DEVELOPMENT OF LOW-FRICTION FACTOR SLIDING ISOLATION DEVICE

Hiroki HAMAGUCHI[1] And Masahiko HIGASHINO[2]

SUMMARY

Sliding bearings with low coefficient of friction enable the base isolation system with longer natural period than previous ones and to be effective even for small to medium earthquakes. This paper introduces the sliding bearings with low coefficient of friction, which is almost under 0.03. It is shown that newly developed materials for the sliding bearings contribute to reduce coefficient of friction. Weather resistance and durability under various kinds of conditions are tested for main materials that compose the sliding bearings, and it is proved that these materials have enough performances for practical seismic isolation system exposed to circumstances of outdoor locations. After that, sliding surface pressure dependence, excitation velocity dependence in coefficient of friction, durability and dynamic excitations for practical use sliding bearings designed to support 200 tons of axial force are tested and their practicality is proved. Also it is shown that compression and shear stiffness of single rubber pads put in series on sliding bearings almost fit to the design formulas suggested for general laminated rubber bearings. Finally a design formula and variation of coefficient of friction are considered.

INTRODUCTION

Sliding bearings, which consist of pairs of sliding plates composed of PTFE (Poly Tetra Fluoro Ethylene) etc. and stainless steel plates, are generally used for the seismic isolation system of structures jointly with laminated rubber bearings since they have no restoring force themselves. This is one of the merits of sliding bearings since the use of sliding bearings enables the natural period of the seismic isolation system to be longer than the system with only laminated rubber bearings. Generally, longer the natural period of the seismic isolation system be designed, lower the earthquake force becomes. Thus, several sliding bearings have been previously developed [1][9] etc., but they are not necessarily effective for small to medium earthquakes because of their high trigger level caused by coefficient of friction that is close to 0.1. Therefore, the quantity of sliding bearings should be reduced for the seismic isolation system to be effective for small to medium earthquake, since the trigger level is in proportion to the multiplication of total vertical forces supported by sliding bearings and coefficient of friction. In such system, it is difficult to lengthen the natural period more than a certain degree because of dominant stiffness of laminated rubber bearings [11]. The purpose of this study is to develop the sliding bearings that have much lower coefficient of friction than previous ones. It will enable the seismic isolation system with longer natural period than previous ones, and they will be effective even for small to medium earthquakes. Similar study is shown in [10]. In the study, polyacetal resin was adopted for sliding plates and it was concluded that it realized lower coefficient of friction than PTFE, but it seemed still high, and weather resistance and durability for practical use were not studied. In this study, additives to PTFE and a coating material on stainless steel plates were newly developed. The effect of developed materials were checked by reduced tests of the sliding bearings including these materials, high weather resistance and durability of main materials were verified by being exposed to various circumstances. Dependence, durability and the dynamic excitation tests were conducted for practical use sliding bearings. Also it was proved that the design formulas generally used for laminated rubber bearings were applicable to the single rubber pads put in series on the sliding plates to soften the rigid initial stiffness of the sliding bearings. As a result of the study, it was shown that the developed sliding

1 *Research and Development Institute, Takenaka Corporation, Japan Email: hamaguchi.hiroki@takenaka.co.jp*
2 *Research and Development Institute, Takenaka Corporation, Japan.*

bearings had low coefficient of friction, which was almost under 0.03, and they were applicable to practical use. Also the design formula and variation range of coefficient of friction were proposed.

DEVELOPMENT OF SLIDING MATERIALS

Pure PTFE is very soft plastic material and generally mixed with stiff additives to endure large axial forces of upper structures for the use of sliding bearings. Previously, the long-term pressure of sliding surface is designed to be under 10MPa. Additives to endure higher pressure of 15 to 30MPa were newly developed since PTFE had a general characteristic that coefficient of friction was lower under higher surface pressure. A coating material on stainless steel plates was also newly developed. It was composed of heat-stiffened resin, which was printed out after sprayed on stainless steel plates. To make sure that newly developed materials were effective for reducing coefficient of friction and had enough durability, following reduced size tests were conducted for 3 types of stainless steel plates (Table 1 and Table 2).

