Presented in this paper is shaking table tests of a bridge isolated by four different sliding bearings in order to investigate the seismic response with emphasis on frictional characteristics of the sliding bearings with different sliding materials, the effect of vertical, transverse excitation and the frictional coefficient difference on seismic responses, and the generation mechanism of vertical force variation at the sliding bearings. The test results showed that combinations of vertical and horizontal excitations as well as longitudinal and transverse excitations generated larger responses compared with merely longitudinal excitation in case of a sliding bearing with high frictional coefficient and large velocity dependence, and that the effect of the four different frictional coefficients on the maximum and residual displacement became clear. Furthermore, it was found that shear keys at rubber buffers might affect vertical force variation at the sliding bearing.

Key Words: seismic isolated bridge, shaking table test, sliding bearing, frictional coefficient, seismic response

1. INTRODUCTION

A seismic isolated bridge with laminated rubber bearings such as lead rubber bearings and high damping rubber bearings, which is intended to decrease the inertia forces during an earthquake by making natural periods of the bridge longer and increasing the damping characteristics, is getting popular after the Hyogo-ken Nanbu Earthquake in 1995. Nevertheless, it is not always cost-effective due to the limitation of applicable sites and structural configurations, as well as relatively high price of the laminated rubber bearing itself. On the other hand, seismic isolation systems using sliding bearings, called “separately functional bearing system”, have recently been used in some cases; the system consists of sliding bearings which carry the vertical force of superstructure and rubber buffers that distribute the horizontal inertia force. As long as frictional force could be controlled properly and sliding behavior could be generated certainly, the system would be an effective way to reduce the influence of seismic motions because inertia force acting at the top of substructure does not exceed the sum of the frictional force at the sliding bearings and restoring force at the rubber buffers. Besides, the system would be superior to the laminated rubber bearing typed isolation bridge in the degree of freedom in designing a seismically isolated bridge.

The separately functional bearing system, however, has not been prevalent for a bridge, and the design method incorporating the effect of frictional damping has not been developed. The reason is mainly that seismic behavior of the bridge with the system has not been clarified well. It has been validated that frictional coefficient of a sliding bearing has bearing pressure dependence and velocity dependence. Besides, vertical force at a sliding bearing varies during an earthquake due to rocking vibration of a girder induced by horizontal seismic motion, vertical inertia force induced by vertical seismic motion, and deflection vibration of a girder induced by vertical seismic motion. Thus, variation of frictional force, the product of the frictional coefficient and the ver-
tical force, makes the seismic behavior complicated\(^3\). Other reasons are assumed that seismic behavior under three dimensional seismic motions has been little examined, as well as that reliability and stability of sliding at the bearing has not been verified well.

Several shaking table tests have been performed by some researchers so far in order to investigate seismic behavior of the separately functional bearing system. Ha et al.\(^9\) and Nagumo et al.\(^5\) verified that the system was effective in reducing the seismic response by conducting unidirectional (horizontal) excitation tests. Okamoto et al.\(^6\) argued the effect of vertical seismic motion on the horizontal seismic response by performing unidirectional (horizontal) excitation tests. Iemura et al.\(^3\) investigated the generation mechanism of vertical force variation at a sliding bearing and a stiffness value of a rubber buffer by conducting unidirectional (horizontal) excitation tests using two different sliding bearings and three different rubber buffers. In addition, they confirmed that vertical seismic motion had little effect on the horizontal seismic response by conducting a two-directional (vertical and horizontal) excitation test. In the investigation, they verified that the vertical seismic response was not affected very much since vertical force variation due to the rocking vibration was cancelled out in respect of a whole bridge (in other words, degree of vertical force decrease at a support was almost the same as degree of vertical force increase at another support) and vertical force variation due to the vertical inertia force did not result in the frictional force variation (in other words, the frictional coefficient decreased as the vertical force increases). Nagashima et al.\(^7\) and Kimoto et al.\(^8\) showed that the system improved the seismic performance under three-dimensional seismic motions and that vertical seismic motion had little effect on the horizontal seismic response by conducting three-directional excitation tests.

However, it can be regarded that the seismic behavior with the system has not been clarified well, though several shaking table tests have been performed as mentioned above. All the past tests intended the system with the most common type of a sliding bearing which uses polytetrafluoroethylene (PTFE) and polished stainless steel (SUS), whereas recently different types of sliding bearings using different materials have been proposed in order to achieve lower and higher frictional coefficient than the common type\(^3,10\). In addition, there remains a question regarding the effect of two-directional (longitudinal and transverse) seismic motions on the each directional seismic response, since the past three-directional excitation tests focused only on the effect of vertical seismic motion on the horizontal seismic response.

Above mentioned background motivated us to perform shaking table tests of a model bridge isolated by four different types of sliding bearings\(^11,12\) at the Public Works Research Institute. This paper reports frictional characteristics of the four types of sliding bearings, the effect of vertical, transverse seismic motion and the frictional coefficient difference on the longitudinal seismic response, and the generation mechanism of vertical force variation at the sliding bearing.

### 2. TEST SPECIMEN

A test specimen used in the tests represents a reduced scale common actual bridge, which is a five-continuous steel I girder bridge\(^13\), not a particular bridge. A similarity law was set as shown in Table 1, so that the bearing pressure of the sliding bearing was scaled by a factor of one. Besides, the ratio of the height of the center of gravity to the width of the girder was conformed to that in the actual bridge, so that the effect of vertical force variation at the sliding bearing due to rocking vibration and vertical inertia force of the girder corresponds to that in the actual bridge\(^5\). The scaling factor (S) was set at seven due to the capacity of a three-components force transducer and the shaking table used in the tests. The dimensional data of the test specimen and

