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# SHAKING TABLE TEST FOR FRICTIONAL ISOLATED BRIDGES AND TRIBOLOGICAL NUMERICAL MODEL OF FRICTIONAL ISOLATOR

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## SUMMARY

Several experimental studies of frictional isolators suggest that the coefficient of friction depends on the sliding velocity and the normal pressure. Therefore people are concerned about the impact of the seismic response of frictional isolated bridges. In this study, in order to investigate the effect of variational normal load of isolators on seismic response of bridges, the shaking table tests were conducted. The specimen was a 5 x 3 m girder model supported by a set of 4 frictional isolators and 2 rubber buffers. As factors of causing the variational normal load at isolators in the bridge system, (1) inertia force of the girder due to the vertical motion and (2) rocking behavior of the girder due to the horizontal motion were taken into account. From the tests, it is observed that the hysteretic shape of each isolator was trapezoid and the coefficient of friction varied largely due to the horizontal and vertical ground motion. However adding all hysteresis loops of the isolators, the effect of the rocking behavior of the girder was canceled and the resultant hysteresis loop becomes rectangular shape. As the results it is found that the large amount of hysteretic damping of frictional isolators can be expected even under the variational normal force. Next, in order to express the normal pressure and sliding velocity dependency of frictional force, the numerical model was developed based on the tribology theory and the property of materials. Compared with the experimental results, it is found that the numerical model can simulate well the behavior of frictional isolators under variational normal pressure and sliding velocity.

## INTRODUCTION

After the Hyogo-ken Nanbu Earthquake, the advantage of the seismic isolator has been recognized and a variety of isolators has been developed and adopted in the construction and retrofit of bridges and buildings. A frictional isolation system is one kind of seismic isolators and consists of frictional isolators

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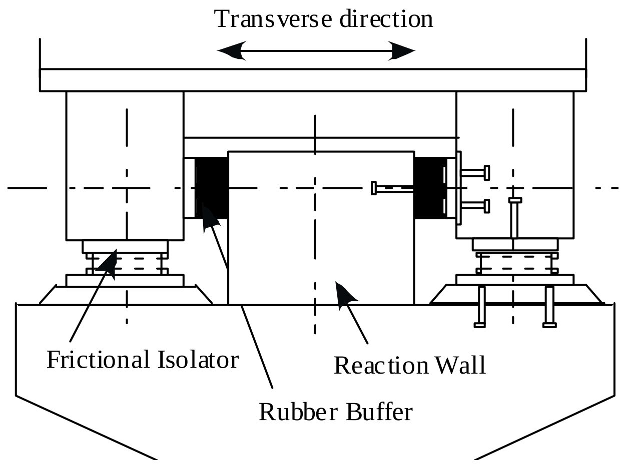



**Figure 1: Frictional isolation system**

and rubber buffers. Since the capability of energy dissipation of frictional isolators depends on the normal load, we have to pay attention to the variation of the normal load. Furthermore the actual coefficient of friction is not constant as the Coulomb's law says. It depends on not only the sliding velocity but also the normal pressure on isolators. Some concerns have been expressed about the seismic performance of frictional isolated bridges. Okamoto et al. has examined the dynamic behavior of bridges with sliding type base isolation system [1, 2]. Authors also have investigated the seismic response by the pseudodynamic test, considering factors fluctuating the normal force of isolators in continuous bridge system [3, 4]. On the other hand, many numerical models for frictional isolators have been proposed, which can take into account the sliding velocity or the normal pressure dependency. Constantinou et al. proposed the velocity dependent model for the coefficient of friction [5]. This exponential model is widely used in many researches. And some normal pressure dependent models are also proposed [6]. The problem in these modeling is that they are developed based on the experimental results. Therefore it is suspicious that the proposed model can be used for other isolators. In this paper, the shaking tests of bridges with the frictional isolators were conducted in order to evaluate the seismic response with the variational normal load and sliding velocity due to the seismic response of the girder. Moreover the numerical frictional force model is developed based on the tribology theory.

