Behavior of Bridge Bearings for Railway Bridges under Running Vehicle

Eunsoo Choi†, Wan-Dong Yu*, Jinho Kim* and Sunhee Park*

Abstract

Open steel plate girder (OPSG) bridges are the most prevalent railroad bridge type in Korea, constituting about 40% of all railroad bridges. Solid steel bearings, known as line type bearings, are placed in most OSPG railway bridges. However, the line type rigid bearings generate several problems with the bridge’s dynamic behavior and maintenance in service. To compare and investigate the dynamic behaviors of line type, spherical and disk bearings, the vertical displacements of each bearing, including fixed and expansion type, under running vehicles are measured and analyzed. The displacements of disk and spherical bearings are measured after replacing the line type bearings with spherical and disk bearings. This study also analyzed dynamic behaviors of bridges. Furthermore, the deformation of the PTFE (Polytetrafluoroethylene) plate that is placed inside of expansion type spherical and disk bearings is measured and its effect on the dynamic behavior of the bridges is discussed. The up-lift phenomenon at the bearings installed for the steel bridges is estimated. The vertical displacements at mid-span of the bridges are compared according to the bearing types. Finally, the 1st mode natural frequencies are estimated, and the relationship to the vertical displacement is discussed.

Key words: Railway steel bridges, Spherical bearing, Disk bearing, Line type bearing, PTFE, Up-lift phenomenon

1. Introduction

Open steel plate girder (referred to as OSPG hereafter) bridges are composed with two steel girders as shown in Fig. 1. These bridges have been constructed and used for a long time, from the early days of railway construction in Korea, because they are inexpensive and easy to construct [1]. Accordingly, OSPG bridges make up 40% of railway bridges in Korea [2]. However, OSPG bridges are generally suffering from their poor capacity to absorb the impact caused by trains, and consequently most of the impact force may be directly transferred to the solid steel bearings, called line type bearings, depicted in Fig. 2. This transfer results in noise and riding quality problems, and produces cracks and crushing of the bearing concrete pedestals, and the pier cap in particular, as illustrated in Fig. 3. Because of these problems, the period of maintenance work becomes shortened. According to an evaluation of seismic performance of OSPG bridges using the fragility curve, the line type bearing is more vulnerable than other members of the bridge, such as the pier [3]. Thus, the line type bearings are being replaced by modern bridge bearings that improve seismic performance. The representative bridge bearings that can replace the line type bearings are disk bearings, a type of elastic bearings, and spherical bearings, one of the rigid steel bearings.

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Fig. 1 Cross-section of OSPG bridge
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Disk bearings support vertical load by using a polyurethane rubber pad, and are designed to absorb rotational deformation by revolving the pad. Also, the polyurethane disk can be used for bridge bearings without reinforcement, since its hardness is greater than natural rubber [4]. Spherical bearings also support vertical load, but by a high tensile brass circular pad, and are designed to absorb rotational deformation by revolving along with the curved surface of the circular pad. For this rotation, carbon powder, a kind of solid lubricant, is put between the curved surfaces to decrease the rotational friction. In the spherical bearings case, rubber or brass rings are used to seal the bearings to protect against the insertion of harmful foreign substances into the inside of the bearings. The rubber or brass rings, the materials to seal the bearings, do not have good durability, and may break and corrode, so that maintenance is needed [5]. For maintenance, separable bearings have been developed that do not require crushing the concrete to change some part or all of the components of the bearings. The developed spherical bearings are now applied in the field [6].

This study analyzes and compares the dynamic behavior of the bridge bearings and that of the bridges, when the disk and spherical bearings are installed instead of line type bearings. Thus, characteristics of the bearings are investigated in service.

2. Bearings and Field Tests

2.1 Bearings of bridges

The OSPG bridges, Socheon bridge and Pyeongcehon bridge, used for field tests, are 12 m type railway bridges, and located on the way between Oksan and Sangjoo. Socheon bridge has substructures of steel girder reinforced by steel plate and thus stiffness of the bridge is increased [7]. The dimensions of the line type bearings that were originally installed in OSPG bridges are shown in Fig. 4. According to the result of static load tests on the line type bearing, cracks appear at a horizontal load of...
The disk bearing shown in Fig. 5 has several components such as: 1) steel sole plates which are connected to bridge girders and pier caps or abutment surfaces; 2) a middle steel plate that has a pin at the center and separates the PTFE from the polyurethane disk; 3) a PTFE sheet which allows the translational movement of a bridge’s deck due to thermal expansion; and 4) a polyurethane pad disk which provides elastic support in the vertical direction and allows rotation. A fixed type of the bearing shown in Fig. 5(b) does not have the PTFE and top sole plate since it does not need to permit translational movements.

