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Analysis and repair of sliding material in large movable bearings for long-span bridges

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ABSTRACT: In Japan, "PTFE with filled fiber reinforcement" is commonly used as sliding material on movable sliding bearings, although in recent years, some damage was observed in large bearings of long-span bridges. The damage consisted on the protrusion of the sliding material from its original position along to the bridge axis direction. This paper shows the results of the FEM analysis and loading tests which were carried out to verify the damage causes. Besides, the repair method is described after considering the results of the previous analyses. After replacing the damaged bearings, similar damage was observed in some of the bearings after few years. A harder material, the polyamide resin, was selected to replace the PTFE. In the present paper the conducted experiments to confirm the effectiveness of the new material and the new proposed structure are also described, analyzing the obtained results and its implications in the new repair strategy.

1 INTRODUCTION

Supporting the weight of the superstructure, accommodating the horizontal displacements of the girders due to temperature changes, and accommodating the rotations originated by the deflection of the girder are the three characteristics required for bridge bearings. Especially in long-span bridges, due to the heavy weight of the superstructure and the large length of the expansion girder, the size of the bearings becomes large and it is necessary to accommodate repeated long horizontal movement.

In Japan, "PTFE with filled fiber reinforcement" is commonly used as sliding material on movable sliding bearings, although in recent years, some damage was observed in large bearings of long-span bridges. The damage consisted on the protrusion of the sliding material from its original position along to the bridge axis direction. The damaged bearing has a PTFE plate which size is about to be φ1000 mm, and the vertical load bearing capacity is about 20,000 kN.

2 OBSERVED DAMAGE

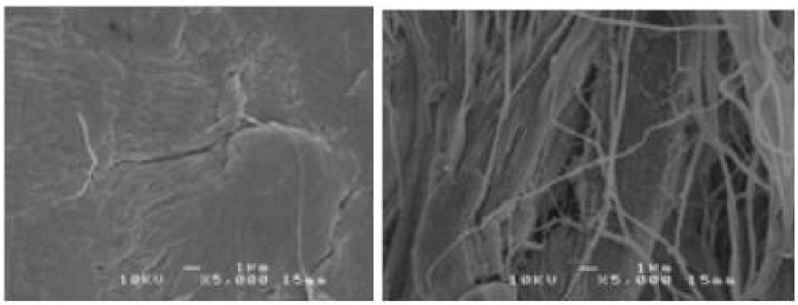
The protruded sliding plate is shown in Picture 1, and the photo obtained during the examination by an electron microscope is shown in Picture 2. The upper surface of the protruded PTFE plates (the sliding surface) was smooth, whereas the bottom surface showed a fibrous aspect in the extension direction. It seems that the material was rolled out by the friction force created by the expansion of the bridge superstructure.

3 CAUSE ESTIMATION

Table 1 shows the comparison between the design dimensions of the bearings object of study. PTFE plates are designed based on surface pressure; the design surface pressure does not depend on the design reaction force and is the same level of conventional bearings.

Based on the characteristics of long-span bridges and on the characteristics of the protrusion, the following points are considered to have influenced the appearance of the damage.