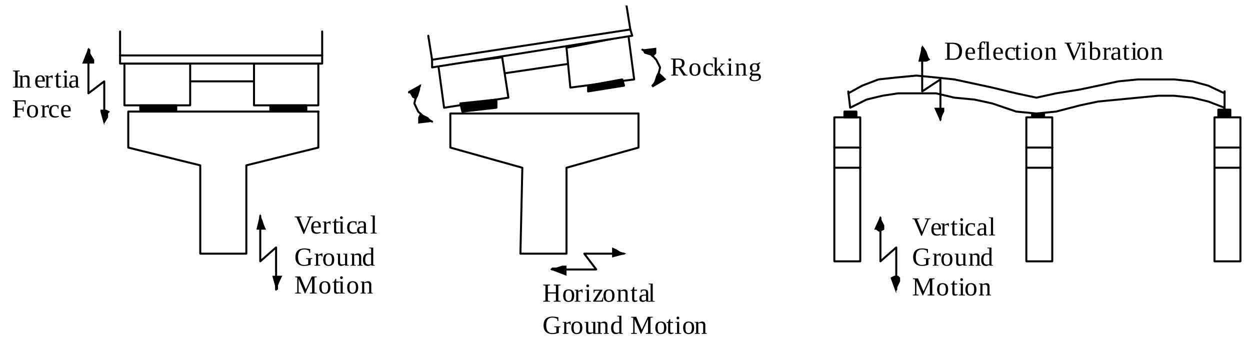
## FRICTIONAL ISOLATION SYSTEM

The frictional isolation system consists of the frictional isolators which support the superstructure and provide the energy dissipation and the rubber buffers which set the natural period and provide the restoring force. The most common interface of the frictional isolator consists of polytetrafluoroethylene (PTFE) in contact with polished stainless steel (SUS). Since the rubber buffers don’t have to support any weight of the superstructure, they can be designed as small as possible. As the results, it is possible to reduce the cost. The typical frictional isolation system is shown in Figure 1.

## CHARACTERISTICS AND CONSIDERATIONS OF FRICTIONAL ISOLATORS

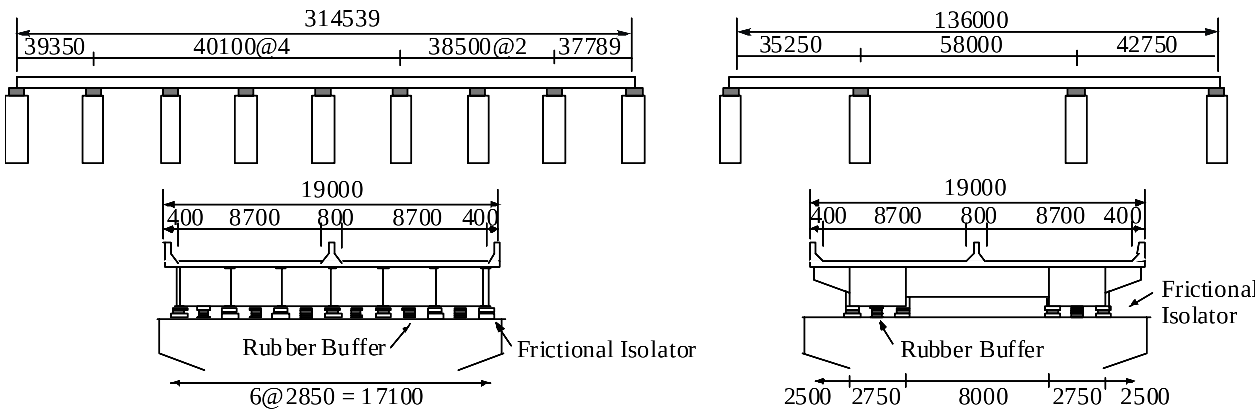
### Friction properties of PTFE in contact with SUS

According to the Coulomb’s law, the coefficient of friction is independent from the normal pressure and the sliding velocity on the frictional surface. However it is only the empirical law and from the recent experiments on the friction between PTFE and SUS, it is observed that




(Factor A) (Factor B) (Factor C)

**Figure 2: Factors of conjugating the normal force on isolators in continuous bridge system**




Bridge 1: I Girder Model Bridge 2: Box Girder Model

**Figure 3: Prototype bridges**

- Friction increases with increasing sliding velocity up to a certain point after which it remains constant or decreases gradually.
- Friction decreases with increasing normal pressure.
- Friction changes by the roughness and the temperature.

**Mechanism of variation of normal force of isolators**

Considering the installation of isolators to bridge structures, there are some factors which conjugate the normal force of the isolators as follows (Figure 2):

a) Inertial force of the girder due to vertical ground motions
b) Rocking behavior of the girder due to horizontal ground motions
c) Deflection vibration of the girder due to vertical ground motions

The variational normal force conjugates the coefficient of friction and the frictional force which is expressed by the product of them is varied complicatedly. Therefore some concerns have been expressed about the seismic performance of the frictional isolated bridges under the variational normal force.

