EFFECTS OF STEEL BEARING PERFORMANCE ON GLOBAL SEISMIC RESPONSE OF A BRIDGE

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ABSTRACT :

The present study discusses the effects of a steel bearing performance on bridge response during a strong ground motion. For this purpose, a hybrid seismic response experiment for a bridge system is conducted and the hybrid seismic test results are further discussed with the aid of a numerical analysis. In the experiment, a steel pin bearing specimen is prepared. Numerical model applied in the experiment is a two-degrees-of-freedom model. A slip-type hysteresis is experimentally identified for the longitudinal and transverse directions, respectively. In this respect, a slip mode as well as a stiffness increase is observed arising from existence of space around the pin. In addition, the degree of superstructure response is affected by a slip-type hysteresis, particularly in the longitudinal direction. In the analysis, a numerical model for the steel pin bearing is developed based on the slip-type hysteresis characteristics. Then, the response of a bridge with the aid of the devised steel pin bearing is examined. As a result, the devised numerical steel pin bearing model can well assess global bridge responses associated with nonlinear bearing performance observed in the experiment. In addition, the pier ductility factor as well as the degree of superstructure response is clearly affected by the slip-type hysteresis.

KEYWORDS: bridge, earthquake resistance, hybrid experiment, bearing support, earthquake response analysis

1. INTRODUCTION

Effects of seismic limit state performance of steel bearing on a superstructure are one of the critical issues in earthquake resistance capability of bridges. Bearing failure such as set bolts breakout, roller pull-out and pin cut-off etc. brought large relative displacement and gaps in elevated bridges of Hanshin Expressway during the 1995 Hyogo-ken Nanbu earthquake. In this connection, rubber bearings or seismic isolation devices are replacing older steel bearings. However, steel bearings are still in use in existing bridges across Japan. Though, current steel bearings may have sufficient strength and/or ductility capacity for a moderate ground shaking, local and global seismic response of a bridge associated with steel bearing performance has not been well understood so far.

Physical nature of steel bearing required in developing dynamic seismic response analysis model of a bridge system has been investigated for last two decades or so. The simplest way may be in such a manner that fixed and movable bearings are modeled as a nodal in a frame structure analysis. In addition, bi-linear models are sometimes employed to represent bearing performance. Yield and ultimate strength calculation procedures based on real failure modes during the Hyogo-ken Nanbu earthquake are also presented, subsequently a tri-linear model for fixed and movable bearings are developed. These observations suggest that a systematic nonlinear model for steel bearings has not yet been established.

Under these circumstances, a hybrid seismic response experiment can be a powerful tool to examine earthquake response nature of a total bridge system. Seismic hybrid tests have been extensively used in earthquake resistance study of bridges, focusing on nonlinear performance of a reinforced concrete column, a steel column and various bearing devices like a seismic isolation bearing. However, no seismic hybrid experiments have been conducted on nonlinear behavior of steel bearing so far.

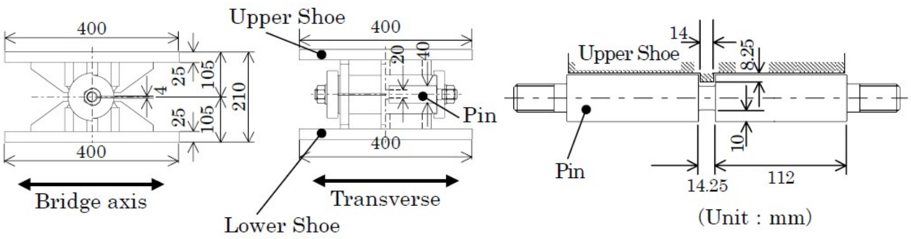


Figure 1. Dimension of bearing specimen

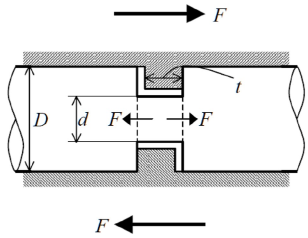


Figure 2. Shear key structure of the pin

The objective of the present study is then to discuss the effect of near limit state in regard to fixed steel bearing on seismic performance of a total bridge system. First, the hybrid seismic experiment is described. Second, experiment results are discussed in view of superstructure response, restoring force characteristics and others. Third, the developing numerical pin bearing model based on the hybrid test results is explained. Finally, concluding remarks throughout the present study is summarized. The terms 'fixed' and 'steel' is dropped unless confusion arises in the present paper.

