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Development of Spherical Sliding Bearing

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Abstract

The spherical sliding bearing, "NS-SSBTM", is a seismic isolation device which reduces the response of the structure by the earthquake motion for its slider moves on the spherical surface of the concave plate to lengthen the natural period of the structure and its friction for damping. "NS-SSB" has advantages to realize stability and lengthen of natural period easily, and reduce the isolation layer of structure. This paper describes the basic structure of "NS-SSB" and its performance based on various experiments and thermal conductivity analysis.

1. Introduction

The dangers of long-period ground motions that persist over a long time, which have long been acknowledged, are attracting renewed attention after damage caused by such ground motions was recognized after the 2011 off the Pacific coast of Tohoku Earthquake. As a result, seismic isolation systems are required to have larger ultimate deformation and a longer period, causing an increase in the combined use of a rubber bearing and a sliding bearing in pursuit of a longer period. However, the ultimate deformation of a rubber bearing is restricted due to its shape, and the period of a base-isolated story is affected by the variation of rubber materials. In the case of base isolated buildings with a large ratio of live load such as distribution warehouse facilities, it is possible that the period of a base-isolated story may vary depending on the loading conditions.

Spherical sliding bearings are pendular seismic isolation devices, which allow a slider to move on a concave spherical surface. This type of bearing obtains restoring force from the spherical surface, as well as damping performance from the sliding friction. Since the natural period is influenced by the spherical radius alone, it is easier to increase the period than that of the rubber bearing, which is susceptible to the vertical load. In addition, the ultimate deformation can be increased simply by increasing the outside diameter of the spherical surface. While in countries outside Japan many spherical sliding bearings have been successfully used, ^{1, 2} in Japan the prevalence of this type of bearing is yet to prosper although commercialization has been started. ^{3, 4}

One of the possible reasons is that the allowable bearing stress

of the spherical sliding bearing in Japan is equivalent to that of the rubber bearing, making the outside dimensions of the bearing larger for the range of movement of the slider than the rubber bearing. Given this, Nippon Steel & Sumikin Engineering Co., Ltd. developed a spherical sliding bearing called NS-SSB[™], a compact-size bearing unit achieved by using a bearing stress approx. three times higher than that of the conventional spherical sliding bearings. Since NS-SSB was first adopted as the seismic isolation bearing for a distribution warehouse facility in 2014, its use for distribution warehouse facilities and condominium buildings has been increasing. This paper describes the basic structure and characteristics of NS-SSB, and reports the results of the horizontal performance verification based on full-scale tests and of the examination through thermal conductivity analysis.

2. Outline of NS-SSB

2.1 Basic structure of NS-SSB

As shown in **Fig. 1** and **Fig. 2**, NS-SSB is a bearing of double pendulum type using a double sliding surface mechanism that has concave spherical sliding plates on top of and under the slider. The sliding plates are made from stainless steel plates, the surfaces of which are processed into the spherical shape brought to a mirrorequivalent finish, and are attached to other steel plates called concave plates. The slider has a sliding material placed on each upper/ lower surface that is processed to have the same spherical radius as the sliding plates. Many of the conventional spherical sliding bearings use polytetrafluoroethylene (PTFE) resin for the sliding material. The strength of this resin makes the reference bearing stress

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(equivalent to the allowable bearing stress for sustained loading) of spherical sliding bearings equivalent to that of rubber bearings, etc. On the other hand, NS-SSB uses doubled fabric composed of a PTFE fabric and adhesion-enhanced high strength fiber in order to obtain stable frictional force under high bearing stress, which was determined as a result of various basic tests. This allows NS-SSB to achieve a reference bearing stress of 60 MPa, that is approx. three times higher than reference bearing stresses of conventional bearings, or 20 MPa, also allowing NS-SSB to have plane outside dimensions as compact as conventional bearings.

2.2 Behavior and sliding characteristics of NS-SSB

When being subjected to a displacement caused by the story drift at the base-isolated story, the NS-SSB slider moves along the spherical surfaces of the upper and lower sliding plates as shown in Fig. 2(b). The position of the slider is on a straight line that connects the centers (a and b') of the upper/lower spherical surface radiuses moved along with the horizontal displacement. The amount of movement of the slider is 1/2 that of the displacement caused by the story drift at the base-isolated story.