Picture1. Damage of Movable Bearing

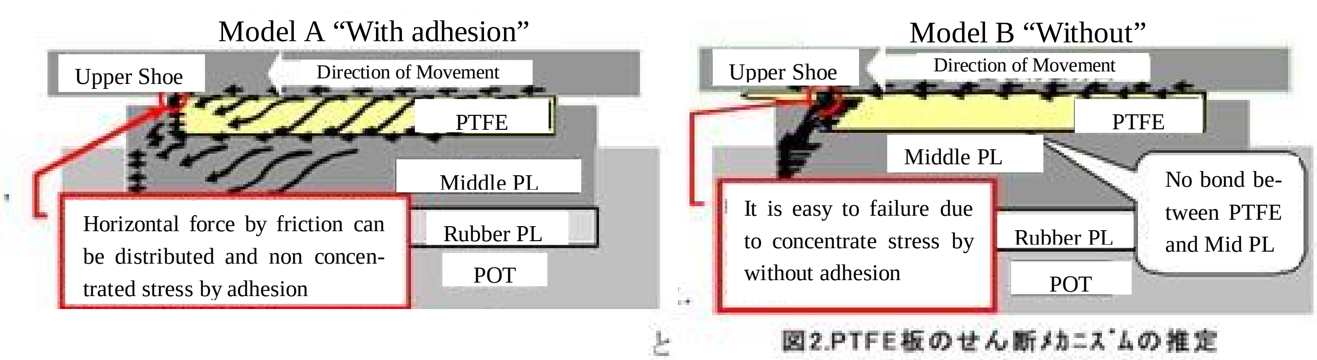


(a) Sliding Surface of PTFE   (b) Surface of bottom PTFE

Picture 2. Photo by Electron Microscope(x5000)

Table 1. Design Dimensions of the Bearing

	Number of Inspection	1	2	3
	Adhesion bond of PTFE	Rubber Type	Rubber Type	Rubber Type
	Diameter of PTFE (mm)	1010	970	730
Vertical Load (kN)	Vertical Maximum Load (Temporary)	29,253	22,887	14,754
	Vertical Maximum Load (Nominal)	17,874	20,581	8,643
	Vertical Dead load	11,949	13,361	6,072
Pressure Stress of PFE (N/mm^2)	Pressure of Nominal	22.3	27.9	20.6
	Pressure of Dead load	14.9	18.1	14.5
Movement (mm)	Movement (Earthquake)	870	910	920
	Movement (Temperature)	+/-219	+/-252	+/-260



(a) With adhesion between PTFE and Middle PL   (b) Without adhesion

Figure 1. Mechanism of shear failure on PTFE edge

– Influence of adhesion effect of the PTFE and the middle plates
– Influence of the surface pressure, due to large reaction force during installation
– Influence of sliding distance, due to large ordinary displacements
– Influence of the scale effect, due to large bearing size

The reason why adhesion is one of the main focuses is because in a dynamic model, the stresses are concentrated on the PTFE plate edges, since it is estimated that the PTFE plate is not adhered like shown in the model B of Figure 1. If the PTFE plate is adhered like the model A in Figure 1, the horizontal force from the sliding surface is uniformly transferred to a middle plate via the adhered area.