The spherical bearing basically has good seismic performance, and it is composed of a system that transfers the load to ground through the hemisphere bearing plate restrained by an upper and lower plate. The plain surface is used for contacting the surface of the bearing plate with the upper plate for stretching, and the spherical surface is also used for that, with the lower plate for rotation. Replacing the existing bearing with the general spherical bearing structure, shown in Fig. 6(a), affects operating trains, and it creates some problems, due to limited working time and restricting the passing of trains. The separated spherical bearing, which has the upper plate connected with the sole plate by bolts as shown in Fig. 6(b), was designed after considering these problems. Thus, when replacing an existing bearing, it can replace the frame and high tensile brass plate by using disassembling bolts, not crushing concrete and removing welded parts. There is a comparison of characteristics of both bearings in Table 1.

### Table 1. Comparison of characteristics of disk and spherical bearings

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Spherical bearing</th>
<th>Disk bearing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical support</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Rotational degree</td>
<td>Large (good to apply to bridges having a slope)</td>
<td>Possible to hold a large degree (0.04 rad.)</td>
</tr>
<tr>
<td>Durability</td>
<td>Vulnerable sealing durability</td>
<td>Good</td>
</tr>
<tr>
<td>Weight</td>
<td>Heavy</td>
<td>Lighter (respectively)</td>
</tr>
<tr>
<td>Check for damage</td>
<td>Difficult to check (cannot see components)</td>
<td>Easy to check (open structure)</td>
</tr>
<tr>
<td>Negative reaction</td>
<td>Possesses</td>
<td>Does not possess</td>
</tr>
</tbody>
</table>

![Fig. 6 Shape of spherical bearings](image)

![Fig. 7 Replacement procedure of disk bearing](image)
are shown in Fig. 9. A fixed disk bearing was installed at each of the two girders at the abutment, indicated by (A) in the Fig. 9. An expansion disk bearing was also installed like the fixed one at the pier, indicated by (B) in the Fig. 9.

Once the replacement of the bearings was completed, a locomotive, as depicted in Fig. 10, was run on the bridge. The six-axle locomotive with 215.8 kN per axle was initially run across the bridge at 5 km/h in each direction. Beginning with 10 km/h, the locomotive was then repetitively run across the bridge in 10 km/h increments in each direction, up to 80 km/h. This study was conducted by running the same vehicle tests before and after replacing the bearings to measure the behavior of the line type bearings, the disk bearings and the spherical bearings, and that of the bridges for each bearing state.

3. Test Result and Analysis

With the train running from Oksan to Sangjoo, in the case of the Socheon bridge, the train arrived at the abutment and exited at the pier, while the train arrived at the pier and exited at the pier for the Pyeongcheon bridge.

Fig. 8 Replacement procedure of the spherical bearing

Fig. 9 OSPG bridge; length and bearing locations

Fig. 10 Axle loads of the locomotive
Fig. 11 shows the two bridges, and this study measured data for the left span in the figure.

### 3.1 Vertical displacement of bearings

Vertical displacement of the disk bearing is measured at Socheon bridge, and the displacement of the line type and spherical bearings are measured at Pyeongcheon bridge. The disk and spherical bearings of the expansion type are installed with a circular plate of PTFE that absorb the longitudinal direction motions, such as temperature expansion [8]. The fixed bearings do not have PTFE, however, so the disk bearing uses a shear pin, and the spherical bearing utilizes the friction of the high tensile brass pad to control the motion of both the longitudinal and lateral direction.