| Table 1 | Table 2 |  |
|---|---|---|
| **Table 1 Similarity law.** | **Table 2 Dimensional data of actual bridge and specimen.** |  |
| **Similarity Law** | **Actual Bridge** | **Specimen** |
| **Scaling Factor** | **Longitudinal Span** | **Bearing Pressure** |
| **[Basal Condition]** | **40 m** | **5.71 m** |
| **Length** | **1/7** | **1/7** |
| **Girder Weight** | **3,158 kN** | **64 kN** |
| **Area** | **64 kN** | **1/7** |
| **Girder Mass** | **5,158 kN** | **129 kN** |
| **Area** | **5,158 kN** | **1/7** |
| **Rubber Buffer Stiffness** | **3362 kN/m** | **23.53 kN/m** |
| **Girder Mass** | **20 N/mm²** | **3362 kN/m** |
| **Resistance Ratio** | **1/72** | **1/72** |
| **Natural Period** | **0.393 sec.** | **0.393 sec.** |
| **Rubber Buffer Stiffness** | **1.04 sec.** | **1.04 sec.** |
| **Rubber Buffer Size** | **0.314 m** | **0.314 m** |
| **Displacement (Disp.)** | **1/7** | **1/7** |
| **Girder Shear Elastic Modulus** | **1/72** | **1/72** |
| **Girder Weight** | **1/72** | **1/72** |
| **Time** | **1/7** | **1/7** |
| **Velocity** | **1/7** | **1/7** |
| **Inertia Force** | **1/7** | **1/7** |
| **Displacement (Disp.)** | **1/7** | **1/7** |
| **Inertia Force/Rubber Buffer Stiffness** | **1/7** | **1/7** |
| **Bearing Pressure** | **6306*2=12,612 kN** | **6306*2=12,612 kN** |
| **Natural Period** | **6306*2=12,612 kN** | **6306*2=12,612 kN** |
| **Rubber Buffer Size** | **371*371*41 mm** | **371*371*41 mm** |
| **Bearing Pressure** | **371*371*41 mm** | **371*371*41 mm** |
| **Girder Mass** | **6,306 kN** | **6,306 kN** |
| **Bearing Pressure** | **1/72** | **1/72** |
| **Inertia Force** | **129 kN** | **129 kN** |
| **Bearing Pressure** | **1/72** | **1/72** |
| **Displacement (Disp.)** | **1/72** | **1/72** |
| **Girder Weight** | **129 kN** | **129 kN** |
| **Bearing Pressure** | **1/72** | **1/72** |
| **Bearing Pressure** | **129 kN** | **129 kN** |
| **Natural Period** | **64 kN** | **64 kN** |
| **Bearing Pressure** | **64 kN** | **64 kN** |
| **Girder Weight** | **3362 kN/m** | **3362 kN/m** |
| **Bearing Pressure** | **3362 kN/m** | **3362 kN/m** |
| **Girder Mass** | **1/72** | **1/72** |
| **Bearing Pressure** | **1/72** | **1/72** |
| **Girder Mass** | **1/72** | **1/72** |
| **Bearing Pressure** | **1/72** | **1/72** |
| **Bearing Pressure** | **1/72** | **1/72** |
| **Bearing Pressure** | **1/72** | **1/72** |

### Notes

1. Assuming two sliding bearings and a rubber buffer at each pier.
2. Assuming two intermediate spans of the continuous bridge.
3. Assuming 500 mm as design displacement, 175 % as design shear strain, 1 N/mm² as shear elastic modulus
4. Assuming a design bearing pressure as 20 N/mm²
the actual bridge are shown in Table 2. Following the similarity law, the span length in the longitudinal direction, the girder spacing in the transverse direction and the superstructure weight of the test specimen were set at 5.71 m, 1.43 m and 257 kN, respectively.

The specimen overview and set up are shown in Fig. 1 and 2, respectively. The test specimen, which focuses on the superstructure and the bearing system, consists of H-beams representing the girder, weights, four sliding bearings and two rubber buffers. The weights were fixed to tops and bottoms of the H-beams in order to adjust the height of the center of gravity. Longitudinal, transverse and vertical directions correspond to X, Y and Z directions, respectively. Four types of sliding bearings with different frictional coefficient and material were used in the tests as shown in Table 3. Type 1 and 2 are the common type consisting of PTFE and SUS, which target 0.10 for Type 1 and 0.15 for Type 2 as frictional coefficient depending on differences of the design bearing pressure and the SUS polishing degree. Type 3 is a high frictional coefficient type consisting of sintered metal and SUS, which targets

### Table 3 Sliding bearings and rubber buffers.

| Type | Sliding Material | Other Material | Design Bearing Pressure | Target Frictional Coeff. | Rubber Buffer (Design Value) |
|------|------------------|----------------|-------------------------|--------------------------|-----------------------------|
| 1    | PTFE = 82 mm     | SUS (No.3 or No.6) | 12 N/mm²                | 0.15                     | Laminated Rubber Bearing (RB) K=3333 kN/m |
| 2    | PTFE = 66 mm     | SUS (mirror finish) | 20 N/mm²                | 0.1                      |                               |
| 3    | Sintered Metal = 75 mm | SUS (No.2B) | 15 N/mm²                | 0.25                     |                               |
| 4    | AFPR = 60 mm     | SUS (fluorinate) | 22 N/mm²                | 0.05                     | Lead Rubber Bearing (LRB) K=17770 kN/m K2=2734 kN/m Qd=76.4 kN (assuming 100% as effective shear strain) |

The specimen overview and set up are shown in Fig. 1 and 2, respectively. The test specimen, which focuses on the superstructure and the bearing system, consists of H-beams representing the girder, weights, four sliding bearings and two rubber buffers. The weights were fixed to tops and bottoms of the H-beams in order to adjust the height of the center of gravity. Longitudinal, transverse and vertical directions correspond to X, Y and Z directions, respectively. Four types of sliding bearings with different frictional coefficient and material were used in the tests as shown in Table 3. Type 1 and 2 are the common type consisting of PTFE and SUS, which target 0.10 for Type 1 and 0.15 for Type 2 as frictional coefficient depending on differences of the design bearing pressure and the SUS polishing degree. Type 3 is a high frictional coefficient type consisting of sintered metal and SUS, which targets
Table 4 Test program.