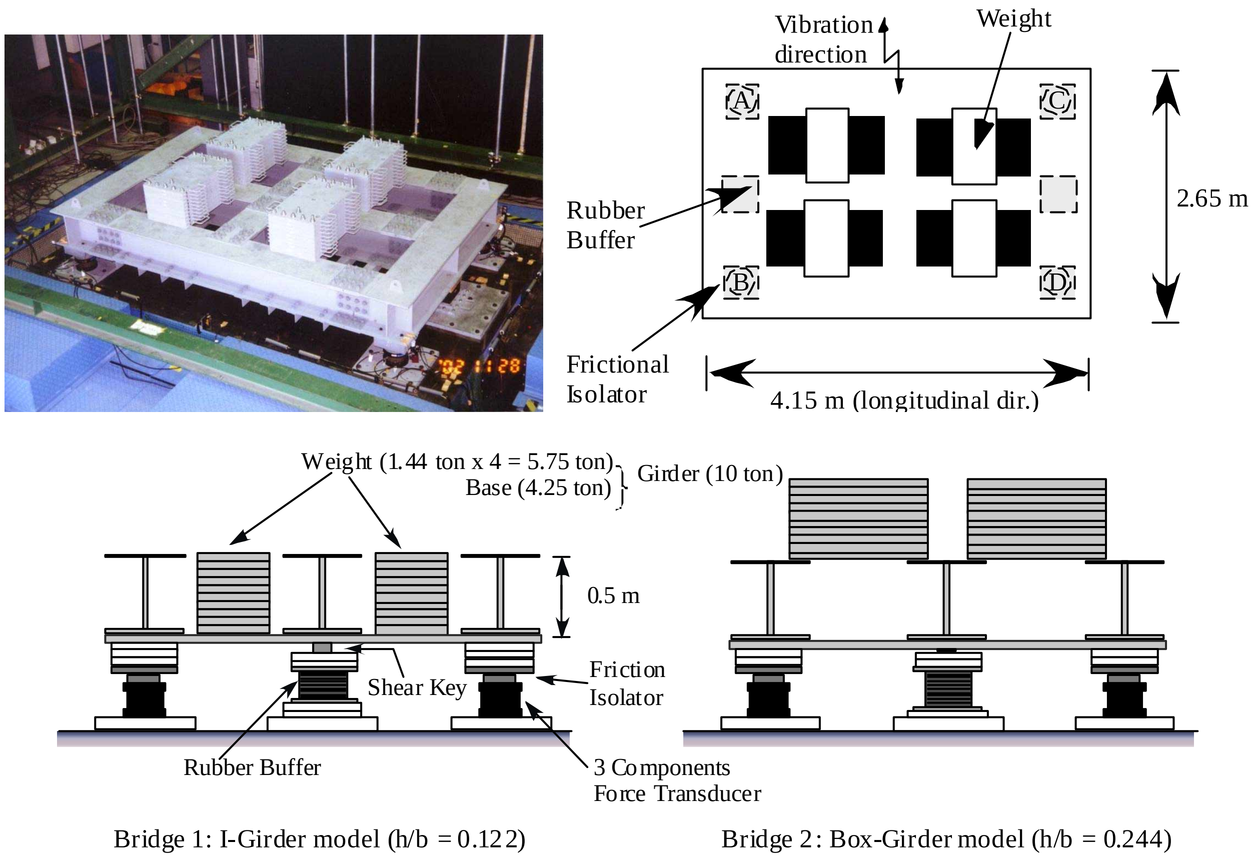



**Figure 4: Test specimens**

## SHAKING TABLE TEST

The shaking table tests were carried out at the Disaster Prevention Research Institute, Kyoto University in order to investigate the seismic behavior of the frictional isolated bridges. We focused on the horizontal seismic responses of the superstructure in case the normal force of the isolators is varied.

### Similarity law

Among the factors in Figure 2, the inertia force (Factor A) and the rocking of the girder (Factor B) were focused in the tests. In order that the effect of these factors in the tests corresponds to that in the real bridges, the ratio of the height of the center of gravity to the width of the girder (h/b), the acceleration and the pressure of the isolator are scaled by a factor of 1. The similarity law used in the tests is shown in Table 1.

### Prototype bridges

The prototype bridges (Figure 3) in this tests are

- 8 span continuous steel I-girder bridge (Bridge 1)
- 3 span continuous steel box-girder bridge (Bridge 2).

These bridges are planned to adopt the frictional isolation system. The ratio of h/b is different in these bridges. The h/b of the bridge 1 and 2 are 0.122 and 0.244, respectively.

### Test specimen

*Superstructure model*

The test specimen consists of a girder of 10 ton and four frictional isolators and two rubber buffers (Figure 4). The ratio of h/b is set to each bridge model by the location of the weight. Because of the capacity of the