Figs. 12 and 13 show the vertical displacement time history responses of the three bearings at locomotive speeds of 5 km/h and 80 km/h, respectively. The vertical displacement of the fixed spherical and line type bearings theoretically do not occur, since the bearings are rigid steel bearings. However, the vertical displacements were observed, because the rigid bearings also support vertical load by contact surfaces and they were not completely in contact with each other. The vertical displacement of the spherical in Fig. 12(a) was approximately 0.034 mm, when the three axle load passed as a group. The line type bearings also were observed to have similar behavior to the spherical bearing, but the line type bearing behavior was like the disk bearings in Fig. 12(a). Since the line type bearings, including both fixed and expansion bearings, are one of the rigid steel bearings, the vertical displacement of the bearings with load by axle load group should only be a tiny amount of displacement (about 0.084 mm) as shown in Fig. 12 (b). But the peak displacement of the fixed line type bearing was 0.217 mm as shown in Fig. 12(a). It means that the contact surfaces were not completely in contact with each other, and maintained a float condition then touched by the axle load. There are several reasons for float condition of the bearing, such as poor installation of the bearings, torsion of the bridge and etc. The OSPG railway bridges are light weight construction as compared with their stiffness, and thus it was not completely in contact with the steel girder, and became a float condition, by self-weight. While it was in float condition, the peak vertical displacement of line type bearings was similar to the peak vertical displacement of the disk bearings, 0.236 mm.
The floated line type bearing directly transferred impact from vertical motion to concrete, and it could produce damages such as cracks on concrete. The peak vertical displacement of the fixed disk bearing was 0.236 mm, and since the load when it was observed was 273.7 kN, the stiffness could be calculated as 1159.7 kN/mm.
In Fig. 12(b), vertical displacement of the expansion spherical and disk bearings was bigger than the fixed bearing because of PTFE, which was placed in the expansion bearings. The peak displacement of spherical and disk bearing was 0.252 mm and 0.409 mm, respectively. Thus, the bigger displacement of expansion bearings was understood to be due to the vertical displacement of the expansion bearings, which included the deformation of the PTFE pad.

Figs. 12 (c) and (d) show the vertical displacement time history responses of the direction from Sangjoo to Oksan at a locomotive speed of 5 km/h, and the trend of this response is similar to Figs. 12(a) and (b) when the direction is from Oksan to Sangjoo. However, there were differences between the train directions at the measured point from the roadbed and from the side span, influenced by the continuity of rail. When the train reaches the measured point from the roadbed, the rail does not affect the behavior of the bridge, but for the other case, an up-lift phenomenon produced by the bending of connected rail was observed at the end. This up-lift phenomenon could have an impact on the concrete of the bridge bearings.

In Fig. 13, the similar trends of the curves can be found with lower speed, but vibration characteristics influenced the vertical displacement of the bridge bearings and were reflected with the high speed. Thus, vibration time could be called the natural frequency of the bridge. Especially, the vibration was observed after the train had left, and so this is the vibration of the bridge bearings by free vibration. When the train was running with high speed, the up-lift phenomenon was also observed.

Fig. 14 shows the vertical displacement of three bearings according to the locomotive speed, and there were almost no differences among the increment of speeds and the steering directions. When running with high speed, however, there was some effect of the vibration characteristic, but there were almost no changes in the peak point.

### 3.2 Deformation of PTFE

The PTFE plate used in the bearings was 250 mm in diameter and 4.5 mm thick. The tensile strength of general PTFEs range from 7 MPa to 28 MPa, and the elongation to fracture varies from 100% to 200% strain [9]. The compressive stress at 1% strain is 4.2 MPa. Thus, the Young’s modulus is approximately 410-750 MPa, and their frictional coefficients are very low, with 0.01 to 0.03 for the purpose. However, the frictional coefficients increase up to 0.1 under high speed motion.

The expansion line type bearings are formed to put the steel girder on the circular rigid steel to allow motion in the longitudinal direction. In this case, the frictional coefficients are bigger than 0.5, since steel and steel are in contact each other. The large frictional coefficients produce large resistance, when the steel girder moves in the horizontal direction for some reason, such as the temperature expansion, and it induces compressive or tensile stress on the steel girder. To minimize such an additional stress, smaller frictional coefficients of the bridge bearings for movement in the horizontal direction were more beneficial. As mentioned above, the PTFEs are used for this purpose, and its frictional coefficients are very small compared with that of steel, with 0.5.

As mentioned above, the Young’s modulus of PTFEs is about 410-70 MPa, and PTFEs are deformed by load. Hence, the PTFE pads inside of the disk and spherical bearings were deformed by the train axle load, and this deformation of the PTFE pad was the reason for the bigger vertical displacement of the expansion bearings compared to the fixed bearings. Thus, the vertical deformation of PTFE pad could be calculated as minus vertical displacements of fixed bearings from that of expansion bearings. In Fig. 15, vertical deformation of the PTFE pad of each bearing is illustrated in relationship with the speed of each locomotive, and the increment of speed was less.
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For the disk bearings, the average vertical displacement of the PTFE was 0.263 mm, while that of the spherical bearings was 0.203 mm, and thus, the vertical stiffness of each bearing was 1040.7 kN/mm and 1348.3 kN/mm, respectively. Considering the estimated stiffness of polyurethane rubber pad of 1159.8 kN/mm, the expansion disk bearings were formed by connecting two elastic bodies in series, and the expansion spherical bearings would be regarded as elastic bearings, not rigid steel bearings. The similar vertical displacement between expansion spherical bearings and the fixed disk bearings shown in Fig. 12 provides the experimental basis of the above theory.