| Case | Input Motion(1) | X direction | | | Y direction | | | Z direction |
|------|----------------|-------------|---|---|-------------|---|---|-------------|
| | | Sliding | Intensity Level | Sliding | Intensity Level | Sliding | Intensity Level |
| | | Bearing | Max. Acc. (cm/sec²), (Scaling(2)) | | Max. Acc. (cm/sec²), (Scaling(3)) | | Max. Acc. (cm/sec²), (Scaling(4)) |
| | | Command Value | Measured Value | | Command Value | Measured Value | | Command Value | Measured Value |
| 1 | Sinusoidal Wave | Type 1 | 426 | 500 | Type 1 | 500 | 473 | Type 1 | 400 | 362 |
| | Period: 0.5 sec | Type 2 | 350 | 402 | Type 2 | 400 | 374 | Type 2 | 400 | 370 |
| | # of Wave: 10 | Type 3 | 650 | 909 | Type 3 | 650 | 652 | Type 3 | 400 | 370 |
| | | Type 4 | 850 | 1280 | 1238 | -- | -- | -- | -- | -- |
| 2 | Sinusoidal Wave | Type 1 | 425 | 532 | Type 1 | 500 | 473 | Type 1 | 400 | 362 |
| | Period: 0.5 sec | Type 2 | 350 | 532 | Type 2 | 400 | 374 | Type 2 | 400 | 370 |
| | # of Wave: 10 | Type 3 | 850 | 1280 | 1238 | -- | -- | -- | -- | -- |
| | | Type 4 | 425 | 532 | 532 | -- | -- | -- | -- | -- |
| | | Type 2 | 350 | 422 | 422 | -- | -- | -- | -- | -- |
| 3 | Sinusoidal Wave | Type 1 | 425 | 532 | Type 1 | 500 | 473 | Type 1 | 400 | 362 |
| | Period: 0.5 sec | Type 2 | 325 | 402 | Type 2 | 400 | 374 | Type 2 | 400 | 370 |
| | # of Wave: 10 | Type 3 | 650 | 909 | Type 3 | 650 | 652 | Type 3 | 650 | 652 |
| 4 | Sinusoidal Wave | Type 1 | 642(100%) | 754 | --- | --- | --- | --- | --- | --- |
| | Period: 0.5 sec | Type 2 | 642(100%) | 742 | --- | --- | --- | --- | --- | --- |
| | # of Wave: 10 | Type 3 | 862(100%) | 1033 | --- | --- | --- | --- | --- | --- |
| | | Type 4 | 962(100%) | 1314 | --- | --- | --- | --- | --- | --- |
| 5 | Takatori Wave | Type 1 | 425 | 532 | Type 1 | 500 | 473 | Type 1 | 400 | 362 |
| | Type 2 | 425 | 532 | Type 2 | 400 | 374 | Type 2 | 400 | 370 |
| | Type 3 | 850 | 1280 | 1238 | -- | -- | -- | -- | -- |
| 6 | Takatori Wave | Type 1 | 425 | 532 | Type 1 | 500 | 473 | Type 1 | 400 | 362 |
| | Type 2 | 425 | 532 | Type 2 | 400 | 374 | Type 2 | 400 | 370 |
| | Type 3 | 850 | 1280 | 1238 | -- | -- | -- | -- | -- |
| | | Type 4 | 425 | 532 | 532 | -- | -- | -- | -- | -- |
| | | Type 2 | 350 | 422 | 422 | -- | -- | -- | -- | -- |
| 7 | Takatori Wave | Type 1 | 642(100%) | 754 | --- | --- | --- | --- | --- | --- |
| | Type 2 | 642(100%) | 742 | --- | --- | --- | --- | --- | --- |
| | Type 3 | 862(100%) | 1033 | --- | --- | --- | --- | --- | --- |
| | Type 4 | 962(100%) | 1314 | --- | --- | --- | --- | --- | --- |
| 8 | Onneto Wave | Type 1 | 425 | 532 | Type 1 | 500 | 473 | Type 1 | 400 | 362 |
| | Type 2 | 425 | 532 | Type 2 | 400 | 374 | Type 2 | 400 | 370 |
| | Type 3 | 850 | 1280 | 1238 | -- | -- | -- | -- | -- |
| | | Type 4 | 425 | 532 | 532 | -- | -- | -- | -- | -- |
| | | Type 2 | 350 | 422 | 422 | -- | -- | -- | -- | -- |
| 9 | Onneto Wave | Type 1 | 425 | 532 | Type 1 | 500 | 473 | Type 1 | 400 | 362 |
| | Type 2 | 425 | 532 | Type 2 | 400 | 374 | Type 2 | 400 | 370 |
| | Type 3 | 850 | 1280 | 1238 | -- | -- | -- | -- | -- |
| | | Type 4 | 425 | 532 | 532 | -- | -- | -- | -- | -- |
| | | Type 2 | 350 | 422 | 422 | -- | -- | -- | -- | -- |
| 10 | Onneto Wave | Type 1 | 425 | 532 | Type 1 | 500 | 473 | Type 1 | 400 | 362 |
| | Type 2 | 425 | 532 | Type 2 | 400 | 374 | Type 2 | 400 | 370 |
| | Type 3 | 850 | 1280 | 1238 | -- | -- | -- | -- | -- |
| | | Type 4 | 425 | 532 | 532 | -- | -- | -- | -- | -- |
| | | Type 2 | 350 | 422 | 422 | -- | -- | -- | -- | -- |

1) Sinusoidal Wave: Total # of input waves are 22 by adding each 6 taper waves before and after 10 sinusoidal waves

2) Takatori Wave: Amplitude of the JR Takatori Station record during the 1995 Hyogo-ken Nanbu Earthquake (X: NS, Y: EW, Z: UD)(16) are scaled (see Fig. 4.)