Test results of sliding surface pressure dependence in coefficient of friction are shown on the left side of Figure 1. General tendency shown in [9][10] etc., that coefficient of friction became lower according as the increase of sliding surface pressure, was reproduced in all types of test pieces. On the other hand, there was large difference in values of coefficient of friction among 3 types of test pieces. Coefficient of friction of No.1 was almost the same as previous ones, while No.2 and No.3 had about one-third of previous ones. Test result of durability shown on the right side of Figure 1 indicated that there were few changes of coefficient of friction after sliding 100 meters length in test No.1 and 3. It was considered that sliding bearings of No.1 and 3 had enough durability since it had been estimated that the total sliding length of a certain seismic isolated structure using sliding bearings didn't exceed 100 meters in 100 years. It was a apparent problem in No.2 that there was clearly larger variation of coefficient of friction than the other 2 cases probably caused by the condition of lubricating oil and it was judged that such wet mechanism was not suited for durability/stability-needed systems with few maintenance. As a result of above tests, it was shown that No.3 had highest performances concerning both coefficient of friction and durability/stability. Compression stiffness of PTFE with developed additives was also measured, and it was shown that it had no excessive remaining deformation even after compression by the pressure of 60MPa, and it had enough stiffness. Finally, as a result of these reduced tests, it was known that pairs of PTFE with developed additives and stainless steel plates with developed coating material proved to have low coefficient of friction, which is about one-third of previous ones, and have enough durability.

Table 1:Outline of Reduced Test Pieces

Test Piece No.	Material of Sliding Plates / Size(mm, ϕ:diameter-t:thickness)	Additional Materials on Stainless Steel Plates
1	PTFE + developed additives / ϕ80-t2	
2	PTFE + developed additives / ϕ80-t2	Fluoride lubricating oil
3	PTFE + developed additives / ϕ20-t1	Developed coating material (heat-stiffened resin)

Table 2:Test Cases

Test Item	Test Piece No.	Surface Pressure (MPa)	Excitation Amplitude(cm)	Excitation Velocity(cm/sec)	Number of Excitation
Surface Pressure Dependence	1	5 / 15 / 30 / 45 / 60	± 8.0	6.4	10
	2				
	3		± 3.5	15	
Durability	1	30	± 8.0	10	600
	2				300
	3		± 3.5	24	1,280

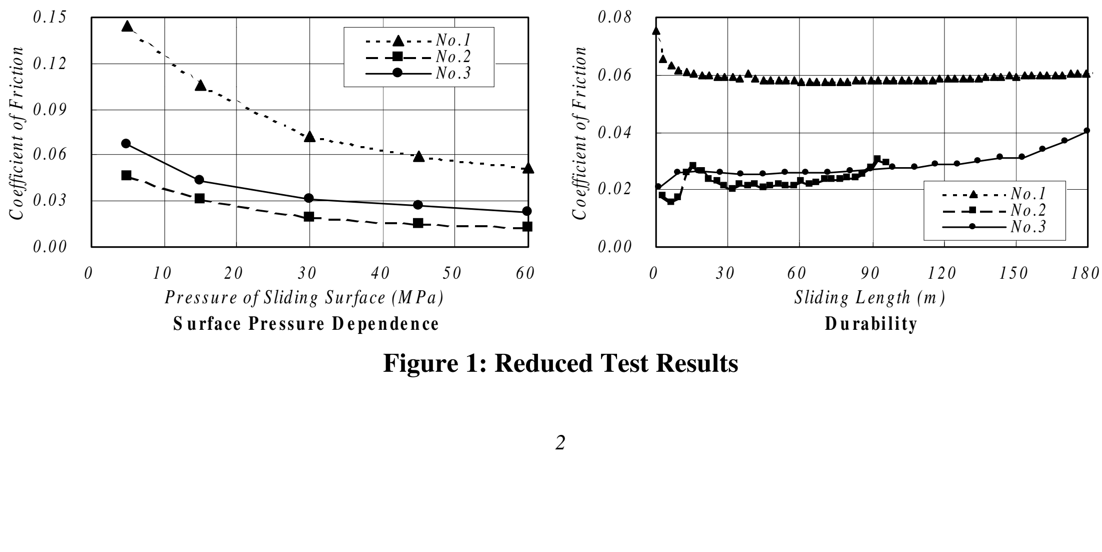


Figure 1: Reduced Test Results

COMPOSITION OF SLIDING BEARING

Previous sliding bearings generally have laminated rubber bearings put in series on them because of their high coefficient of friction. That is, since sliding bearings themselves have rigid-plastic hysteresis, they don't start to slide and cause large response acceleration to upper structures in cases of small to medium earthquakes which don't exceed the trigger level of sliding bearings. Thus these laminated rubber bearings have a role to soften the initial rigid stiffness of sliding bearings and reduce the response acceleration of upper structures by their shear deformation instead of sliding in such cases. In the sliding bearings developed in this study, laminated rubber bearings are not needed any longer and only single rubber pads are enough for softening the initial rigid stiffness of sliding bearings because of their low coefficient of friction. The single rubber pads deform at most 150% of their thickness until the bearings start to slide, and also absorb the relative slant between upper and lower structures. Composition of the sliding bearing with a single rubber pad is shown in Figure 2.