3.3 Up-lift phenomenon

As mentioned above, the up-lift phenomenon is produced on the OSPG bridges by the entering and exiting movement of the train. The up-lift phenomenon occurs because the bridge bearings were floating from the steel girder due to the continuity of rail when the train was located at the side span of the measured point.

Fig. 16 show the up-lift displacement of three bearings that relate to the locomotive direction. The bridge bearings generally do not have materials that resist the up-lift phenomenon immediately. Especially, the line type bearing is a structure that has two steels in contact with each other, and thus, self-weight is the resistance to the up-lift phenomenon. Therefore, up-lift displacements of the bearings were larger than for that of the other bearings. The up-lift amount of the fixed line type bearings were observed to be two times bigger than the amount of the expansion line type bearings, and it would be considered that the fixed bearings were observed to have relatively smaller up-lift, because of floating bearings. Average up-lift displacement of the expansion line type bearings is 0.15 mm, and this is the biggest displacement among the bridge bearings.

The average up-lift displacement of the fixed disk bearings are 0.012 mm, and this value is just approximately 14% of the expansion one, of 0.086 mm. A polyurethane rubber pad with bumps is placed in the disk bearings, and the upper and lower plates also have bumps, and this increases frictional resistance to prevent horizontal direction expansion by compressive load. Bumps of polyurethane rubber pad and steel plate are almost completely stuck after being in service for quite a long time, and thus, it produces a similar phenomenon to being glued. The smallest up-lift displacement was observed at the fixed disk bearings and it is because adhesion resists the up-lift. However, the PTFE plate was not stuck to the steel plate.
but the polyurethane rubber pad was strongly stuck with
the plate, and the structure could not resist up-lift. Thus,
up-lift is relatively bigger, but it is a developed value
(57.3% of the expansion line type bearings) compared
with the value of the expansion line type bearings.
There were almost no differences between the average up-
lift values of fixed and expansion spherical bearings of
0.050 mm and 0.056 mm, respectively. The spherical bear-
ings that were installed at Pyeongcheon bridge have the set
of negative reaction resistance devices at the side of bear-
ings, and these are designed to immediately resist up-lift.
General spherical bearings have negative reaction resis-
tance devices inside, however, it cannot immediately resist
up-lift, but can resist large up-lift, as the safety devices that
are isolated. The spherical bearings that were installed at the
Pyeongcheon bridge used rubber springs to linearly resist
up-lift, and it returns to its original place by the elasticity of
rubber, when the up-lift phenomenon have been removed.

3.4 Vertical displacement at mid-span of
bridges
This study analyzed displacement properties and
changes of the OSPG bridges at the mid-span according to
the bearing type. Fig. 17 shows the vertical displacement
time history responses of the three bearings at locomotive
speeds of 80km/h. In the case of the Pyeongcheon bridge
(Fig. 17 (c)), both the line type and spherical bearings are
rigid steel bearings, and large vibration was not produced
by the train entering and exiting the span. Just when the
axle load group was located at the mid-span, the vibra-
tions were observed. Thus, the remaining vibration after
the train exited the span was relatively small. However,
there were relatively large vibrations at the Socheon
bridge, when the train was entering, exiting and after leav-
ing the span. The disk bearings are elastic bearing, but the
vibration characteristics are not large differences. There-
fore, it could be judged that the increment of vibration at
the Socheon bridge was not produced because of the elas-
tic support of the disk bearings but just because of unique
properties of the Socheon bridge. At the OSPG bridges,
sidewalk and other facilities are located beside the bridges,
and these facilities could affect the vibration characteris-
tics, that is to say, damping characteristics. The reason for
the larger vibration at the Socheon bridge could be said to

Fig. 17 Time history of vertical displacements at mid-span according to bearing types

Fig. 18 Vertical displacement ratio as a function of velocity
be the effect of this kind of damping, but not an effect of the disk bearings, one of the elastic bearings.

For analyzing the effect of the replacement bearings at each locomotive speed, the ratio of vertical displacement of the spherical or disk bearings to that of line type bearing are shown in Fig. 18. Average vertical displacements of the disk bearings and spherical bearings were 1.063 and 0.895, respectively. It is reasonable that the vertical displacements of the disk bearings are larger than that of the line type bearings with 6.3%, because the disk bearings are elastic bearings. The spherical bearings are, however, one of the rigid steel bearings like the line type bearings, and the expansion spherical bearings behaved similarly to the floated fixed lined type bearings. So the vertical displacements of the spherical bearings should not be changed from that of the line type bearings. But the vertical displacements of the spherical bearings at the mid-span were decreased an average 10.5%. The reason is that the support area of spherical bearings is larger than the area of the line type bearings as shown in Figs. 4 and 6. Therefore, the pure span length with spherical bearings is decreased, and thus, vertical displacement of the spherical bearings also decreased.