3) Onneto Wave: Amplitude of the Onneto Bridge record during the 1994 Hokkaido Toho-oki Earthquake (X: HA, Y: HB, Z: UD)(16) are scaled (see Fig. 4.)

4) Results of 1000cm/sec² are used for discussions of frictional characteristics, whereas results of 850cm/sec² are for discussions of the effect of vertical seismic motion

0.25 as frictional coefficient, whereas Type 4 is a low frictional coefficient type consisting of aramid fiber reinforced plastic (AFRP) and fluorinate SUS, which targets 0.05 as frictional coefficient. Laminated rubber bearings (RB) were used as the rubber buffer and were combined with the sliding bearings of Type 1, 2, and 3. On the other hand, lead rubber bearings (LRB) were used as the rubber buffer and were combined with the sliding bearing of Type 4 intending to make the girder displacement less with the damping effect of the rubber buffers because the frictional damping effect of Type 4 was assumed to be small. Prior to the shaking table tests, performance tests for all the sliding bearings and the rubber buffers were carried out by biaxial testing machines in order to free high stiffness of the rubber buffers at the virgin loading and to grasp the properties.

3. TEST METHODOLOGY

Measurement instrument alignment is shown in Fig. 3. Three three-components force transducers were installed under the four sliding bearings for the measurement of frictional and vertical forces. A test program composed of ten cases as tabulated in Table 4. Although measured values of input motion intensity level departed from command values in some cases due to the limitation of the shaking table reproducibility, the measured values in the same command cases were almost the same in terms of intensity level and phase characteristic. Case 1-4 mainly aims to grasp frictional characteristics of the sliding bearings and the generation mechanism of vertical force variation using sinusoidal wave as the input waveform. Between Case 3 and 4, which were two-directional (X and Z) excitation cases, sinusoidal periods in Z direction were different. Sinusoidal periods in X direction were set as 0.5 second, which is close value to the natural period of the specimen (0.39 second), in order to generate larger response of the specimen and to investigate the frictional characteristics at higher velocity range. Case 5-10 used two strong ground motion records, the JR Takatori.
Station record during the 1995 Hyogo-ken Nanbu Earthquake (Takatori Wave) and the Onnetto Bridge record during the 1994 Hokkaido Toho-oki Earthquake (Onnetto Wave), as the source of input waveform as shown in Fig. 4. Time scales were reduced to 40% (nearly equal to 1/\sqrt{7}) for both records according to the similarity law. Case 6 and 9 were two-directional (X and Z) excitation cases to identify the effect of vertical ground motion by comparing with Case 5 and 8, unidirectional (X) excitation cases. Case 7 and 10 were three-directional (X, Y and Z) excitation cases to identify the effect of transverse ground motion by comparing with Case 6 and 9. Since the shaking table reproducibility was unclear before performing the tests, the intensity level of input motion was increased in steps until the girder displacement reached target value (approximately 72 mm=150% shear strain of the rubber buffer) or the vertical force reached the capacity of the three-component force transducer (Compression: 150 kN, Tension: not uplifted). Accordingly, the intensity level of input motion is different in each type of the sliding bearing. For Type 3, Case 3 and 4 were not performed since the vertical force possibly reached the capacity of the three-components force transducer by vertical excitation. In addition to the ten cases as indicated in Table 4, two more cases, Case (1): X, Y, Z directions - Takatori Wave 100%, Case (2): X direction - Onnetto Wave 250%, Y direction - Onnetto Wave 150%, Z direction - Onnetto Wave 150%, were performed as common inputs for all the four types of sliding bearings in order to investigate the effect of frictional coefficient difference on the seismic response. After completing the ten and two cases of excitation, the girder was hoisted up, then the sliding bearings and the rubber buffers were replaced with next type. Excitation of each type was sequentially performed in order from Case 1, and setup adjustment of the girder was not done between cases since the residual displacement of the girder was only 0.8 cm at the most.

4. FRICTIONAL CHARACTERISTICS OF SLIDING BEARINGS

For all the four types of sliding bearings, sliding behavior occurred as expected in the tests. Fig. 5 shows an example of time histories of frictional
force, vertical force and girder displacement (Type 1, Case 1). The vertical force corresponds to variation from vertical force due to dead load (=64 kN). It was observed that the frictional force at the sliding bearing showed plateaus due to the sliding behavior and hit a peak at the fourth cycle of oscillation, followed by gradual decrease. The vertical force at the sliding bearing decreased by 25 kN at the maximum, whereas increased by only 4 kN, during oscillation. Accordingly, it was assumed that influence of the bearing pressure variation on the frictional characteristics became less prominent in the unidirectional (X) excitation case than in two-directional (X and Z) excitation case since the bearing pressure variation is small, 5 N/mm² in the case (Type 1, Case 1). The generation mechanism of vertical force variation at the sliding bearing will be discussed in chapter 6.

Fig. 6 and 7 show hysteresis loops (frictional coefficient vs. disp.) for Case 1 and 3, respectively. The frictional coefficient corresponds to the value of the frictional force divided by the vertical force of each instant. As indicated in Table 4, Case 1 is the result of the intensity level of 1000 cm/s², whereas Case 3 is that of 850 cm/s², for Type 4.
Frictional coefficients of Type 1 and 2 (PTFE and SUS) came close to around 0.15 and 0.1 from around 0.2 and 0.15 at the beginning as oscillation proceeded, respectively. Hysteresis loops of Case 1, unidirectional (X) excitation case, shaped a rectangle with rounded curves at the four corners, which seems to be responsible for velocity dependence; frictional coefficient decreases near zero of the velocity and becomes constant over around 5 cm/sec\textsuperscript{2}). Hysteresis loops of Case 3, two-directional (X and Z) excitation case, shaped a trapezoid, which seems to be responsible for bearing pressure dependence; frictional coefficient increases as the bearing pressure decreases\textsuperscript{2}). In other words, since the excitations in X and Z directions were done in the same phase and the bearing pressure became the minimum at the minimum displacement, the frictional coefficient increased at the minimum displacement due to the dependence.