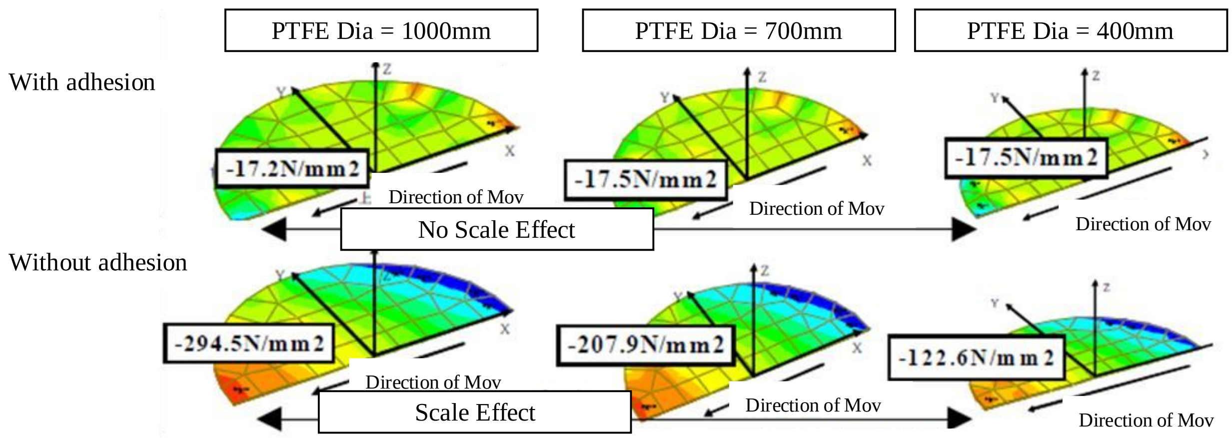


Figure 2. FEM analysis for checking "scale effect" and "adhesion" of PTFE

4 ANALYTICAL EXAMINATION

Firstly, in order to analyze the cause of the occurred damage, an investigation involving the analysis of the condition of the damaged bearing, the verification of the design, and surface observation by an electron microscope was carried out. As a result of these studies, special attention was paid to the connection of the steel plate for attaching the PTFE (adhesive strength), and the relationship between the stress concentration and the scale effect of the sliding material was studied by FEM analysis.

The 5mm thickness PTFE plate was modeled with solid elements and a comparative analysis was carried out between model A and model B. In model A, the periphery of the lower 3mm thickness and the bottom surface were fixed; while in model B, the periphery was fixed whereas the bottom surface was free to move in the in plane direction (no friction). Their diameter was also changed and the stress concentration was verified.

The load acting on the PTFE plate was vertical and the friction coefficient was set to 0.1, so the uniform vertical load was 10 times the horizontal load. As shown in Figure2, when there was no adhesion, the stress was concentrated on the PTFE plate edges, and the scale effect can also be observed.

5 TEST EXAMINATION

Due to the conclusions that could be withdrawn from the previously conducted FEM analysis, regarding the influence of the adhesion and the scale effects, a protrusion verification test was conducted.

5.1 *Test Method*

5.1.1 *Adhesion tensile shear strength test*

In order to verify the adhesion strength of the PTFE and the middle plates, the test was conducted to comply with "Adhesives - Determination of tensile lap-shear strength of rigid-to-rigid. Bonded assemblies" in JIS K 6850. According to this, the test pieces shall be the adhesion test pieces specified in the JIS. In order to verify the adhesion strength with a PTFE plate, the test shall be conducted with a PTFE plate placed in between the adhesion areas (see Figure 3). The PTFE plate thickness is 1.5mm. The adhesive applied to the test pieces is chloroprene rubber adhesive (rubber adhesive), which has been used in pot bearings. In addition, the adhesion surface of the steel material shall be machined. The piece was fixed by clamping jaws at a distance of 50mm from the edge of the overlaid area, and the displacements were applied at constant speed. Once the adhesion area was fractured, the test was finished.

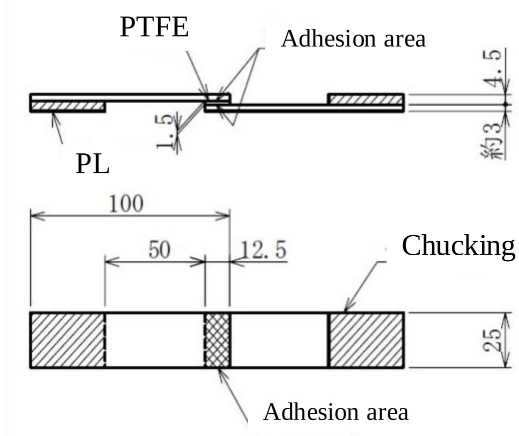


Figure 3. Adhesion tensile shear strength test

5.1.2 *Adhesion influence verification test*

In order to verify the level of protrusion if the PTFE and the middle plates have adhesion, a verification test was conducted with strip type PTFE plates. The test was conducted with L200, L400 and L600 test pieces (thickness 5mm× width 20mm× length 200mm, 400mm and 600mm). The surface pressure during the test was $20N/mm^2$, the horizontal displacement was applied in one direction, and the plate thickness and amount of protruded material were measured.

5.1.3 *Surface pressure influence test*

The test was conducted to verify if protrusion occurred when the PTFE plates slide under the surface pressure. The test was conducted under the condition that the middle plate with the PTFE plate attached was set to the lower shoe concave area, then the vertical load was loaded via the stainless plate attached to the upper shoe, and ±150mm displacement was given in the horizontal direction. The number of cycles was 11, and four different surface pressures were applied, 10, 20, 30 and 45 N/mm^2. The condition of the PTFE plate was checked during the test, and the friction coefficient was calculated with the obtained hysteresis curve. The dimensions were φ190mm and 730mm, whereas the thickness was 5mm. Moreover, the PTFE plate was not adhered to the middle plate, it was just inserted.