The natural periods of rubber bearings are determined by rubber





stiffness and vertical load. In contrast, NS-SSB has sliding characteristics in which the natural period T_0 of NS-SSB's secondary stiffness is $2\pi\sqrt{(2R_s/g)}$ (g: gravitational acceleration) according to the principle of the pendulum, and is determined by spherical radius R_s alone. Furthermore, as shown in **Fig. 3**, the analytical model of the damping force of the hysteresis loop is theoretically a bilinear model represented by frictional force Q_d and secondary gradient K_2 according to the spherical radius. The coefficient of friction is dependent on velocity, bearing stress, and temperature.

As shown in Fig. 2(c), if the top or bottom concave plate is inclined, the slider position alone moves according to the inclination angle without causing a change in the sliding properties of NS-SSB. For this reason, NS-SSB is hardly affected by the accuracy with respect to the installation surface. This makes NS-SSB suitable for the pile head base-isolating structure, which does not use a footing beam and involves the pile-head rotation angle during an earthquake.

3. Performance Verification Tests for NS-SSB 3.1 Outline of the tests

The horizontal properties of NS-SSB were verified through various performance verification tests conducted on full-scale specimens as shown in **Fig. 4**, using a 2MN biaxial testing machine owned by Nippon Steel & Sumikin Engineering shown in **Fig. 5**. Some of these performance verification tests are described as follows.





Fig. 5 Set-up of experiment





1.50 6 μ(V) / μ(400mm/s) 1.00 0.50 Ο φ200 φ100 0.00 0 100 700 200 300 400 500 600 Velocity, V (mm/s) Fig. 8 Velocity dependence of friction

3.2 Basic performance verification test

A test was conducted to verify the basic performance of NS-SSB including the coefficient of friction, using full-scale specimens with the slider diameter set from 150 mm to 600 mm, spherical surface radius R set to 2500 mm and 4500 mm (natural period of secondary stiffness set to 4.5 seconds and 6.0 seconds). The horizontal load applied was constant-amplitude vibrations sinusoidally-repeated under the vertical load equivalent to the reference bearing stress of 60 MPa. The vertical load was set from 1060 kN to 16960 kN in accordance with the slider diameter, and the horizontal loading condition was four cycles at ± 200 mm amplitude at maximum velocity 20 mm/s. As an example of the test results, Fig. 6 shows hysteresis loops, which is the relationship between the value obtained from horizontal load divided by vertical load at the moment and horizontal displacement, of the specimens with a slider diameter of 350 mm and 500 mm tested . Under such vibration conditions, the coefficient of friction was around 4% to 5%, which might have differed depending on the temperature conditions, exhibiting stable friction history. The secondary stiffness as determined by the spherical radius was also consistent with the design value.

3.3 Ultimate deformation verification test

To verify the horizontal performance at the ultimate deformation of NS-SSB, a test was conducted on full-scale specimens of a slider 200 mm in diameter with spherical radius R_s of 4500 mm, for ultimate deformation up to 600 mm. The horizontal load applied was incremental displacement amplitude vibrations sinusoidally-repeated under a vertical load of 1885 kN, which is equivalent to the reference bearing stress of 60 MPa. The horizontal loading condition was one cycle at each amplitude, maximum amplitude ±600 mm, at the maximum velocity of 20 mm/s. The hysteresis loop is shown in **Fig. 7**. The loop exhibits a continued stable friction history up to the ultimate deformation of 600 mm. The secondary stiffness is also consistent with the design value.

3.4 Various dependency verification tests

As described in a published paper, ⁵⁾ various dependencies of NS-SSB have been tested. However, since the description was on the results of tests conducted using small-scale specimens with slider diameters of 70 mm and 100 mm, we conducted a test on full-scale specimens to verify the dependence on velocity, bearing stress and repetition durability.