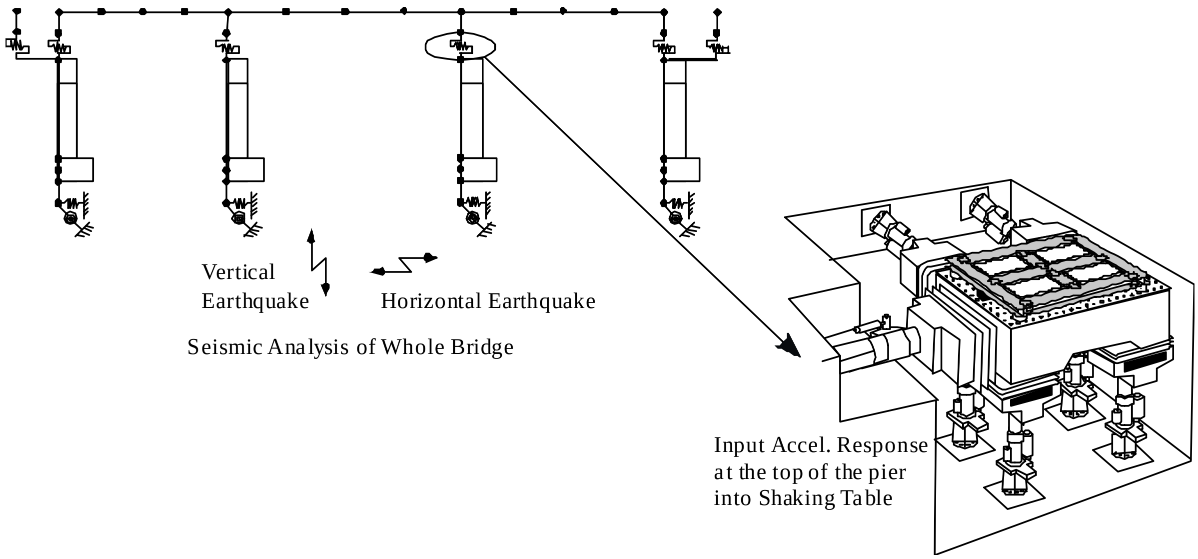



**Figure 5: Test proceadure**

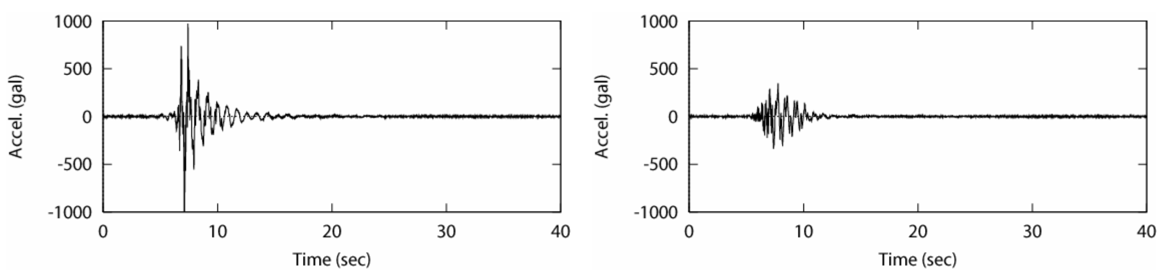



**Figure 6: Input earthquake (left: EW, right: UD)**

shaking table, the middle span part is modeled as the specimen. The scale factors of Bridge 1 and 2 are 10.69 and 12.17, respectively.

*Frictional isolator*

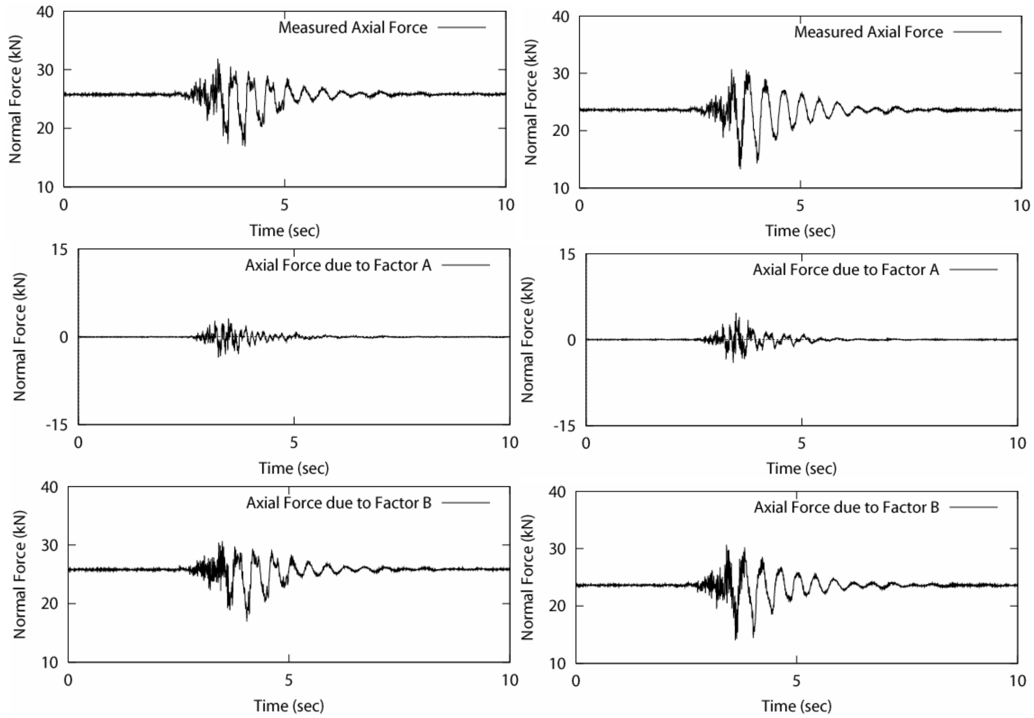
The frictional isolator consists of the fiber reinforced PTFE and the SUS plate. The diameter of the PTFE plate (43 mm) is decided so that the normal pressure of the isolator is 16.9 MPa. From the results of the preliminary tests, the dependencies of the sliding velocity and the normal pressure are observed.

*Rubber buffer*

The laminated rubber bearing is used as the rubber buffer. The stiffness of the buffer in the prototype is @18.5 kN/mm for Bridge 1 and 13.7 kN/mm for Bridge 2. The gap between the girder and the buffer is installed so as not to support the weight of the girder. The horizontal inertia force of the girder is transmitted by the shear key.