5.1.4 *Sliding distance influence test*

The test was conducted to verify if protrusion occurred when the PTFE plates, loaded in vertical direction, undergo sliding displacements during a certain period of time. The test was conducted under the following conditions: a vertical pressure of $20N/mm^2$, and a ±150mm displacement given in the horizontal direction. The friction coefficient was calculated with the obtained hysteresis curve. In the middle of the test, the PTFE plate shape was checked and the test continued until protrusion was observed. The dimensions of the PTFE plates were φ190mm and 730mm, whereas the thickness was 5mm. Moreover, the PTFE plate was not adhered to the middle plate, was just inserted.

5.2 *Test Results*

The protrusion verification test results can be observed in the flow chart shown in Figure 6. The details of the results of each test are as follows.

5.2.1 *Adhesive tensile shear strength test*

The PTFE plate and its mate steel adhered surface show remaining of rubber adhesive and present ductile fracture state. Tensile shear strength was approx. $0.5N/mm^2$. If we apply a friction coefficient of 0.1 to the allowable vertical pressure of the PTFE plate (30 N/mm^2) the obtained shear strength of $3N/mm^2$ is six times larger than the obtained shear strength.

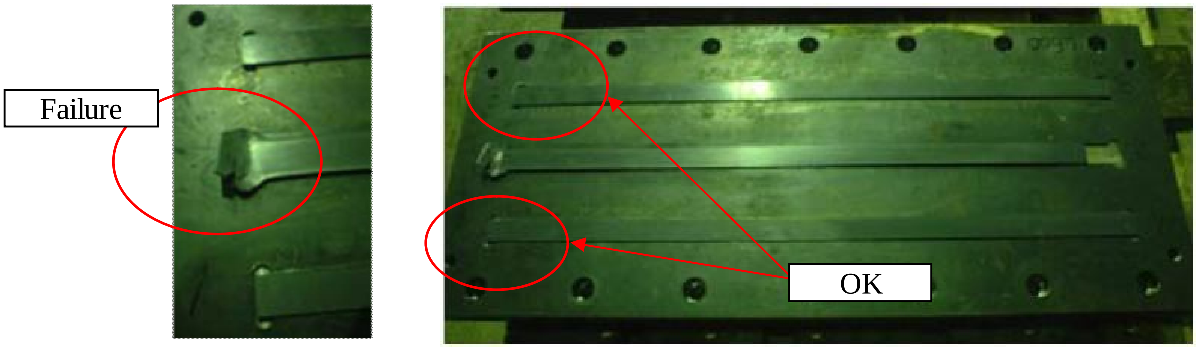


Figure 4. Test result of Adhesive influence verification test (L600)

Figure 5. Test result of Adhesive influence verification test (With Teflon powder)

5.2.2 *Adhesive influence verification test*
The test piece where Teflon powder was applied to the sliding surface bottom (back of the PTFE plate) showed a higher degree of protrusion than the test piece where no powder was applied. In addition a tendency of force concentration at the edges if the friction force at the bottom is low could be recognized. Among the L=200,400 and 600 tests, L400 and L600 test pieces presented prominent protrusions, as observed in Figure 4 and Figure 5. Even under the same surface pressure, the increment in the area of the test piece leads to larger forces concentrated in the edges, which leads to the protrusion of the PTFE under low friction conditions in the bottom plate.