(1) Velocity dependency

For good control of the vertical load of the testing machine, single pendulum type specimens were used. We used nine full-scale specimens with a slider diameter of 200 mm. The horizontal load applied was constant-amplitude vibrations sinusoidally-repeated under a vertical load of 1 885 kN equivalent to the reference bearing stress of 60 MPa. The amplitude was set to ± 100 mm (equivalent to ± 200 mm with double pendulum type sliders), the number of cycles four, and loading velocity nine levels from 0.5 to 300 mm/s (equivalent to 1 to 600 mm/s with double pendulum type sliders). Each specimen was tested under multiple velocity conditions. Temperatures were controlled so that the atmospheric temperature and the sliding plate surface temperature were $20^{\circ}C \pm 2^{\circ}C$ at the beginning of the loading.

With respect to the coefficient of friction in the third cycle (Y-intercept values in the friction history), **Fig. 8** shows the ratio of test values at each velocity to the average test value when the velocity converted to that of double pendulum type sliders was 400 mm/s. It indicates a dependence peaking at 50 mm/s seen from the relationship between the temperature increase caused by frictional heat and thermal conductivity. This is consistent with the tendency in the thermal conductivity analysis results described later. The results at 20 mm/s and 100 mm/s differ from the past test results. This is possibly because frictional heat is distributed differently in accordance with the ratio of the sliding area to the slider area, which varies de-

pending on the slider diameter.

(2) Bearing stress dependency

We used five specimens with a slider diameter of 350 mm, and one specimen with a 500 mm diameter. The horizontal load was constant-amplitude vibrations sinusoidally-repeated for four cycles with a maximum velocity of 20 mm/s and amplitude of \pm 200 mm. The bearing stress was set to five levels of 15, 30, 60, 90, and 120 MPa for a 350 mm diameter, and four levels of 5, 10, 30, and 60 MPa for a 500 mm diameter. With respect to the coefficient of friction in the third cycle (Y-intercept values in the friction history), **Fig. 9** shows the ratio of test values at each bearing stress to the average test value at the reference bearing stress of 60 MPa. The fullscale test results of dependency on bearing stress generally correspond well to the results of the past tests that used small-scale specimens at 30 MPa to 120 MPa.

(3) Repetition durability

The past test verified the repetition durability performance of NS-SSB by applying continuous repetitive vibrations to small-scale specimens with a slider diameter of 100 mm. This time, we used full-scale specimens with a slider diameter of 200 mm for testing. In the test, we applied 10 sets of intermittent repetitive vibrations equivalent to the maximum accumulated sliding distance (±200 mm $\times 25$ cycles=20 m) caused by a level 3 earthquake (a huge earthquake that is equivalent to the seismic intensity of 7 on the Japanese seismic scale from 0 to 7 and that may overpower structure design made based on assumed quakes). The maximum velocity was 20 mm/s. The resulting changes in coefficient of friction are shown in Fig. 10 in which the accumulated sliding distance is indicated on the horizontal axis. During the 25-cycle continuous vibrations, the coefficient of friction gradually declines due to frictional heat. It almost returns to the original value during the next loading following an interval. However, since the sliding material wears as a result of intermittent and repetitive loading, the coefficient of friction slightly increases and is approx. 8% higher during the 10th set than that during the 1st set.





4. Consideration of Frictional Properties Using Thermal Conductivity Analysis

4.1 Outline of thermal conductivity analysis

Described in the previous chapter were the results of various performance verification tests using full-scale specimens. However, there are limitations to verifying the dynamic performance of full-scale specimens due to capabilities of the testing machine. Therefore, we have established a method for using thermal conductivity analysis to evaluate the history of temperature and coefficient of friction during repetitive testing for small-scale specimens by setting the relationship between the sliding material's coefficient of friction and temperature as well as the initial value of NS-SSB's coefficient of friction. The details of this thermal conductivity analysis method are described in a reference listed at the end of this paper.⁶⁾ Its analytical model and environmental conditions are as shown in **Fig. 11** with a flat sliding surface with upper/lower surfaces set as adiabatic boundaries and side faces as natural heat transfer surfaces.