Frictional coefficient of Type 3 (sintered metal and SUS) decreased and came close to the constant as oscillation proceeded as in Type 1 and 2. The shape of the hysteresis loops looked like a drum; the frictional coefficient is around 0.4 at the maximum displacement and around 0.2 at the zero displacement. This seems to be mainly responsible for velocity dependence; frictional coefficient reaches the largest near zero of the velocity and decreases as the velocity increases\textsuperscript{9}).

Frictional coefficient of Type 4 (AFRP and fluorinate SUS) came close to around 0.03 from around 0.05 at the beginning as oscillation proceeded as in other types. The shape of the hysteresis loops looked like a drum due to the velocity dependence as in Type 3\textsuperscript{10}).

Fig. 8 and 9 show hysteresis loops (frictional coefficient vs. girder displacement) and the dependences of frictional coefficient obtained from the per-
formance tests, which were carried out by biaxial testing machines prior to the shaking table tests, respectively. Hysteresis loops of the performance tests under velocity and bearing pressure condition close to Case 1 are selected. By comparing between Fig. 6 and 8, results of the performance tests showed good agreement with those of the shaking table tests in the hysteresis loops, though local peaks of the frictional coefficient were seen at the first cycle of oscillation in the performance tests of Type 1, 3 and 4, and the frictional coefficient of Type 3 with large velocity dependence in the performance tests was larger than in the shaking table tests by 15 %. It seems that the coefficient were seen at the first cycle of oscillation hysteresis loops, though local peaks of the frictional force possibly decreases to a large extent due to the significant velocity dependence as indicated in Fig. 10. The hysteresis loops (frictional force vs. girder displacement), frictional force in the case of 771 cm/sec^2 was increased in steps as mentioned above, and the intensity level of input motion may cause large difference of seismic response in two-directional excitation cases. In fact, the intensity level of input motion on the horizontal seismic response will be larger and the girder displacement became 1.7 times at the largest. Since, when once the girder move, frictional force possibly decreases to a large extent due to the significant velocity dependence as indicated in Fig. 10. The hysteresis loops (frictional force vs. girder displacement), frictional force of the testing machine, for the performance tests.

5. EFFECTS OF SEVERAL FACTORS ON SEISMIC RESPONSE

(1) Effect of vertical seismic motion

Table 5 shows the maximum girder displacement, acceleration and dissipated energy at sliding bearings in the unidirectional (X) excitation and two-directional (X and Z) excitation cases. By comparing both cases, the effect of vertical seismic motion on the horizontal seismic response will be discussed here.

For Type 1 and 2, differences between both cases were relatively small, about 15% at the largest. For Type 3, responses of two-directional excitation cases were larger and the girder displacement became 1.7 times at the largest. Since, when once the girder move, frictional force possibly decreases to a large extent due to the significant velocity dependence as indicated in Fig. 6 and 9, slight difference of input motion intensity level may cause large difference of seismic response in two-directional excitation cases. In fact, the intensity level of input motion was increased in steps as mentioned above, and the maximum girder displacement was about 12 cm in a sinusoidal wave excitation case with the intensity level of 771 cm/sec^2, whereas only 1 cm with the level of 705 cm/sec^2, as indicated in Fig. 10.

Table 5 Effect of vertical seismic motion.

| Sliding Bearing | Input Case | Max. Girder Disp. in X Dir. (mm) | Max. Girder Acc. in X Dir. (cm/sec^2) | Dissipated Energy at 4 Sliding Bearings in X Dir. (kN*cm) |
|-----------------|-----------|---------------------------------|--------------------------------------|--------------------------------------------------|
| Type 1          | 1 w/o Z Input | 74.5 | 1.725 | 14,232 |
|                 | 3 with Z Input  | 83.7 | 1.900 | 15,583 |
|                 | 5 w/o Z Input  | 57.5 | 1.788 | 15,341 |
| Type 2          | 1 w/o Z Input  | 94.1 | 1.016 | 8,731 |
|                 | 3 with Z Input  | 72.1 | 1.604 | 10,742 |
| Type 3          | 1 w/o Z Input  | 58.9 | 1.331 | 5,592 |
|                 | 3 with Z Input  | 75.1 | 1.298 | 5,497 |
| Type 4          | 1 w/o Z Input  | 43.5 | 1.005 | 6,734 |

1) (w/o Z Input)/(with Z Input)
cm/sec² dropped to about 50 kN at the zero displacement, while frictional force in the case of 705 cm/sec² was about 150 kN. **Fig. 11** shows time histories of girder displacement during zero to ten second, and vertical force, frictional force and inertia force near four second of Case 6. Inertia force corresponds to the product of girder mass and plus and minus inverted acceleration recorded by an accelerometer mounted on the girder. It shows that the inertia force fluctuated on the same level with the frictional force until the girder started to move, and then exceeded it after the girder started to move, when the vertical force and the frictional force descended as designated at a broken line circle in the figure. Therefore, it is likely that the descent of frictional force associated with the descent of vertical force triggered the girder movement and the larger girder displacement was generated in the case with vertical seismic motion.

For Type 4, responses of two-directional excitation cases were larger in sinusoidal wave excitation cases and the girder displacement became 3.4 times at the largest, whereas responses of two-directional excitation cases were almost the same as those of unidirectional excitation cases in the strong ground motion record cases. Although one reason of this larger responses in two-directional excitation cases may be the velocity dependence of frictional coefficient as in the case of Type 3, the main reason seems to be the shear stiffness reduction of LRBs due to the temperature raise since frictional coefficient is low and the frictional effect is small. As indicated in **Fig. 12**, hysteresis loops (frictional force and restoring force vs. girder displacement), frictional force was relatively small compared with restoring force at LRBs and stiffness of LRBs in Case 1 was higher than in other cases. The restoring force at LRBs corresponds to the subtraction of frictional force at the sliding bearings from inertia force, which is the product of the girder mass and recorded accelerations at the girder. It may be that temperature of lead plugs in LRBs significantly raised when performing Case 3 and 4 due to many excitations until then including the case generated 200 % shear strain and short interval time, approximately 10 - 15 minutes, between cases. Since a hysteresis loop (force vs. displacement) of a LRB has been verified to be dependent on the temperature, this dependence seems to have affected on the hysteresis loop, and therefore the girder displacement.

