(c) (d)

Figure 1. Specimen configuration: (a) a-a cross section, (b) b-b cross section, (c) outward appearance and (d) concave plate and slider

Table 1. Specimen dimensions

Specimen size	φ (mm)	Φ (mm)	W (mm)	T (mm)
φ300	300	770	820	152.0
φ400	400	870	920	162.9

3 Test setup

The experiments were conducted at the University of California, San Diego, in the Caltrans Seismic Response Modification Device (SRMD) Test Facility [7]. The overview of the test setup is shown in figure 2. After the specimen is placed inside the facility, an axial force can be added to control the contact pressure between the slider and the concave plate. Additionally, four horizontal actuators can make the loading table move in horizontal directions to control the velocity and loading path.

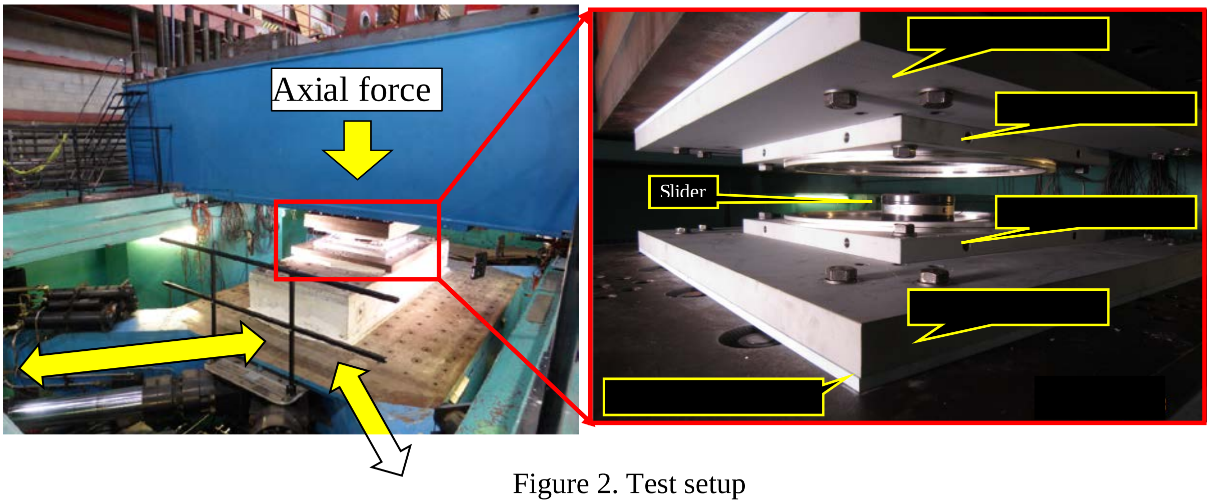


Figure 2. Test setup

4 Measurement plan

The reaction forces (horizontal and vertical) and relative displacement between the upper and lower concave plates during the tests were measured with load cells installed in the horizontal and vertical actuators and displacement transducers installed along the actuators, respectively. A thermocouple was also attached between the lower concave plate and the base adapting plate, as shown in figure 3, because it is difficult to attach the thermocouples directly on the sliding surface considering its influence on the friction coefficient.

In this condition, the temperature increase at the sliding surface caused by friction heating during the tests cannot be measured immediately because of the thermal conduction of the lower concave plate; hence, only the data at the beginning of the tests can be considered to be useful as initial temperature, and these values were recorded as T_0. The method to simulate the temperature increase caused by friction heating during the test will be introduced in Part 2.