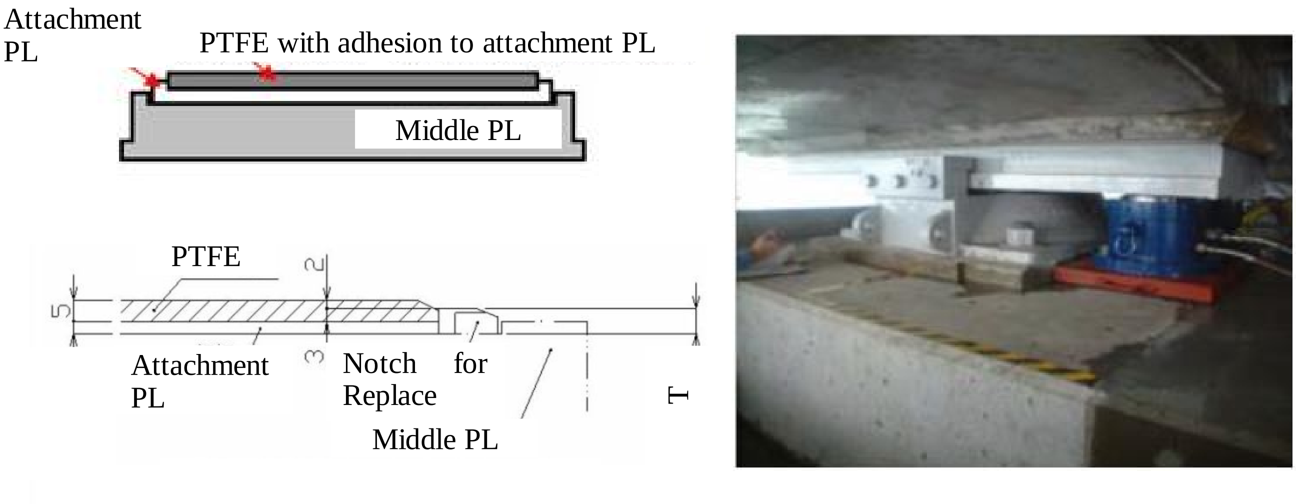
5.2.3 *Surface pressure influence verification test*
According to the test results, all the friction coefficients showed values lower than 0.1. In addition, lower coefficients of friction were observed when increasing the surface pressure, so that the original friction characteristics of the PTFE could be obtained by this method. For the φ190mm test piece, protrusion was not observed. On the other hand, for the φ730mm test piece, no protrusion was observed after applying surface pressures ranging from 10 to 20N/mm^2, but after the 30N/mm^2 stage, a 4-5mm protrusion in the horizontal direction of excitation as well as a 2-3mm protrusion in the vertical direction, were recognized. Finally, after applying a vertical pressure of 20N/mm^2, two protrusions 10mm width occurred.

5.2.4 *Sliding distance influence verification test*
As in the previous test, all the obtained friction coefficients were under 0.1, and by increasing the number of applied cycles, the friction coefficient was reduced. For the φ730mm test piece, no warp or protrusion took place from 1st to 71st cycles, but after 101 cycles, an approx. 8mm protrusion in a 45 degree direction and a warp could be recognized. On the other hand, for the φ190mm test piece, even after 101st cycles, no protrusion appeared.

6 PROPOSAL FOR A NEW BEARING STRUCTURE

Since the replacement of the main body of a bearing is complicated in long-span bridges with large reaction forces, the focus of this study was to examine the possibility of replacing only the sliding plate. The keyword for the design of the new sliding plates is therefore that they should be replaceable. In the conventional and concave intermediate steel plate where the PTFE plate is embedded, a concave thin structural steel plate is inserted, and the sliding plate where the PTFE is adhered is inserted, allowing for an easy replacement of the

PTFE plate. The PTFE edges of the new structure are chamfered to control flange forming, and an epoxy adhesive, which adhesion strength was verified, was used for the PTFE and the thin steel plates. In order to ensure safety if adhesion is gone, the PTFE is inserted in a digging-in section of the thin steel plate, (see Figure-6(a)).



(a) Structure for replaceable (b) Replacing

Figure 6. New bearing structure for replaceable

In order to avoid modification in the bearing height as much as possible, the structural steel plate thickness shall be 6mm or 9mm as standard. The PTFE plate diameter shall be as similar as possible to the one of the steel plate. The steel plates have notches in the proper positions that make them a replaceable structure.