As stated above, although vertical seismic motion had little effect on the horizontal seismic response for Type 1 and 2, vertical seismic motion generated larger horizontal seismic response for Type 3 with high frictional coefficient and significant velocity dependence. Besides, for Type 4, frictional force at sliding bearings was relatively small compared with restoring force at LRBs and temperature dependence of a LRB might affected on the seismic response in some cases.
Effect of transverse seismic motion

Table 6 shows the maximum girder displacement, acceleration and dissipated energy at sliding bearings in the two-directional (X and Z) excitation cases and three-directional (X, Y and Z) excitation cases. By comparing both cases, the effect of transverse seismic motion on longitudinal seismic response will be discussed here.

For Type 1, 2 and 4, differences between both cases were relatively small, about 10 % at the largest.

For Type 3, there was a case that the girder displacement with transverse seismic motion became 1.7 times of that without transverse seismic motion. Although one reason of this larger response in the case with transverse seismic motion may be that transverse seismic motion might trigger the girder movement as in the case of the influence of vertical seismic motion, the other reason seems to be the reduction of frictional coefficient in the longitudinal (X) direction due to the girder movement in the transverse (Y) direction. As indicated in Fig. 13, hysteresis loops (frictional coefficient vs. girder displacement), frictional coefficient in X direction of Case 7 with Y direction input was below that in X direction of Case 6 without Y direction input. The cause of this reduction seems that deviation of sliding vector from X direction led frictional force in X direction to be the component of frictional force in sliding vector as is seen from comparison of frictional coefficients between in X direction and in resultant direction in Fig. 13. Trajectory of the girder is shown in Fig. 14. Furthermore, another reason seems that frictional coefficient of Case 7 decreased more due to the velocity dependence since the maximum velocities were 39.8 cm/sec in Case 6, 60.7 cm/sec in Case 7, respectively. However, comparison between Case 9 and 10 showed the opposite

| Sliding Bearing | Input Case | Max. Girder Disp. in X Dir. | Max. Girder Acc. in X Dir. | Dissipated Energy at 4 Sliding Bearings in X Dir. |
|-----------------|------------|-----------------------------|----------------------------|---------------------------------|
|                 |            | (mm)                        | (cm/sec²)                  | (kN*cm)                        | Ratio¹)                         |
| Type 1          | 6 w/o Y Input | 46.7                        | 1.08                       | 2.799                          |                                 |
|                 | 7 with Y Input | 50.9                        | 1.09                       | 3.031                          | 1.08                            |
|                 | 9 w/o Y Input | 41.4                        | 1.01                       | 8.731                          |                                 |
| Type 2          | 10 with Y Input | 42.4                        | 1.02                       | 8.456                          | 0.97                            |
|                 | 6 w/o Y Input | 57.1                        | 1.314                      | 3.292                          | 0.94                            |
|                 | 7 with Y Input | 57.1                        | 1.314                      | 3.292                          |                                 |
| Type 3          | 9 w/o Y Input | 43.9                        | 1.09                       | 6.686                          |                                 |
|                 | 10 with Y Input | 44.7                        | 1.02                       | 6.263                          | 0.94                            |
| Type 4          | 6 w/o Y Input | 28.7                        | 1.003                      | 2.182                          |                                 |
|                 | 7 with Y Input | 49.1                        | 1.297                      | 2.835                          | 1.31                            |
|                 | 9 w/o Y Input | 30.2                        | 1.087                      | 6.413                          |                                 |
|                 | 10 with Y Input | 27.4                        | 0.91                       | 5.481                          | 0.85                            |
| Type 4          | 6 w/o Y Input | 27.0                        | 1.435                      | 892                            |                                 |
|                 | 7 with Y Input | 25.6                        | 1.419                      | 771                            | 0.86                            |
|                 | 9 w/o Y Input | 29.5                        | 1.568                      | 3.194                          |                                 |
|                 | 10 with Y Input | 28.6                        | 0.97                       | 2.541                          | 0.80                            |

1) (w/o Y Input)/(with Y Input)
result; the girder displacement with transverse seismic motion became 0.9 times of that without transverse seismic motion. This reason was assumed that the intensity level of input motion in X direction of Case 9 was larger than of Case 10 by about 100 cm/sec², while the intensity levels of input motion of Case 6 and 7 were almost the same, as shown in Table 4. Therefore, it seems reasonable to say that horizontal two-directional (X and Y) excitation possibly affect the response of each direction due to the decrease of apparent frictional coefficient in each direction, especially for Type 3 with high frictional coefficient and large velocity dependence.

As stated above, although transverse seismic motion had little effect on the longitudinal seismic response for Type 1, 2 and 4, there was a case that the girder displacement in the longitudinal direction became 1.7 times by the input of transverse seismic motion for Type 3.

(3) Effect of frictional coefficient difference
Table 7 shows the maximum girder displacement, acceleration and dissipated energy at sliding bearings of the two common input cases, Case (1) and (2). By comparing the results of Type 1, 2 and 3, which were

Table 7 Effect of frictional coeff. difference.