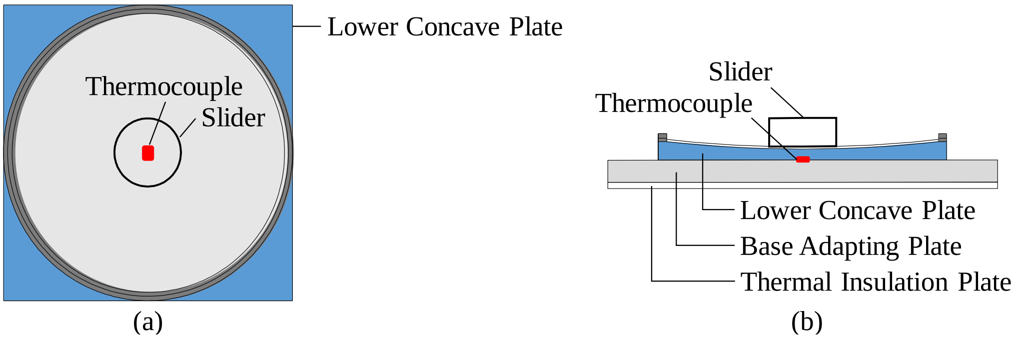


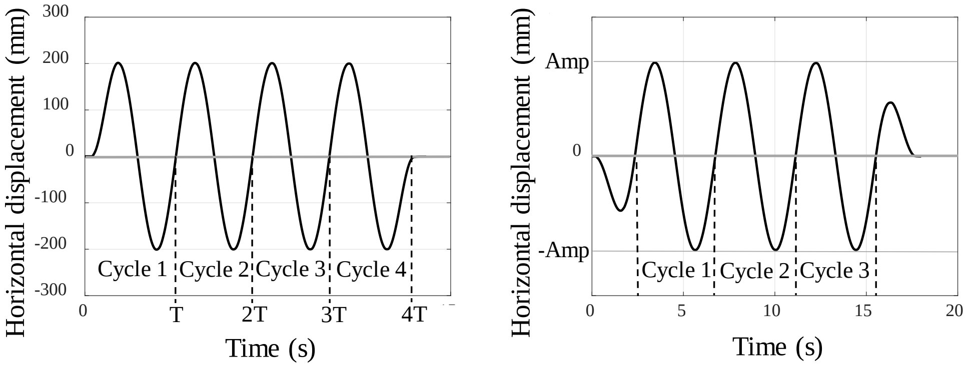
Figure 3. Temperature measurement plan

5. Test procedure

Two series of full-scale unidirectional dynamic tests were conducted. The dependency test was conducted to verify the applicability of the dependency equations of pressure and velocity of the specimens. The ASCE test, which complied with the provisions of ASCE/SEI 7-16 [7], was performed for the validation of the stability of the specimens and evaluation of friction models.

The loading of both the dependency test and the ASCE test are controlled by horizontal displacement. The loading protocol of the dependency test is a 4-cycle sinusoidal displacement variation with a 200 mm amplitude, as shown in figure 4 (a), and the test procedure is shown in table 2. Additionally, the loading protocol of a 3-cycle ASCE test is shown in figure 4 (b), and the test procedure is determined based on 17.8.2.2 in standard ASCE/SEI 7-16 [7], as shown in table 3. In tables 2 and 3, spec. num. shows the diameter of the slider, pressure is the contact pressure between the slider and the concave plate, amplitude is shown as Amp in figure 4 (b), velocity is the maximum velocity of the loading protocol, period is the effective period of the DCFPB (shown as T in figure 4 (a)) and the accumulated displacement is counted after each test. Three different specimens with identical sizes were used for each slider size for the velocity dependency test, pressure dependency test and ASCE test.

In table 3, two tests with identical loading protocols, T01 and T13, are placed at the beginning and the end of the test to consider the influence of accumulated displacement on the isolator properties. The lateral force of T02 is designed corresponding to wind design, whereas T03~T11 are designed to consider the influence of the rate of loading (velocity and pressure). Test 12 is designed to consider the influence of long duration excitation (for a DCFPB, the influence is mainly determined by the temperature increase caused by friction heating) and is separated into 3 parts because of the limit of the testing machine.



(b)

Figure 4. Loading protocol: (a) dependency test and (b) ASCE test (3 cycles)

Table 2. Test procedure (dependency test)

Spec. num.	Test num.	Pressure	Amplitude	Velocity	Period	Cycle num.	T_0
		N/mm^2	±mm	mm/s	s		°C
				1) Velocity dependency test			
φ300 φ400	T01	60	200	20	62.83	4	19.81
	T02			50	25.13	4	21.42
	T03			100	12.57	4	22.67
	T04			200	6.28	4	23.34
	T05			400	3.14	4	23.82
	T06			600	2.09	4	19.98
	T07			800	1.57	4	22.48
				2) Pressure dependency test			
	T08	40	200	20	62.83	4	20.39
	T09			400	3.14	4	22.21
	T10	80		20	62.83	4	22.76
	T11			400	3.14	4	23.04