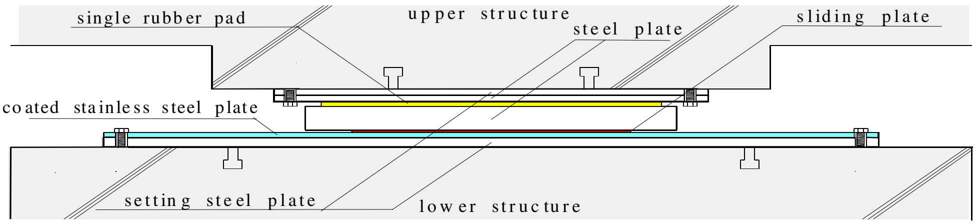


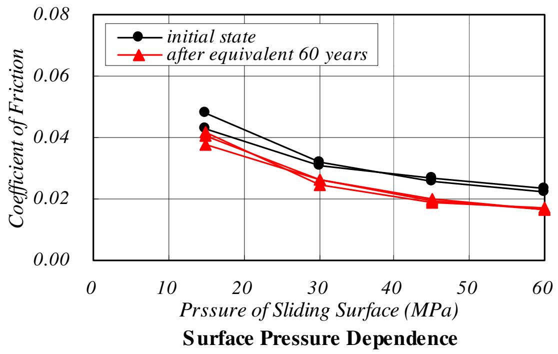
Figure 2: Composition of the Sliding Bearing with Single Rubber Pad

WEATHER RESISTANCE AND DURABILITY OF MATERIALS

Sliding bearings are keep exposed to circumstances of outdoor locations for several decades. Therefore, it is important to make sure that materials used for sliding bearings have much weather resistance and durability.
Sliding plates that consist of PTFE with additives adhered to steel plates with epoxy resin adhesives and heat-stiffened resin coated stainless steel plates were exposed to various circumstances. After that, several characteristics were tested for PTFE with additives, coated surface and adhesive strength. Test cases and results are shown in Table 3. In accelerated ageing test, according to the case of laminated rubber bearings, test pieces were exposed to the circumstance of 100 degrees centigrade for consecutive 19 days that corresponded to 60 years. In moisture-resistance test, test pieces were exposed to the circumstance of 65 degrees centigrade and 95% humidity for 6 weeks. Also in chemical-resistance test, test pieces were soaked in 5% dilute solution of sulphuric acid, calcium hydroxide and sodium chloride for 6 weeks. As a result of accelerated ageing test, characteristics of both PTFE with additives and coated surface hardly changed and activation energy could not be estimated. Measurement of adhesive strength ended by the failure of PTFE, and the values were about 8 times of predicted maximum shear force, which indicated that epoxy resin adhesives had enough strength. Also after moisture-resistance tests and chemical-resistance tests, the variation of characteristics in test pieces were hardly recognised. Both sliding surface pressure dependence and excitation velocity dependence in coefficient of friction were compared between initial state and state after being exposed to accelerated ageing test. The results are shown in Figure 3. It was considered that both values of coefficient of friction and dependence tendency hardly changed after equivalent ageing 60 years.