The coefficient of friction is determined using the following formula that considers friction surface temperature, velocity, and deterioration,

$$\mu(\theta, v, L) = \mu_{20}^{400*} \{1.13^* e^{-0.006\theta}\}^* \{1 - 0.50^* e^{-0.030v}\}^* W(L)$$

where

- μ_{20}^{400} : The initial coefficient of friction is 0.062 when the bearing stress is 60 MPa, initial temperature 20°C, and velocity 400 mm/s
- θ : Temperature (°C)
- v: Velocity (mm/s)
- W(*L*):Coefficient representing the effect of deterioration according to accumulated sliding distance L (mm)
 - $= 1.0 (L \le 8000)$
 - $= 1.0 + 0.2 * (L 8000) / 52000 (8000 \le L \le 60000)$

Through the thermal conductivity analysis, we examined the friction properties for slider diameters of 150 mm to 500 mm at a velocity of 400 mm/s, and dependence on velocity for a 200 mm diameter as well.

4.2 Results of analysis

(1) Loading velocity and temperature increase

Figure 12 shows temperature distribution at the beginning of the 4th cycle of sliding by applying repeated sinusoidal vibrations for a slider diameter of 200 mm under the condition of the initial temperature set to 20°C, a of velocity 20 mm/s and 400 mm/s, and an amplitude of ± 200 mm. In the case of the 20 mm/s velocity, due to a long loading time, frictional heat that was transferred to the center of the slider and the base plate raised the overall temperature, resulting in a temperature increase of approx. 10°C on the sliding plane after the 3rd cycle. With the 400 mm/s velocity, on the contrary, due to a short loading time, the temperature rose only on the slider's sliding plane. After the 3rd cycle, the temperature increase on the sliding plane was approx. 60°C.

(2) Effect of the slider diameter

The 3rd cycle friction coefficient for each slider diameter after repeated loading under the condition of the initial temperature of 20°C, the velocity of 20 mm/s and 400 mm/s, and the amplitude of \pm 200 mm are plotted on the chart shown in **Fig. 13**. While the slider diameter had little influence with the 20 mm/s velocity, in the case of the 400 mm/s velocity, an upward tendency of the coefficient of friction, although slight, was shown along with the decrease in the diameter of the slider. This is led by a difference in velocity dependency between the 100 mm and 200 mm diameters, as described in 3.4(1), in view of the fact that when the ratio of the sliding area to



Fig. 11 Thermal conductivity analysis model



Fig. 13 Diameter of slider and friction coefficient

the area of the slider increases, frictional heat is distributed. Conversely, when the slider diameter is 200 mm or larger, there is little difference in the ratio of the friction coefficient at 20 mm/s or at 400 mm/s among the slider diameters. If dynamic characteristics can be determined using the 200 mm diameter slider with which full-scale



specimen testing can be conducted, a coefficient of friction of the 400 mm/s velocity can be estimated based on other full-scale test results of the 20 mm/s velocity.

(3) Effect of the velocity

The relationship between the coefficient of friction and velocity during the 3rd cycle with the 200 mm diameter slider is shown in **Fig. 14**. Again in this analysis, the coefficient of friction was larger at medium velocities between 50 mm/s and 200 mm/s than that at 400 mm/s. This shows the same tendency as the result of the velocity dependence test using full-scale specimens with the 200 mm diameter slider as described in 3.4(1).

5. Conclusion

For the spherical sliding bearing NS-SSB, we conducted performance verification tests using full-scale specimens, and clarified the

friction history characteristics, ultimate deformation performance, various dependencies and repetition durability characteristics of the coefficient of friction of NS-SSB. Furthermore, we verified the dynamic performance of full-scale specimens through thermal conductivity analysis.

Having been struck again by the Kumamoto earthquakes in April, 2016, the increase in demand for seismic isolation of buildings is likely to be accelerated in Japan. We will strive to spread the use of NS-SSB, which has advantages such as the capability of lengthening the period of the base-isolated story, compact size, and stable seismic isolation performance against varying live loads. At the same time, we will work on the improvement of NS-SSB including the expansion of the variation regarding the coefficient of friction, ultimate deformation amount, and application to other types of structures besides those in which NS-SSB has been used to date.

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