(a) Case (1): X, Y, Z Dir. - Takatori Wave 100 %

| Sliding Bearing | 1     | 2     | 3     |
|----------------|-------|-------|-------|
| X Dir.         | Max. Girder Disp.(mm) | 49.7  | 56.0  | 27.0  |
|                | Max. Girder Acc.(cm/sec²) | a)  | 1,159 | 1,280 | 850   |
|                | Max. Input Acc.(cm/sec²) | b)  | 771   | 764   | 769   |
|                | Ratio [a/b]                | 1.50 | 1.68  | 1.11  |
|                | Dissipated Energy at 4 Sliding Bearings (kN*cm) | 2,855 | 3,236 | 1,505 |
|                | Dissipated Energy at 2 Rubber Buffers (kN*cm) | 676   | 1,194 | 22    |
| Y Dir.         | Max. Girder Disp.(cm)     | 3.32  | 4.03  | 1.39  |
|                | Max. Girder Acc.(cm/sec²) | a)  | 744   | 846   | 796   |
|                | Max. Input Acc.(cm/sec²) | b)  | 771   | 799   | 790   |
|                | Ratio [a/b]                | 0.96  | 1.06  | 1.01  |
|                | Dissipated Energy at 4 Sliding Bearings (kN*cm) | 1,972 | 1,735 | 1,374 |
|                | Dissipated Energy at 2 Rubber Buffers (kN*cm) | 292   | 637   | 61    |
|                | Dissipated Energy at 4 Sliding Bearings (kN*cm) | 4,827 | 4,971 | 2,879 |
|                | Dissipated Energy at 2 Rubber Buffers (kN*cm) | 968   | 1,831 | 83    |
|                | Dissipated Energy at 4 Sliding Bearings and 2 Rubber Buffers (kN*cm) | 5,795 | 6,802 | 2,962 |

(b) Case (2): X Dir. - Onnetto Wave 250 %, Y Dir. - Onnetto Wave 150 %, Z Dir. - Onnetto Wave 150 %

| Sliding Bearing | 1     | 2     | 3     |
|----------------|-------|-------|-------|
| X Dir.         | Max. Girder Disp.(mm) | 44.1  | 45.9  | 25.1  |
|                | Max. Girder Acc.(cm/sec²) | a)  | 1,070 | 1,072 | 1,007 |
|                | Max. Input Acc.(cm/sec²) | b)  | 1,153 | 1,147 | 1,143 |
|                | Ratio [a/b]                | 0.93  | 0.93  | 0.88  |
|                | Dissipated Energy at 4 Sliding Bearings (kN*cm) | 8,456 | 6,263 | 5,481 |
|                | Dissipated Energy at 2 Rubber Buffers (kN*cm) | 292   | 637   | 61    |
| Y Dir.         | Max. Girder Disp.(cm)     | 2.54  | 2.74  | 0.93  |
|                | Max. Girder Acc.(cm/sec²) | a)  | 681   | 664   | 738   |
|                | Max. Input Acc.(cm/sec²) | b)  | 639   | 621   | 636   |
|                | Ratio [a/b]                | 1.07  | 1.07  | 1.16  |
|                | Dissipated Energy at 4 Sliding Bearings (kN*cm) | 4,079 | 2,851 | 5,061 |
|                | Dissipated Energy at 2 Rubber Buffers (kN*cm) | 162   | 529   | 226   |
|                | Dissipated Energy at 4 Sliding Bearings (kN*cm) | 12,535 | 9,114 | 8,542 |
|                | Dissipated Energy at 2 Rubber Buffers (kN*cm) | 1,072 | 1,709 | 721   |
|                | Dissipated Energy at 4 Sliding Bearings and 2 Rubber Buffers (kN*cm) | 13,607 | 10,823 | 9,263 |
combined with identical RBs, the effect of frictional coefficient difference (frictional coefficient: Type 3> Type 1> Type 2) on seismic response will be discussed here.

The maximum girder displacement was in order of Type 2> Type 1> Type 3 in both cases. Dissipated energy at sliding bearings did not show a definite correlation; it was in order of Type 2> Type 1> Type 3 in Case (1), while Type 1> Type 2> Type 3 in Case (2). As shown in Fig. 15, hysteresis loops (frictional force vs. girder displacement), magnitude order of the dissipated energy for Type 1 and 2 was dominated by girder displacement in Case (1), whereas by frictional force in Case (2). Acceleration amplification ratio (the maximum girder acceleration/the maximum input acceleration) did not show a definite correlation as well; the maximum ratio was 1.7 in Case (1), while the maximum girder acceleration reduced to about 90% in X direction for all the three types in Case (2). It should be noted here that rubber buffer stiffness used in the tests was determined referring to a common actual bridge as described in Chapter 2, not intending to reduce the acceleration amplification ratio. In other words, the test specimen used in this tests modeled a superstructure, a part of an isolated bridge, and the natural period must be longer than the one so that acceleration response spectrum of input seismic motions are below peak accelerations of the input motions, if intending to reduce the acceleration amplification ratio of a SDF system like the specimen.

Residual displacement seems to be proportion to the frictional coefficient since it possibly becomes as large as that so that frictional force is equal to restoring force of a rubber buffer. Indeed, the test results showed the tendency; mean values of residual displacement in all the excitation cases were 0.8 mm for Type 1, 1.7 mm for Type 2, 3.8 mm for Type 3 and 0.4 mm for Type 4.

As stated above, although sliding bearing with larger frictional coefficient generated smaller girder displacement and larger residual displacement, dissipated energy at sliding bearings and acceleration amplification ratio did not show a definite correlation with frictional coefficient. Therefore, in designing a seismically isolated bridge, frictional coefficient should be carefully determined based on design policy; which factor should be focused in terms of energy dissipation at sliding bearings, reduction of girder response.

6. GENERATION MECHANISM OF VERTICAL FORCE VARIATION AT SLIDING BEARINGS

It is pointed out that vertical force at a sliding bearing varies during an earthquake due to the following three factors3), and contribution of each factor on vertical force variation will be discussed here.

(a) Rocking vibration of girder induced by horizontal seismic motion
(b) Vertical inertia force induced by vertical seismic motion.
(c) Deflection vibration of girder induced by vertical seismic motion.