Based on the results of the performance verification tests, the removal of the existing sliding plate and its replacement by the new sliding plate was conducted in the existing bridge (see Figure 6(b)). The conducted work verified the simplicity of the replacement strategy.

7 RE-REPAIR STRATEGY

After the replacement of the damaged bearings, some of the sliding plates of the new bearings suffered protrusion once again. In this chapter, the re-repair strategy for the sliding plates is analyzed, and a sliding plate shape modification, as well as a new material for the sliding surface, the Polyamide resin, are proposed and studied.

7.1 *Observed Damage*

The protruded sliding plate is shown in Picture-3. It presents a fractured surface that seems torn off in crescent shape, and the surface was pushed to the side intermittently.

Picture 3. Re-Damage of Movable Bearing

7.2 *Damage Cause Estimation*

As the estimated causes for the first repair, the following three points were enlisted.

- The sliding plate dimension (φ950mm) was larger than those used for other bridges. This led to stress concentration on the edges of the sliding plate by the scale effect.
- The dead load reaction force (surface pressure 26N/mm^2) and ordinary displacement (±250mm) were larger than those for other bridges, which was detrimental for the durability.
- Influence of the adhesion of middle plates and sliding plates. When adhesion disappears, the stress concentration previously described increases.

In addition to this, the following issues were also estimated as damage causes in this case:

- When exposed to temperatures around 23 °C PTFE, the coefficient of linear expansion becomes drastically large, and consequently the difference in thermal expansion between the PTFE plate and the steel plates increase. This generates stress in the connection between the middle plates and the sliding plates decreasing the adhesion.
- The deformation of the upper shoe affects the sliding plates in some way.

7.3 *Sliding Plate New Material Examination*

According to the previously mentioned issues, it seems necessary to study the possibility of replacing PTFE with another material which has a lower temperature dependency, but at the same time has high durability against large reaction forces. In the case of sliding bearings used for bridges, in the great majority of the cases PTFE is used as the sliding material. In this case other possibilities which are common in edification (Table-2) were examined, and polyamide which has a large value of allowable surface stress was selected.

7.4 *Sliding Plate Shape Modification Examination*

As it was mentioned above, the large dimensions of the sliding plate increase the possibility of protrusion. Therefore, the sliding plate in the current design was divided into small sliding surfaces in order to control the stress concentration. The studied possibilities are shown in Table-3.
After taking into consideration the cost performance, and the possibility of stress concentration in the corners, the sliding plate described in plan 2, with multiple round shaped sliding plates, was chosen. Moreover, the conduction of a durability test was also planned, due to the fact that the bearing stress would be over the allowable bearing stress (30N/mm^2), due to the reduction of the bearing area.

Table 2. Combination of sliding materials for buildings

Sliding material	Sliding plate	Standard surface pressure by dead load (N/mm^2)
PTFE	SUS316	20
Polyamide	SUS316	30
PTFE with filler	SUS316+PTFE coating	20

7.5 *Durability Test*

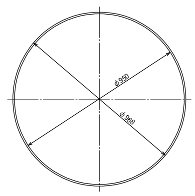
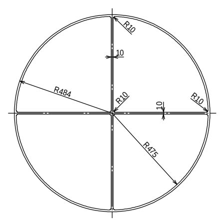
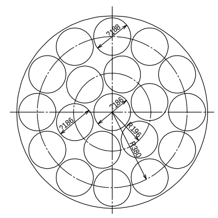
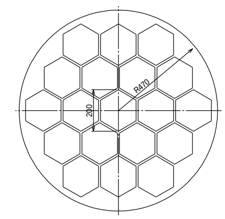
7.5.1 *Small reaction force test*