Table 3:Test Results of Weather Resistance and Durability of PTFE with additives, Coated Surface and Adhesive Strength

Test Piece	Test Item	Unit	Initial value	After accelerated ageing test	After moisture – resistance test	After chemical-resistance test		
						Sulphuric acid	calcium hydroxide	sodium chloride
PTFE with additives	Tensile strength	MPa	18.8	18.7	19.1	19.0	18.8	19.5
	Elongation at fracture	%	322	312	325	320	316	318
	Surface hardness	D	61	62	-	-	-	-
Coated surface	Pencil scratch test	-	3H	3H	3H	3H	3H	3H
	Cross cut test	pts	10	10	10	10	10	10
	Spiral scoring test	pts	5	5	5	5	5	5
Adhesive strength	Cement test	MPa	8.7 failure of PTFE	8.5 failure of PTFE	-	-	-	-



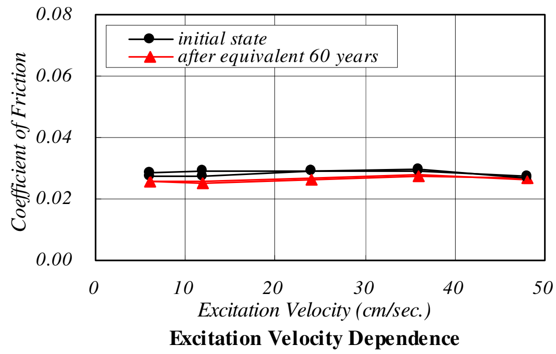


Figure 3: Comparison of Dependence between Initial State and State after being exposed to Accelerated Ageing Test

5. TEST RESULTS OF PRACTICAL USE SLIDING BEARINGS

Various characteristics were tested for practical use sliding bearings that were designed to support 2MN of long-term axial force. 2 types of long-term pressure on sliding surface were considered for practical use sliding bearings, that is 15MPa and 30MPa. A single rubber pad put in series on a sliding plate was vulcanized natural rubber with static shear modulus of 0.55MPa, and its upper and lower surfaces were adhered to steel plates by epoxy resin adhesives. Outline of test pieces is shown in Table 4. Two-axis testing machine was used for the tests, which was able to excite a sliding table horizontally by a dynamic actuator for maximum 0.4MN subjected to maximum 5MN of vertical load. Test items were sliding surface pressure dependence and excitation velocity dependence in coefficient of friction, durability for pairs of sliding plates and stainless steel plates and compression and shear stiffness for single rubber pads. Also dynamic excitation tests for total sliding bearing systems were conducted. Finally from these tests, a design formula and variation of coefficient of friction were considered.

Table 4:Outline of Practical Use Test Pieces

Name of Test Piece	Material	Size(mm)
Sliding Plate (15MPa model)	Steel plate + PTFE with additives	ϕ400-t(16+2)
Sliding Plate (30MPa model)	Steel plate + PTFE with additives	ϕ300-t(16+2)
Stainless Steel Plate	Stainless steel plate + heat-stiffened resin coating	w500-d580-t5
Single Rubber Pad	Steel plate + vulcanized natural rubber + steel plate	ϕ400-t(6+11+6)

Dependence in Coefficient of Friction

Test conditions of sliding surface pressure dependence in coefficient of friction were as follows: ±15cm displacement; 15cm/sec velocity; 0.25Hz frequency; 10 cycle excitations; 5 / 15 / 30 / 45 / 60MPa surface pressures. The test was conducted twice in same condition for different pairs of test pieces. The results are shown on the left side of Figure 4 together with the result of reduced test shown in section 2. Tendency was almost similar to the result of reduced test, but values of coefficient of friction were much smaller than reduced test results. This must be caused by the difference of surface pressure distribution between the practical use test piece and the reduced one as shown in Figure 5, considering the correlation between coefficient of friction and sliding surface pressure. Since PTFE of reduced test was rather soft because of it's small ratio of diameter/thickness (20/1), it deformed plastically and surface pressure distribution became uniform. While surface pressure concentrated along the edge parts by the "crowning" effect in PTFE of practical use test, because the ratio was much larger (300/2) so PTFE was stiff enough and hardly deformed. Therefore, true surface pressures of practical use test pieces were higher than uniform surface pressures. This may be also proved by that the results of practical use tests would fit to the result of reduced ones by horizontally shifting the results of practical use ones to the higher surface pressure side. This is a serious problem for sliding bearings since the pressure distribution of sliding surface is different one by one and it cannot be estimated theoretically. Thus large variation of coefficient of friction should be considered. This subject is further studied in Section 5.5.
Test conditions of excitation velocity dependence in coefficient of friction were as follows: ±15cm displacement; 6 / 12 / 24 / 36 / 48cm/sec velocity; 0.1 / 0.2 / 0.4 / 0.6 / 0.8Hz frequency; 10 cycle excitations; 15 / 30MPa surface pressures. Test results are shown on the right side of Figure 4 together with reduced test results conducted separately. Slight increasing tendency according as the increase of excitation velocity was almost the same in both practical use test and reduced test results. The reason for the difference of values of coefficient of friction is as mentioned above.