The vibration characteristics can be confirmed through the impact factors in Fig. 19, and it was calculated by regarding responses of 5 km/h as the static response. Impact factors of the disk bearings bridge were similar with or smaller than the factors of the line type bearings at the Socheon bridge. Thus, it cannot be said that the vibration is increased by using disk bearings at the OSPG bridges. At the locomotive speed of 80 km/h, the impact factor increased, but it was not because of the disk bearings, since the line type also increased. In the case of the spherical bearings, impact factors were similar to or bigger than that of the line type bearings, and thus, it could be said that the impact factors are increased by using spherical bearings.

### 3.5 Natural frequency change

This study observed natural frequency changes caused by replacing the bearings. In the earlier studies, 1st natural frequencies before and after installing disk bearings was estimated to be 15.625 Hz and 15.137 Hz, respectively [6]. Therefore, 1st natural frequencies were decreased by 3.13% by using disk bearings. The decrement of natural frequencies means the decrement of stiffness of the whole system, and thus the stiffness and natural frequency relation of the multi-story structures are like the equation.

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Fig. 19 Impact factors according to bearing types
where, ‘k’ means stiffness and ‘m’ means mass of the system. Thus, change of natural frequency is proportional to the square of stiffness, so the decrement of natural frequency by 3.13% caused the decrement of stiffness of 9.8%. Decrement of stiffness increases vertical displacement produced by load of system, and so it coincides with the above estimated value of increment of vertical displacement of 6.3%.

For the Pyeongcheon bridge, 1st natural frequencies estimated by using vertical displacement and acceleration are shown in Fig. 19. The estimated value of 1st natural frequencies by using vertical displacement and acceleration of the line type bearings were 12.07 Hz and 12.34 Hz, respectively. Natural frequencies of the spherical bearings were 12.27 Hz and 12.20 Hz, and so the average value becomes 12.23 Hz. Thus, natural frequencies were not changed by replacing bearings from line type to spherical. But this estimated result is not consistent with the measured vertical displacement value at mid-span. Vertical displacement was decreased 10.5% by replacing bearings, and this means increment of stiffness. Natural frequency was estimated by using Equation (1) and it increased 3.24%. The estimated value that considered the increment amount is 12.62 Hz. Therefore, additional study and analysis are needed to resolve these discrepancies.

4. Conclusion

This study analyzed the dynamic behavior characteristics of the spherical and disk bearings that replaced the line type bearings, and the dynamic behaviors and characteristics of each bridge. Vertical displacements of the line type bearings should not typically be produced, but when the bearings are floated bearings, vertical displacement is observed, and its value is similar to that of the expansion disk bearings, one of the elastic bearings. Vertical displacements of the spherical bearings also should not be observed, but vertical displacement is influenced by PTFE plate, and its value was similar to the elastic bearings. These effects have to be considered, when designing and analyzing the spherical bearings. The large vertical displacement was produced by locomotive axle load at the disk bearings as one of the elastic bearings, and the spring effect of the PTFE plate and polyurethane rubber pad acted at the expansion bearings and it also produced large vertical displacement.
Thus, the vertical stiffness of the polyurethane rubber pad at the expansion bearings needs to be larger than the fixed one to decrease the spring effect. That is to say that the area of the polyurethane rubber pad at the expansion bearings should be wider than the one at the fixed bearings.

Up-lift phenomenon was produced by the running train at the OSPG railroad bridges, and the largest up-lift occurred at the line type bearings. This up-lift phenomenon at the line type bearings can cause dangerous damage to the bearings’ concrete due to impacting. There were differences between expansion and fixed disk bearings, and much larger up-lift was observed at the expansion bearings. For the spherical bearings, the expansion and fixed bearings have similar value of up-lift, and it was possible because of the specific elastic resistance device for up-lift that was placed in the bearings.

When comparing the 1st natural frequencies among the bridges at the mid-span, vertical displacement of the bridge with the disk bearings has increased, and so the influenced the decrement of stiffness and the decrease of the estimated natural frequency. However, while the vertical displacement of the bridge with the spherical bearings decreased, 1st natural frequency was not changed, so these results do not coincide with each other. The reasons for this result should be defined through additional study.

References