**Input motion**

Since only the superstructure model was used in the tests, the earthquakes couldn't be inputted directly. Prior to the tests, the seismic analyses of the whole bridge model (Figure 3) were carried out and the acceleration responses at the top of the pier were used as the input motions of the shaking table (Figure 5). The input earthquake motions are shown in Figure 6.




(a) Bridge 1 (b) Bridge 2

**Figure 7: Normal force response on Isolator A**

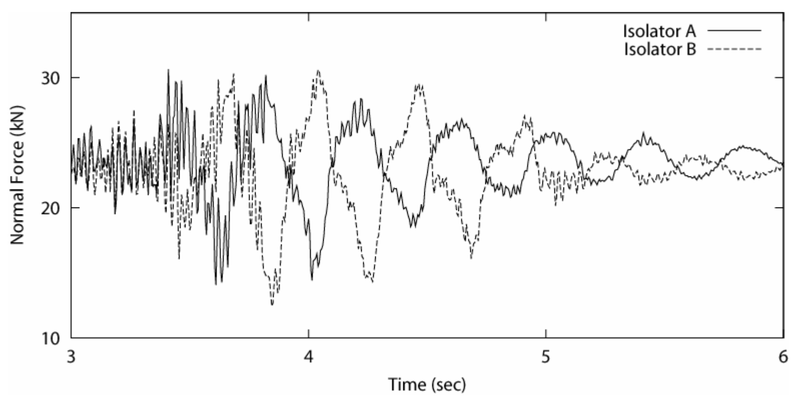



**Figure 8: Normal force histories of isolator A and B due to the rocking of the girder**

## RESULTS

### Variational normal force of isolators

The normal force histories at the isolator A in Bridge 1 and 2 are shown in Figure 7. In this figure, the top history is the recorded normal force and the middle one is the axial force calculated by the product of the mass and the acceleration of the girder (Factor A in Figure 2). The bottom history is the subtraction of the middle one from the top one. This subtraction is induced by Factor B (rocking of the girder). These results suggest that the variation of the normal force induced by Factor B is larger in Bridge 2, which height of the center of gravity is higher than Bridge 1. And the normal force due to Factor B at the isolator A and B, which are located in the opposite side of the shaking direction in Figure 8. This figure presents the rocking behavior very well.