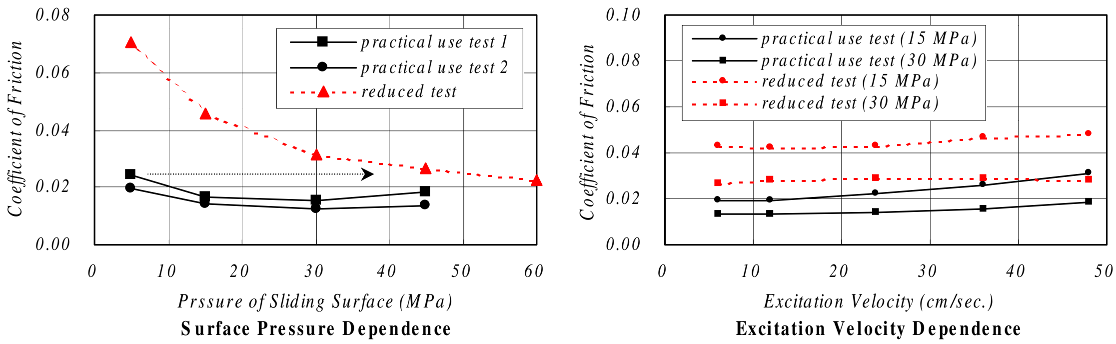
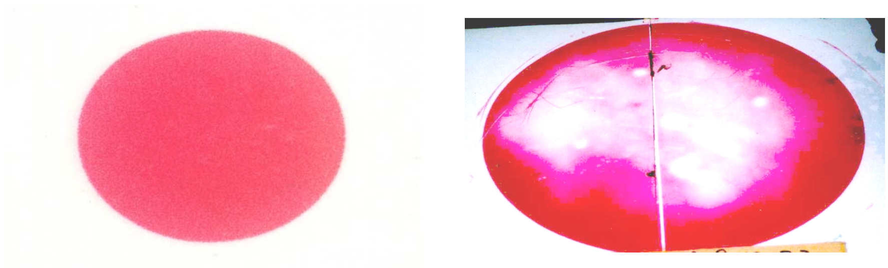


Figure 4: Test Results of Dependence in Coefficient of Friction



Reduced test piece (ϕ20-t1) **Practical use test piece (ϕ300-t2)**

Figure 5: Pressure Distributions of Sliding Surface

Durability of Sliding Surface

Test conditions were as follows: ± 15cm displacement; 15cm/sec velocity; 0.25Hz frequency; maximum 300 cycle excitations (corresponded to 180 meters length); 15 / 30MPa surface pressures. Test results are shown in Figure 6 together with reduced test results conducted separately. Taking the notice of the practical use test results, local fluctuation of coefficient of friction as seen in the result of 30MPa was caused by stopping the excitation and cooling the sliding surface every 18 meters sliding length for protecting PTFE with additives from melting by the excess friction heat. In case of 15MPa, coefficient of friction hardly changed within 180 meters sliding length, while in case of 30MPa, it increased gradually over 80 meters and finally reached 3 times of initial value, probably because of abrasion of only the edge parts. From the results, it was said that in the use of 15MPa, the developed sliding bearings had enough durability for practical use although coefficient of friction was rather high as known from the test results of surface pressure dependence, while in the use of 30MPa, replacement of sliding bearings might happen in lifetime of structures. In reduced tests, there was great stability in coefficient of friction even in the case of 30MPa owing to the uniformity of sliding surface pressure. Finally, it would be recommended that the developed sliding bearings should be used under long-term pressure of maximum 15MPa from a practical view point of the durability / stability and few maintenance as replacement.