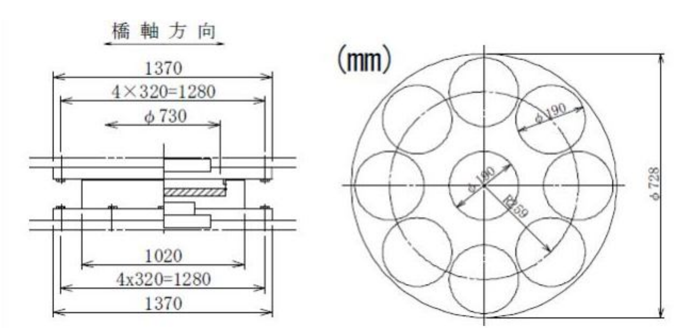
In order to verify the durability (deformation and friction coefficient) of the sliding material, a bearing equipped with a sliding plate with a diameter of 190 mm and a thickness of 5 mm, was loaded to its maximum design reaction (1,276kN, 45N/mm^2), and a lateral displacement cycle (positive and negative) of a prescribed amplitude (100mm) was imposed. During the test the thickness of the sliding material decreased around 0.3mm, after 2000 cycles the response was stable. The friction coefficient fluctuated but remained below 0.08.

7.5.2 *Large reaction force test*

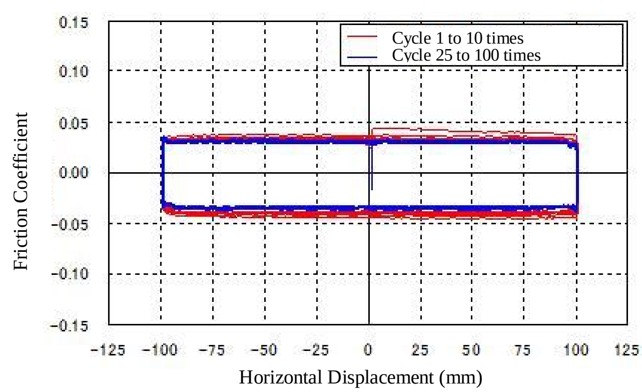
In this case a sliding plate with a diameter of 728 mm, where 9 small rounded shape plates of polyamide with a diameter of 190 mm was tested in a similar way. The applied load was 11,483 kN and the equivalent surface pressure 45 N/mm^2. After the test a small amount of shaved polyamide could be observed but there was no protrusion and no change of dimensions or shape was detected. The friction coefficient was below 0.05 as it can be observed in Figure-8.

Table 3. Sliding plate divide comparison table

		Plan 1	Plan 2	Plan 3
	Current state	4 divisions maintaining max. bearing area	Multiple arrangement of sliding plates with track records	Multiple arrangement of sliding plates with track records maintaining the area as much as possible
Shape (mm)				
Bearing area (mm^2)	708,823	689,654	523,311	493,635
Bearing stress (N/mm^2)	29.6	30.4	40.1	42.6
Issue	Since it exceeds standard size, it is impossible to manufacture with polyamide.	Possible stress concentration on the corners.	Because of the reduction of the bearing capacity area, the allowable bearing stress should increase a 50%.	Possible stress concentration in the corners. It is necessary to increase the manufacturing costs.
Cost performance	-	1.0	1.1	1.4
Required additional test		Durability test	Durability test Contact verification test	Durability test Contact verification test
Judgment	-	△	○	△



(a) Test specimen



(b) Friction measurement result

Figure 8. Large reaction force test

8 CONCLUSIONS

The conducted research provides sufficient evidences for the following conclusions:

i. The tests conducted to the PTFE sliding plates clarify that for the same amount of embedded PTFE, the larger the diameter is the higher the possibilities for protrusion to occur are. In addition, lower friction (adhesion) levels lead to a higher risk of protrusion of the PTFE plate.
ii. The proposed new bearing structure for sliding bearings which includes a concave thin concave steel plate where the sliding plate is inserted facilitates the replacement works in case of damage of the sliding plate.
iii. The results obtained from the tests performed to a sliding plate set up by small rounded shape polyamide sliding plates verified its durability, confirming it suitability to be applied in sliding bearings.

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