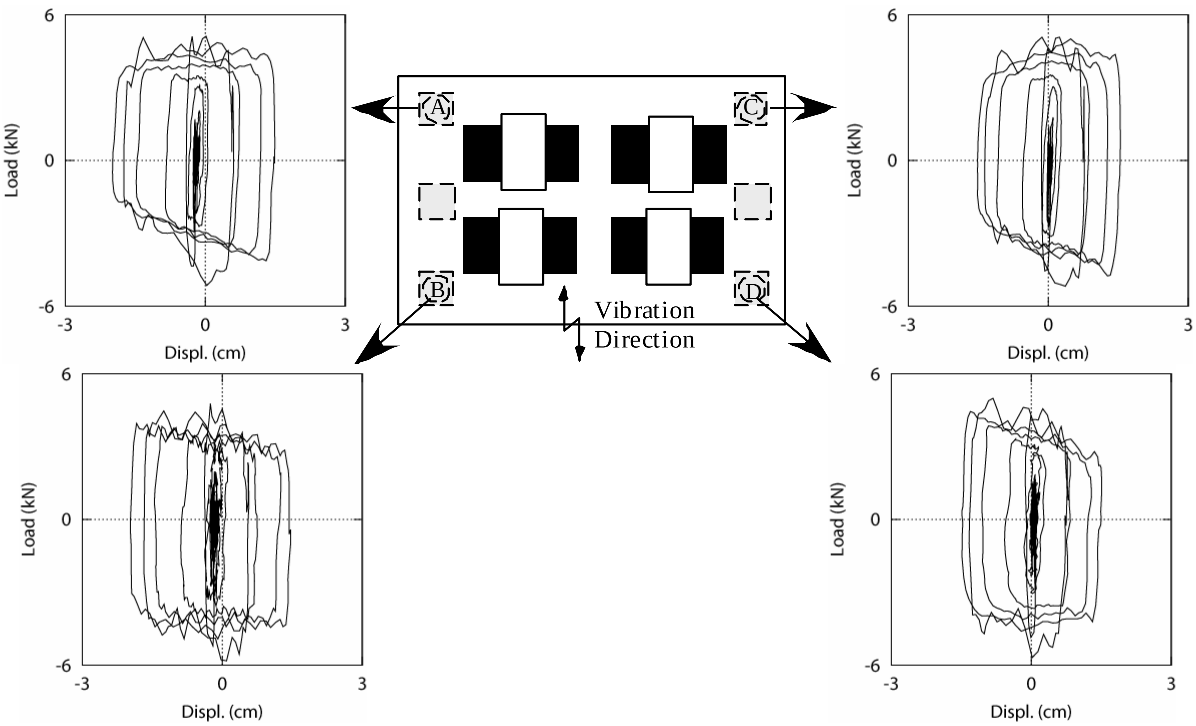



**Figure 9: Hysteresis loops of isolators**

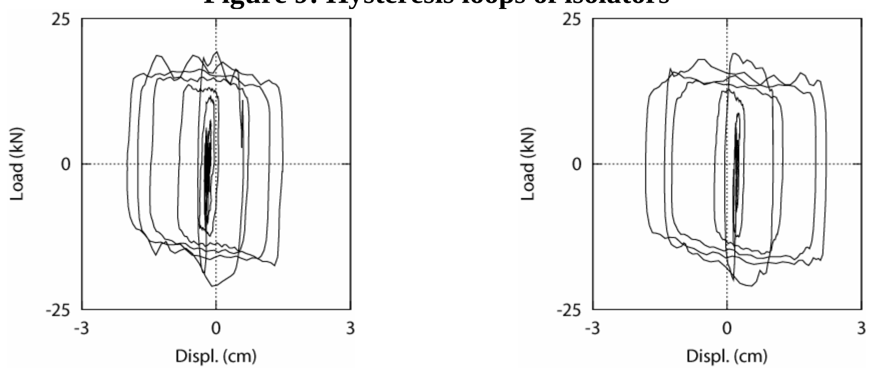



**Figure 10: Hysteresis loop of the sum of isolators**
**(left: with vertical ground motion, right: without vertical ground motion)**

**Hysteresis loops**

The hysteresis loops of isolators in Bridge 1 are shown in Figure 9. The trapezoidal shape means the variational normal force due to the rocking behavior. It seems that the frictional isolators behave complicatedly, but looking at Figure 10 (left) which is the sum of all four hysteresis loops, the resultant hysteresis loop looks like a rectangle. It means that the effect of the rocking behavior is appeared in the response of each isolator but is canceled in the response of the girder. Therefore the rocking behavior of the girder has small influence of the horizontal seismic behavior of the girder.

**Influence of vertical ground motion**

The right hand side of Figure 10 shows the hysteresis loop of the sum of all isolator in case of no vertical ground motion. Compared with the case with vertical ground motion, the fluctuation band of the hysteresis loop is smaller because there is no influence by Factor A in Figure 2. And although there are some differences between the responses, the amounts of the dissipated energy are almost the same (532

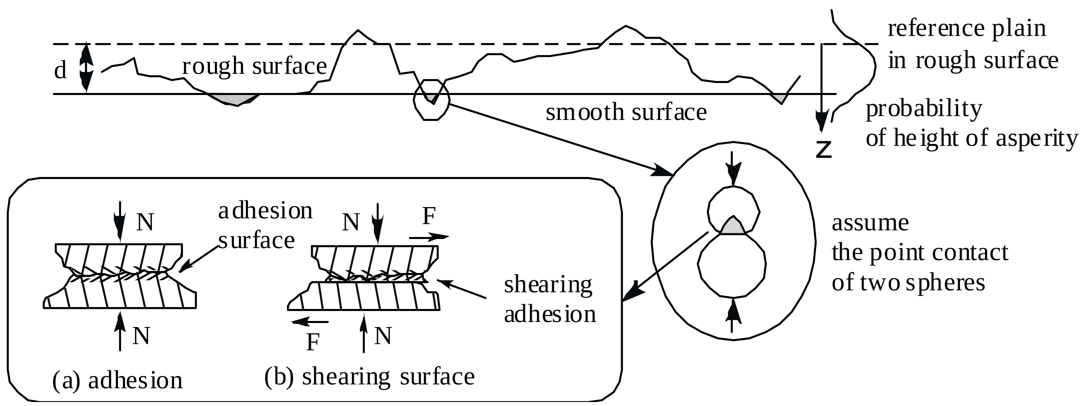



**Figure 11: Contact between two surfaces**

kNcm (left) and 531kNcm (right) in Figure 10) and there is no significant difference in the seismic performance of the frictional isolators in the vertical motion level in these experiments.

## NUMERICAL MODEL OF FRICTION FORCE BETWEEN PTFE AND SUS

### Adhesion theory

A variety of numerical models of the coefficient of friction have been proposed, but the almost all models are derived from the experimental results and have few theoretical background. In this paper the numerical friction model is developed based on the tribology theory.

The adhesion theory was advocated by Bowden and Tabor [7] and nowadays it is accepted to be the fundamental theory of friction in the tribological field. The key concept is the true contact area. Considered the contact of two metal surfaces, they are contacted only at the asperities on the surfaces from the microscopic view. In general the area of the asperities is much smaller than the apparent area, and the area is called the true contact area. Since the large normal pressure is applied at the asperities, the minute contact areas adhere to each other. To slide the interface between two surfaces, it is necessary to destruct the adhesion portion and the resultant of this destructive forces at the asperities is the sliding friction force as the following:

$$F = sA_r \tag{1}$$

where $A_r$ is the true contact area and $s$ is the shear strength of the contact material.