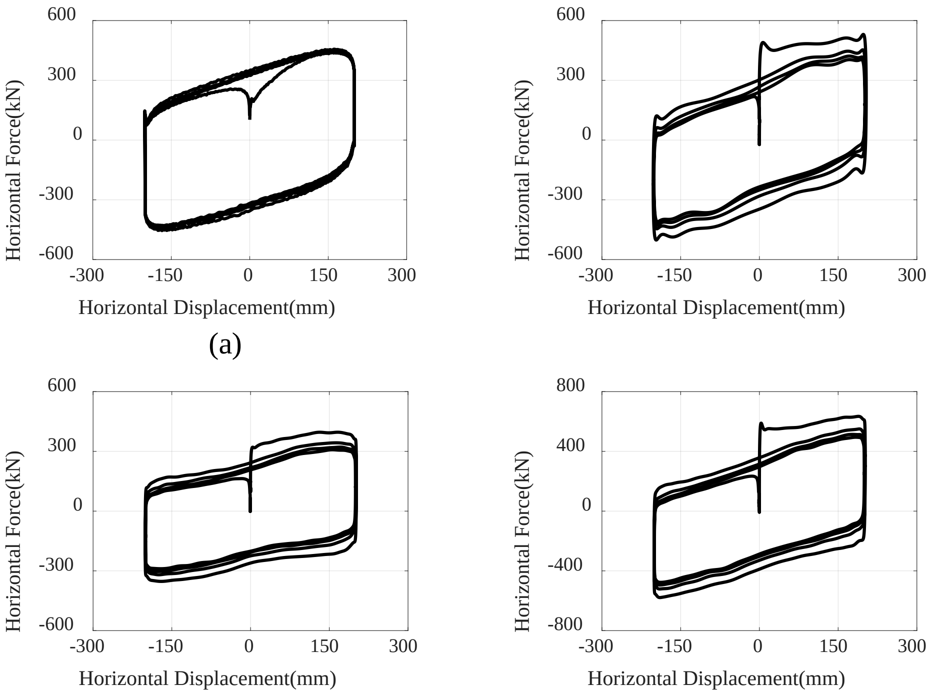
Table 3. Test procedure (ASCE test)

Spec. num.	Test num.	Pressure	Amplitude	Velocity	Period	Cycle num.	Accumulated displacement	T_0
		N\mm^2	±mm	mm/s	s		m	°C
φ300	T01	60	268	392	4.26	3	3.84	20.37
	T02		10	14.646	4.26	20	4.66	22.73
φ400	T03		100	146.369	4.26	3	6.09	22.51
	T04		200	292.738	4.26	3	8.96	22.98

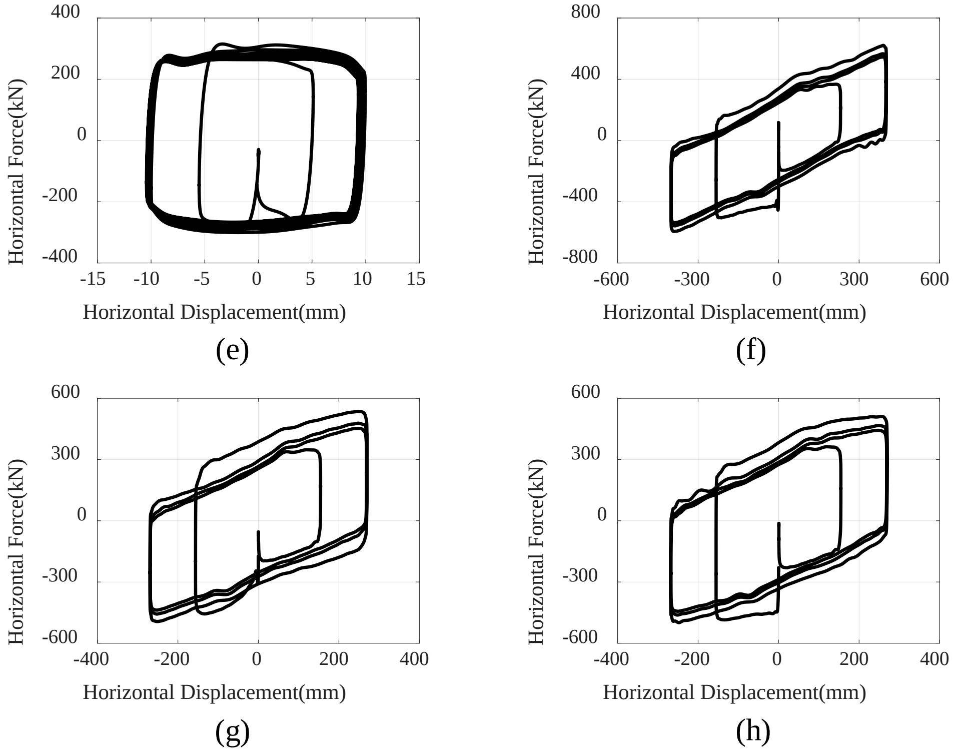
T05		268	392.269	4.26	3	12.79	22.39
T06		400	585.476	4.26	3	18.52	23.36
T07		400	585.476	4.26	3	24.25	22.98
T08	40	400	585.476	4.26	3	29.98	23.09
T09	80	400	585.476	4.26	3	35.71	23.03
T10	30	440	644.024	4.26	1	38.49	23.61
T11	90	440	644.024	4.26	1	41.27	23.63
T12a	60	300	439.107	4.26	7	50.36	20.78
T12b					7	59.46	24.74
T12c					6	67.36	27.49
T13		268	392.269	4.26	3	71.20	24.47