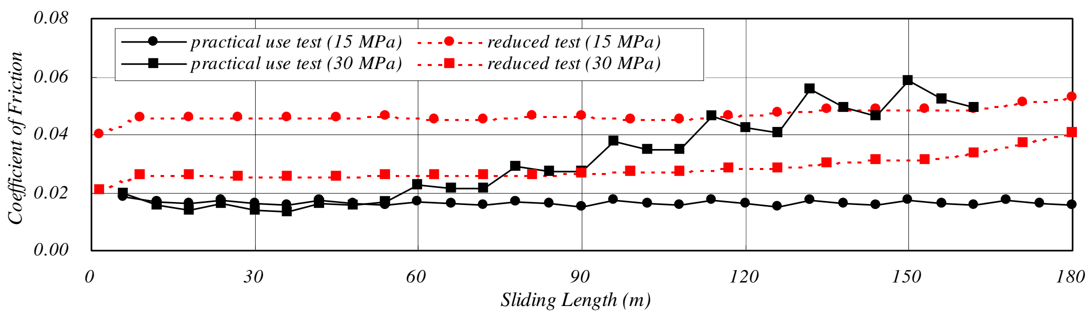


Figure 6: Test Results of Durability

Compression and Shear Stiffness of Single Rubber Pad

To verify the validity of the design formula (1)[2][3][4][5] and (2)[6], used for general laminated rubber bearings, to be applied for single rubber pads of the developed sliding bearings, compression and shear stiffness were measured and compared with the values obtained by these design formulas. Compression stiffness was measured by applying cyclic compression pressure 5 times between 0MPa and 15MPa. Also shear stiffness was measured by applying cyclic shear force 5 times subjected to the practical compression pressure of 15MPa. The trigger level force assuming coefficient of friction to be 0.04 was adopted for maximum shear force. The design formulas are as follows:

$$K_V = \frac{E_{cb}A}{T_R} \tag{1}$$

$$K_H = \frac{P^2}{2k_r q \tan(\frac{qH}{2}) - PH} \tag{2}$$

where,

$$E_{cb} = \frac{E_c E_b}{E_c + E_b}, E_c = 3G(1+2\kappa S_1^{\ 2}), E_b = 20\text{tf/cm}^2, S_1 = \frac{R}{4t_R}$$

$$\kappa = 1.2338 - 0.11307G + 0.0059701G^2 - 0.00010451G^3$$

$$q = \sqrt{\frac{P}{k_r}(1+\frac{P}{k_s})}, k_r = \frac{E_{rb}IH}{T_R}, k_s = \frac{GAH}{T_R}, E_{rb} = \frac{E_r E_b}{E_r + E_b}, E_r = 3G(1+\frac{2}{3}\kappa S_1^{\ 2})$$

A : cross section of rubber pads
T_R : total thickness of rubber pads
R : diameter of rubber pads
t_R : thickness of each rubber pad
G : static shear modulus
κ : correction factor (kgf/cm^2) proposed by Lindley[8]
P : compression force
I : geometrical moment of inertia
H : total height including steel plates between rubber pads

Test results are shown in Figure 7. Both compression and shear stiffness were generally equal to the value obtained by these formulas, although strain hardening of stiffness was observed in compression test. Compression stiffness calculated from formula (1) was 2,140MN/m, while the value estimated from experimental result was 2,240MN/m at 15MPa, and it was only 5% larger than the calculated one. Also shear stiffness calculated from formula (2) was 6.62MN/m, while the value estimated from experimental result was 6.28MN/m at maximum shear force, and it was only 5% smaller than the calculated one. Considering the variation of natural rubber products, it was proved that these formulas were applicable to the design of single rubber pads with great accuracy even their ratio of radius/thickness slightly exceeded the application range of these formulas.