Fig. 16 shows time histories of vertical forces at two supports in the opposite side of shaking direction in Case 1, 2 and 3, and the sum of vertical force at four supports in Case 1 during eight to twelve second for Type 1. Vertical force corresponds to variation from vertical force due to dead load (=64 kN). In Case 1, although vertical forces at two supports alternately decreased, they scarcely increased. In Case 2, although vertical forces at two supports alternately increased and decreased, the extent of decrease was dominant. This variation seems to mainly come from factor (a), if so, the sum of vertical force at four supports does not vary inevitably because the girder compresses one support and floats at the other support at the same time. The sum of vertical force at four supports, however, decreased by about 40 kN, and this means vertical force was carried by other than four supports. During excitations...
of the tests, contact between upper surface of the rubber buffers and lower surface of sole plates was not observed by visual check. When the girder was hoisted up, biting of shear keys, which transmit shear force between the girder and the rubber buffers, into sole plates with rotating was observed as indicated in Fig. 17. These situations resulted in assumption of influence by the shear keys on the two rubber buffers. In other words, although 5 mm clearance between the upper surface of the rubber buffer and the lower surface of the sole plate was set and set bolts were not tightened up for the rubber buffers not to carry vertical force, it was assumed that the girder rose up over the rotating shear keys and the rubber buffers carried vertical force during oscillation as schematized in Fig. 18.

Supposing the effect of shear keys was one of the factors on vertical force variation, contribution of each factor on the maximum vertical force variation of Fig. 16 will be examined here. Contributions of factor (a), (b) were calculated by the maximum horizontal and vertical accelerations recorded at the girder. Even though quantitative evaluation of the effect of shear keys is difficult, 15 kN uplift was
assumed to act at the both rubber buffers at the maximum displacement in the three cases since the maximum displacements in the three cases were almost the same, around 7 or 8 cm. This uplift value comes from back calculation not to conflict in the three cases, assuming that the value was proportion to the girder displacement. Contribution of factor (c) was ignored because the girder stiffness of the specimen did not followed the similarity law and vertical force variation calculated by the maximum vertical amplified accelerations recorded at the center of the girder were small enough, 2 or 4 kN per support. The maximum vertical force variation due to each factor was estimated as follows;

- Factor (a)
  \( (\text{Max. Horizontal Acc. at Girder})*(\text{Girder Mass})* \frac{(\text{Height of Center of Gravity})}{(\text{Span Length})}/2 \)
- Factor (b)
  \( (\text{Max. Vertical Acc. at Girder})*(\text{Girder Mass})/4 \)
- Factor due to Effect of Shear Keys

Assuming 15 kN uplift

**Fig. 19** shows the estimated contributions of three factors on the maximum vertical force variation. Supposing the maximum vertical force variation due to each factor occurred at the same time of the maximum displacement even though there might be a little influence by the damping, the sum of the estimated contributions was almost equivalent to the maximum recorded vertical force variation in **Fig. 16**. Thus, the maximum recorded vertical force variation could be divided into contributions of three factors supposing the effect of shear keys was one of the factors on vertical force variation. Arrhythmic time histories of vertical force in Case 3 compared to those in Case 1 and 2 seems to be responsible for arrhythmic behavior of shear keys due to vertical seismic motion.

As stated above, in addition to three factors, which have been pointed out by other researchers, it is likely that the effect of shear keys was one of the factors on vertical force variation at sliding bearings. Therefore, it seems important that details of rubber buffers, especially shear keys, should be carefully designed not to carry vertical force. Otherwise, unexpected seismic behavior would possibly occur since vertical force variation leads to variations in frictional coefficient and frictional force.

**7. CONCLUSIONS**

In order to investigate a bridge isolated by sliding bearings with emphasis on the frictional characteristics of sliding bearings, the effect of vertical, transverse seismic motion and the frictional coefficient difference on the longitudinal seismic response, and the generation mechanism of vertical force variation at the sliding bearing, shaking table tests were performed using four different types of sliding bearings. Below are the conclusions obtained from the tests:

1. Frictional characteristics of four types of sliding bearings, Type 1 and 2 (PTFE and SUS), Type 3 (sintered metal and SUS), Type 4 (AFRP and fluorinate SUS), were verified. Hysteresis loops (frictional coefficient vs. girder displacement) obtained from sinusoidal excitation tests of Type 1 and 2 shaped a rectangle, whereas those of Type 3 and 4 looked like a drum due to the velocity dependence. Besides, frictional coefficients of all the four types decreased and came close to constant values as oscillation proceeded.

2. Hysteresis loops (frictional coefficient vs. girder displacement) obtained from performance tests by biaxial testing machines were equivalent to those from shaking table tests for all the four types of sliding bearings.

3. Sliding behavior occurred as expected and frictional force estimated from a performance test was generated in the tests for all the four types of sliding bearings.

4. Although vertical seismic motion had little effect on the horizontal seismic response for Type 1 and 2, vertical seismic motion generated larger horizontal seismic response for Type 3 with high frictional coefficient and large velocity dependence. Besides, for Type 4, frictional force at sliding bearings was relatively small compared with restoring force at LRBs and temperature dependence of a LRB might affected on the seismic response in some cases.

5. Although transverse seismic motion had little effect on the longitudinal seismic response for Type 1, 2 and 4, there was a case that the girder displacement in the longitudinal direction became 1.7 times by the input of transverse seismic motion for Type 3.

6. Although sliding bearing with larger frictional coefficient generated smaller girder displacement and larger residual displacement, dissipated energy at sliding bearings and acceleration amplification ratio did not show a definite correlation with frictional coefficient.

7. In addition to generally mentioned three factors, rocking vibration of the girder, vertical inertia force and deflection vibration of the girder, it is likely that the effect of shear keys was one of the factors on vertical force variation at sliding bearings. Therefore, it seems important that details of rubber buffers, especially shear keys, should be carefully designed not to carry vertical force. Otherwise, unexpected seismic behavior would possibly occur since vertical force varia-
tion leads to variations in frictional coefficient and frictional force.

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