### True contact area in contact with PTFE surfaces

The contact at an asperity can be considered as the point contact between two spheres. The radius of the contact area can be predicted by the Hertz's elastic theory. Greenwood and Willamson extended the theory to the contact between a plane and a nominally flat surface covered with a large number of asperities which, at least their summits are spherical and that their heights vary randomly [8] (Figure 11). According to their theory, the true contact area is proportional to the normal load if they contact to each other elastically. If all asperities contact plastically, the equilibrium equation is,

$$p_m A_r = W \tag{2}$$

where $p_m$ is the plastic flow strength of the contact material and $W$ is the normal load. From this equation, it is found that the true contact area is also proportional to the normal load as same as the elastic contact, These results support the Coulomb's empirical law.

However we should take into account the material property of PTFE. PTFE is a polymer material and the apparent equivalent Young's modulus is much smaller than that of metals. Therefore the true contact area increases rapidly with increasing the normal load and eventually saturates to the apparent area. This phenomenon has to be considered in addition to the adhesion theory because it is one reason for the load-dependency of sliding friction of PTFE. The true contact area of PTFE is modeled by the following equation:

$$A_r = A[1 - \exp(-kP)] \tag{3}$$

where $A$ and $P$ are the apparent area and normal pressure.

**Shear strength of PTFE**

Since PTFE is a polymer material, it is considered that the shear strength is a strain rate dependent (viscous material). Although other factors, e.g. temperature and effective contact time, are affected to the strength, the following equation can predict the experimental results on the shear strength of polymer materials under the constant sliding velocity [9]:

$$s = s_0 + \alpha P_r \tag{4}$$

where $s_0$ is the constant in terms of the adhesion and depends on the sliding velocity and $P_r$ is the true pressure. Since $s_0$ is strain rate dependent, the shear strength of PTFE is modeled by the following equation:

$$s = s'[1 - \exp(-nV)] + \alpha P_r \tag{5}$$

where $V$ is the sliding velocity. This exponential model for the velocity dependency is referred to the previous research [5].

**Friction force and coefficient of friction between PTFE and SUS**

Since $W = P_r A_r = PA$, the true pressure can be expressed the following equation using Equation (3):

$$P_r = \frac{P}{1 - \exp(-kP)} \tag{6}$$

Substituting Equation (3), (5) and (6) into (1), we obtain the friction and the coefficient of friction model as follows:

$$F = A[s'\{1 - \exp(-nV)\}\{1 - \exp(-kV)\} + \alpha P] \tag{7}$$

$$\mu = s'[1 - \exp(-nV)]\frac{1 - \exp(-kP)}{P} + \alpha \tag{8}$$

where $s'$ and $n$ are the constants in terms of the sliding velocity and $k$ and $\alpha$ are the constants in terms of the pressure.

**Comparison between experimental and numerical results**

In order to evaluate the performance of the numerical model, the sine acceleration motions were inputed into the shaking table and the friction force data with large variation of the normal pressure and the sliding velocity were obtained. Figure 12 shows a set of recorded data at isolator A. The normal pressure varied from 25 MPa to 5 MPa. As the results, the friction force - displacement hysteresis loop becomes complicated (the left of Figure 13).

On the other hand, the parameters in Equation 7 were identified by the obtained frictional data (s', n, k, alpha = 1.379, 0.197, 0.102 and 0.046). The right hand side of Figure 13 shows the predicted hysteresis

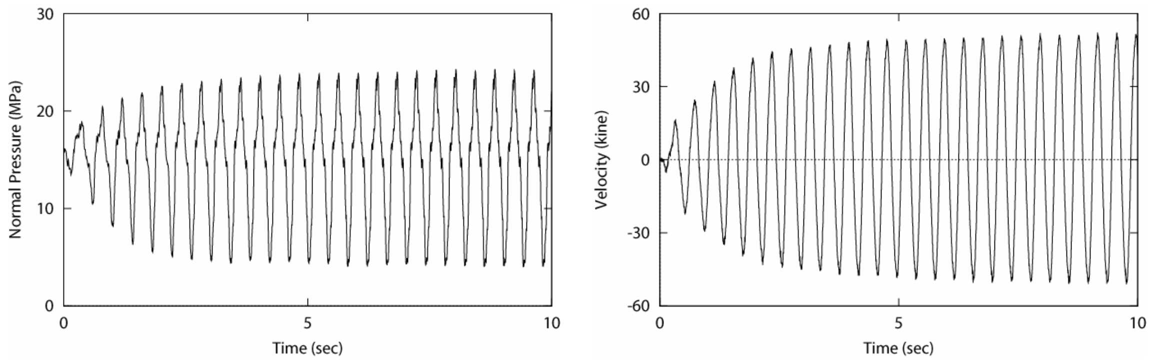



**Figure 12: Normal pressure and velocity time histories at Isolator C**

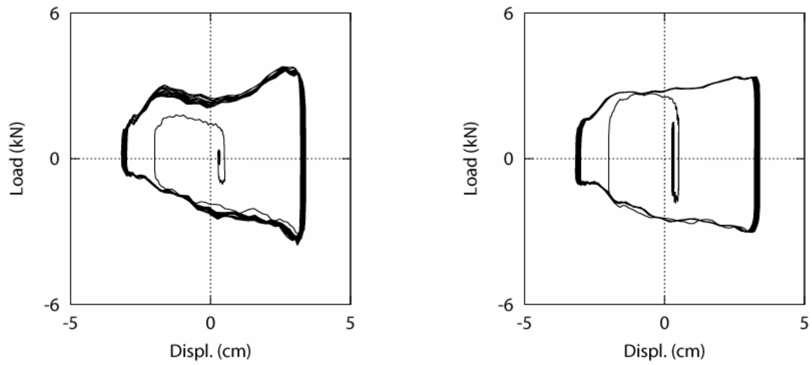



**Figure 13: Comparison between experimental (left) and numerical (right) result**

loop with the variational data in Figure 12. In spite that the experimental friction force varies complicatedly, it is found that Equation 7 can predict the friction force under the variational normal pressure and sliding velocity well.