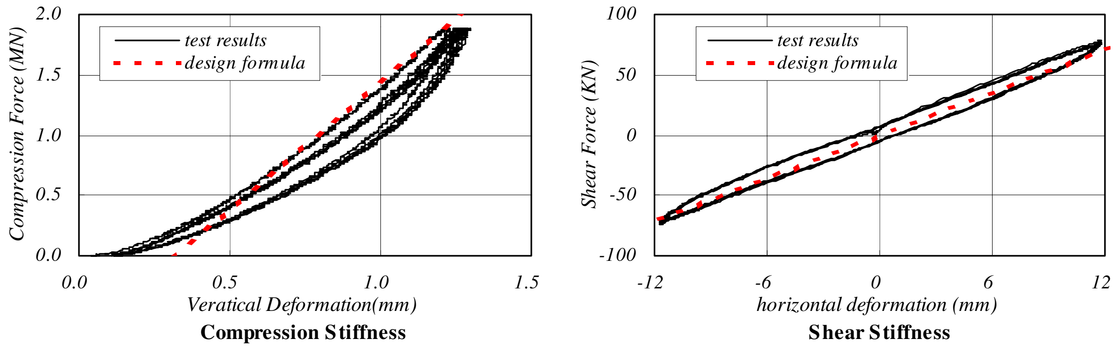
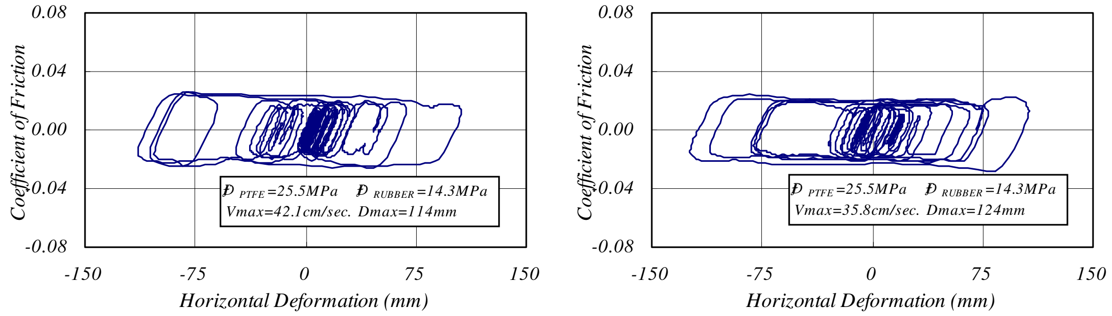


Figure 7: Compression and Shear Stiffness of Single Rubber Pads

Dynamic Excitations for Total Sliding Bearing Systems

Hystereses of sliding bearings were checked by the dynamic excitations subjected to 1.8MN vertical load. Excitation waves were time histories of response relative deformations at the isolation floor of the analytical model of a certain seismic isolated structure supported by sliding bearings jointly with laminated rubber bearings. Adopted waves were response time histories when El Centro 1940 NS and Hachinohe 1968 NS were excitation waves. Natural periods of the seismic isolation system were 1.1sec for initial stiffness and 4.0sec for secondary stiffness. Test results are shown in Figure 8. Obtained hysteresis loops showed apparent normal bi-linear forms and coefficient of friction kept steady among excitations. Initial stiffness obtained by these experiments were almost equal to the value calculated from formula (2).



El Centro 1940 NS **Hachinohe 1968 NS**

Figure 8: Test Results of Dynamic Excitations

Design Formula and Variation of Coefficient of Friction

Since it was important to lead a design formula and estimate the variation of coefficient of friction for the sliding bearings in practice, these results were gathered in Figure 9, although each data was obtained in slight different test condition. Following equation (3) is the obtained formula by the method of least squares from test results:

$$\mu = 0.055\sigma^{-0.351} \quad (3)$$

where, μ : coefficient of friction ; σ : sliding surface pressure (MPa)

Among many imperfection items in the tests, strains and slants of the testing machine, precision of test pieces etc., the difference of surface pressure distribution in each test pieces was considered as the most serious cause of large variation of test results. Since the pressure distribution of each sliding surface cannot be estimated theoretically, it is necessary to take the variation of coefficient of friction into account. It was studied in [7] that creep deformation of PTFE was converged within 20 hours of continuous compression regardless of the ratio of diameter/thickness, and that PTFE with high ratio of diameter/thickness, as used in practical use tests in this study, was extremely stiff and hardly creep-deformed. Also it was verified experimentally by compressing the practical use sliding plate used in this study for continuously 24 hours that there was no difference in the distributions of sliding surface pressures between initial state and state after 24 hours compression. But a general tendency in the distribution of sliding surface pressure to become uniform with time because of slight deformation of PTFE is expected. Judging from test results obtained in this study, most of them were within the rough variation range of -20% to +50% of the values by the design formula. Of course, the range will be narrowed with accumulation of practical use test results.