6. Test results

The relationship between horizontal force and horizontal displacement are depicted in following figures 5. The graphs show the stable hysteresis loop regardless the velocity differences (graph (a) and (b)), pressure differences (graph (c) and (d)), and amplitude differences (graph (e) and (f)). Also, from the figure (g) and (h), even after experiencing a cumulative deformation of 67.36m from the beginning of the test, the performance changes is not observed.



(a)



(e) (f) (g) (h)

Figure 6 Horizontal force and displacement cureve

(a) Velocity dependency test(ϕ 400,T01:20mm/s) (b) Velocity dependency test (ϕ 400,T07,800m/s)
(c) Pressure dependency test(ϕ 400,T09,40MPa) (d) Pressure dependency test (ϕ 400,T11,80MPa)
(e) ASCE test(ϕ 400,T02,±10mm) (f) ASCE test(ϕ 400,T07,±400mm) (g) ASCE test(ϕ 400,T01,initial displacement) (h) ASCE test(ϕ 400,T13, after accumulated displacement 67.36m)

7. Conclusion

In this part 1, full scale dynamic loading test of Spherical Sliding Bearing was conducted to evaluate the effects of surface pressure, velocity, and temperature rise due to friction heat on dyanamic behaviour of spherical friction sliding bearings for seismic isolation structures. In the experiment, various conditions (difference in surface pressure depending on the scale of the superstructure, response speed, amplitude, etc.) considered as parameters were used. It was confirmed that stable behaviour was exhibited under any conditions. Later in part 2, FRICTION MODELS, a friction property models considering various dependency were proposed and those were evaluated by comparing it with this part 1experiment results.

8. Acknowledgments

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9. References

[1] V. Quaglini, P. Dubini, C. Poggi. Experimental assessment of sliding materials for seismic isolation systems. Milan, Italy, 2012, Bull Earthquake Eng 10:717–740.

[2] G. Lomiento, N. Bonessio, and G, Benzoni. Friction Model for Sliding Bearings under Seismic Excitation. University of California San Diego, La Jolla, California, 2013, Journal of Earthquake Engineering, 17:1162–1191.

[3] V. Quaglini, M. Bocciarelli, E. Gandelli and P. Dubini. Numerical Assessment of Frictional Heating in Sliding Bearings for Seismic Isolation. Milano, Italy, 2014, Journal of Earthquake Engineering, 18:8, 1198-1216.

[4] M. Kunar, AS. Whittaker and MC. Constantinou. Characterizing friction in sliding isolation bearings. University at Buffalo, Buffalo, NY, USA, 2015, Earthquake Engng Struct. Dyn. 2015; 44:1409–1425

[5] Standard ASCE/SEI 7-16 [2016] Minimum Design Loads and Associated Criteria for Buildings and Other Structures, American Society of Civil Engineers ASCE, Reston, Virginia.

[6] Nishimoto, K. et al. Bearing Stress and Velocity Dependency of Spherical Sliding Bearing through Large-scale Tests, Paper No. 21223, Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan, August, 2016, Kyushu, Japan. (in Japanese).

[7] G. Benzoni and F. Seible, 1998. Design of the Caltrans Seismic Response Modification Device (SRMD) test facility (IWGFR--96), *International Atomic Energy Agency (IAEA), International Working Group on Fast Reactors*, Vienna (Austria), 325 p, p. 101-115