## SEISMIC RESPONSE UNDER EXTREMELY LARGE VERTICAL GROUND MOTIONS

In order to investigate the response by the large vertical ground motion, the seismic response analysis is carried out. In the analysis, the superstructure of Bridge 1 is modeled as one degree of freedom because the influence of the rocking behavior on the frictional isolators is canceled in the total response of the superstructure. Therefore only the effect of the factor A in Figure 2 is examined in the analysis. The frictional isolator is modeled by Equation 7. The same parameters are used in the previous section.

Figure 14 shows the normal force and hysteresis loop in the case of no vertical ground motion. On the other hand, Figure 15 shows the results under 500 % vertical ground motion of Figure 6 used in the shaking table test. According to these results, the hysteresis loop seems to have the good capacity of dissipating energy. Of course we should pay attention to loosing the normal force on each isolators, but the horizontal response of the frictional isolated superstructure doesn't deteriorate even under the large vertical ground motion.

## CONCLUSION

In this study, the shaking table tests of bridges with the frictional isolators were carried out in order to evaluate the seismic response with the variational normal force and the sliding velocity due to the seismic

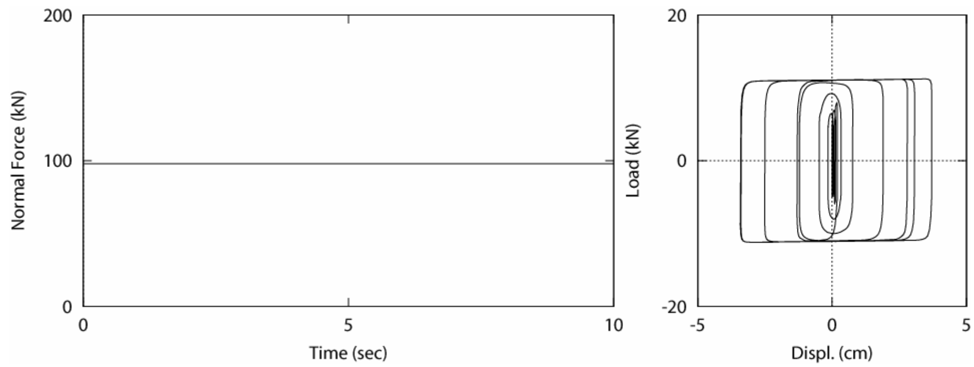



**Figure 14: Seismic response under only horizontal ground motion**

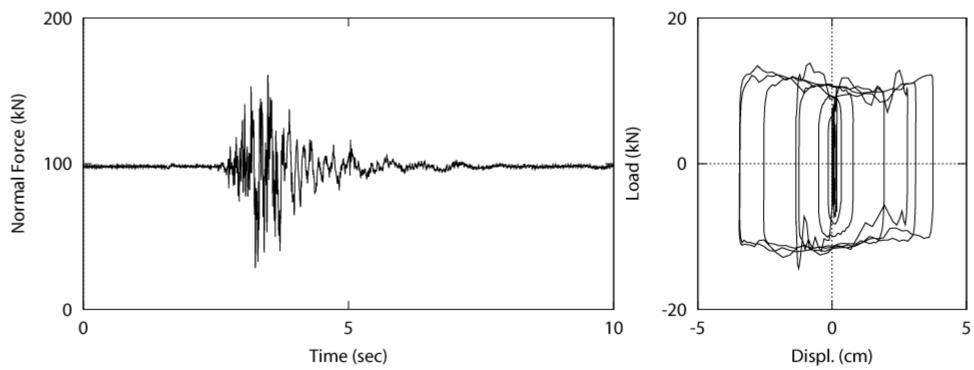



**Figure 15: Seismic response under horizontal and vertical ground motion**

response. Moreover the normal pressure and the sliding velocity dependent fricion force model is developed based on the tribology theory.

From the results of the shaking table tests, the higher the center of gravity of the girder is, the larger the variational band of the normal force on the isolator becomes. Although the each isolator behaves complicatedly under the rocking behavior, the horizontal response of the superstructure is not affected very much because the effect by the rocking is canceled in the total response.

The numerical friction model is developed based on the tribology theory. It is found that the model can predict the friction force under the variation of the normal pressure and the sliding velocity. Using this model, the seismic response analysis of the experimental model was carried out. The results show that it has no substantial influence on the horisontal response of the superstructure even uder the large vertical ground motion. But we should pay attention to loosing the normal load on each isolator.

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