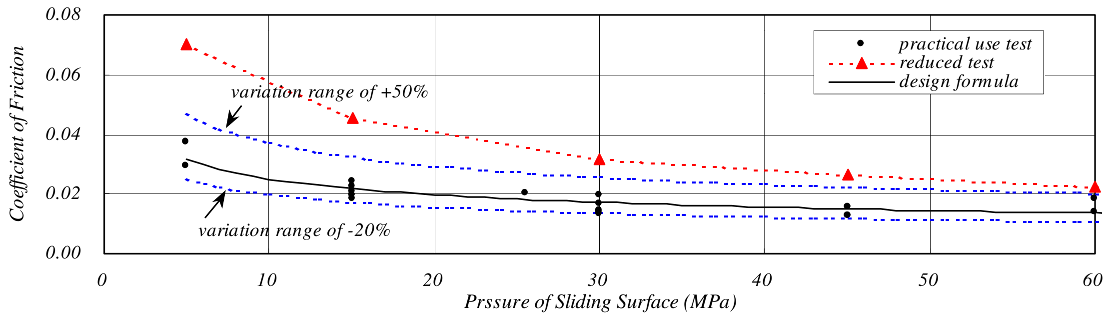


Figure 9: Design Formula and Variation of Coefficient of Friction

CONCLUSIONS

1. Additives to PTFE and a coating material for stainless steel plates were newly developed and the sliding bearings using these materials had lower coefficient of friction than previous ones, which were almost under 0.03.
2. These developed materials and epoxy resin adhesive between PTFE and steel plates had enough weather resistance and durability for practical use of the seismic isolation system.
3. Sliding surface pressure dependence in coefficient of friction was tested and the general tendency was verified that coefficient of friction became lower under higher sliding surface pressure.
4. Excitation velocity dependence in coefficient of friction was also tested and there was a tendency that coefficient of friction slightly increased according as the increase of excitation velocity.
5. Practical use sliding bearings had enough weather resistance and endurance for demands of the seismic isolation system and had steady normal bi-linear hysteresis.
6. Compression and shear stiffness of single rubber pads put in series on the sliding plates almost fitted to the values obtained from the design formulas proposed for general laminated rubber bearings.
7. Coefficient of friction was much influenced by the distribution of sliding surface pressure, but it could not estimated theoretically. Test results obtained in this study were within the rough variation range of –20% to +50% of the values by proposed design formula of coefficient of friction.

REFERENCES

[1] Emori, J., Yamanaka, H., Tanigaki, M., Hirata, Y. and Yamagishi, K. (1998) “An Experimental Study on the Basic Mechanical Characteristics of Elastic Sliding Bearing”, *Summaries of Technical Papers of Annual Meeting, Structure 2*, pp.487-488.

[2] Freakly, P.K. and Payne, A.R. (1987), *Theory and Practice of Engineering with Rubber*, Applied Science Publishers Ltd.

[3] Gent, A.N. and Lindley, P.B. (1959), “The Compression of Bonded Rubber Blocks”, *Proc. Instn. Mech. Engrs,* Vol.173, No.3

[4] Gent, A.N. and Meinecke, E.A. (1970), “Compression, Bending, and Shear of Bonded Rubber Blocks”, *Polymer Engineering and Science*, Jan., Vol.10, No.1

[5] Gent, A.N., Henry, R.L. and Roxbury, M.L. (1974), “Interfacial Stresses for Bonded Rubber Blocks in Compression and Shear”, *Journal of Applied Mechanics*, Dec.

[6] Haringx, J.A. (1949,1949) “On Highly Compressible Helical Spring and Rubber Rods, and their Application for Vibration-Free Mountings”, *Philips Research Reports*, Vol.3, Vol.4

[7] Holstein, W.H. “Laminated Construction Enhances Compressive Strength of TFE sheet”, E.I., du Pont de Nemours and Co., Inc.

[8] Lindley, P.B. (1981), “Natural Rubber Structural Bearings”, *Joint Sealing and Bearing Systems for Concrete Structures*, Vol.1, ACI

[9] Oohashi, T., Tomishima, S., Nishiyama, S., Sawada, T. and Matsumoto, H. (1995) “Development of Base-isolation System consisting of Sliding and Rubber Bearings (Part3 Verification of Friction Coefficient Dependence by means of Experimental Data)”, *Summaries of Technical Papers of Annual Meeting, Structure 2*, pp.583-584.

[10]Takaoka, E., Yasaka, A. and Iizuka, M. (1996) “Base-isolation System Consisting of Sliding and Rubber Bearings (Part1 Tests of Sliding Bearings with Low Friction)”, *Summaries of Technical Papers of Annual Meeting, Structure 2*, pp.733-734.

[11]Tomishima, S., Iijima, S., Katshuta, M. and Hisano, M. (1995) “Development of Base-isolation System consisting of Sliding and Rubber Bearings (Part1 Base-isolation System and Principal Theory)”, *Summaries of Technical Papers of Annual Meeting, Structure 2*, pp.579-580.