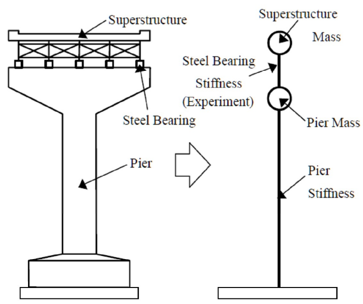


Figure 3. 2DOF model idealization for the hybrid test

2. HYBRID SESMIC RESPONSE EXPERIMENT

In fact, a hybrid experiment scheme employed in the present study is a real-time hybrid experiment that has an actuator response delay compensation function using a digital signal processor (DSP) instead of a pseudo dynamic experiment procedure. Hereafter, the term 'real-time' is dropped unless confusion arises.

2.1. Bearing

The present study concerns the earthquake damage only on a bearing body. Then, possible failure modes such as set bolt breakout between the superstructure and the substructure and/or anchor bolt pullout at the interface between the lower bearing shoe and the column are out of consideration.

The pin-type bearing specimen prepared in the hybrid experiment is schematically illustrated in Figure 1. The pin is a steel cylinder whose middle part diameter is intentionally narrowed for assembling purpose with upper and lower shoes. The metal material was SS400, which is recommended in the Handbook of Bearing Support for Highway Bridge.

To design the pin profile, demand and capacity balance on the transverse direction excitation associated with the applied force F is considered as illustrated in Figure 2. The outer diameter D and the narrowed part diameter d of the steel cylinder can be determined by the tensile strength capacity of the narrowed part and the shear strength capacity at the shear key characterized by thickness t in the shoe.

Finally, 40 mm and 20 mm for the outer diameter and the narrowed part diameters respectively are determined so that the cylinder will sustain breakout under the maximum load capacity of the hydraulic actuator used in the hybrid experiment, i.e., 500 kN. As far as the shoe plate design is concerned, the size is appropriately adjusted to seat the designed cylinder based on the fact that shoe plates stay in elastic deformation subjected to relatively large load.

2.2. Numerical Model Development

The two-degree-of-freedom model (hereafter, 2DOF model) is used in this study as a numerical model for the hybrid test. Figure 3 provided configuration of 2DOF model.

Figure 4 shows a target bridge for developing the 2DOF model. The target bridge consists of 160 m long three-span continuous decks supported by four rectangular reinforced concrete piers with one fixed bearing and

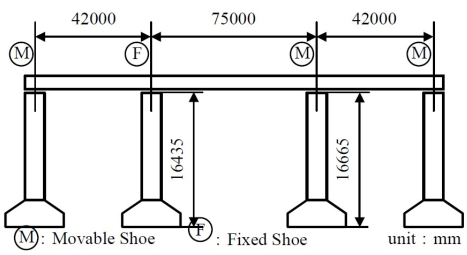
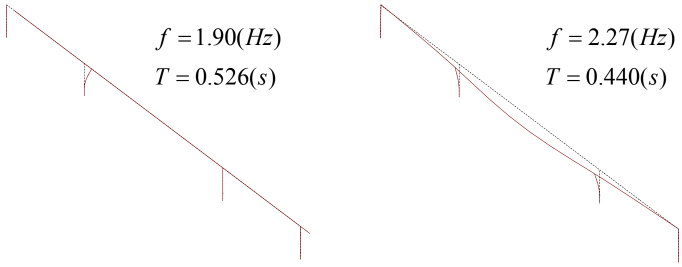


Figure 4. Target bridge (Unit:mm)



(a) Longitudinal direction (b) Transverse direction
Figure 5. 1st Mode shape in 3DFE model

Table 1. Properties of the target bridge

(a) Superstructure of the target bridge

Mass per Unit Length (t/m)		19.0
EI (kN·m^2)	Vertical	1.95×10^7
	Transverse	1.95×10^6
GJ (kN·m^2)		7.739×10^5

(b) Reinforced concrete columns

		1st Point		2nd Point		3rd Ponit	
		M_1(kN·m)	ϕ_1(1/m)	M_2(kN·m)	ϕ_2(1/m)	M_3(kN·m)	ϕ_3(1/m)
Fixed Shoe Column	Bridge Axis	1.52×10^4	3.90×10^{-5}	1.34×10^5	6.55×10^{-4}	1.72×10^5	3.81×10^{-3}
	Transverse	1.15×10^4	3.90×10^{-5}	1.01×10^5	6.55×10^{-4}	1.30×10^5	3.81×10^{-3}
Movable Shoe Column	Bridge Axis, Transverse	1.27×10^4	4.90×10^{-5}	7.06×10^4	7.56×10^{-4}	1.00×10^5	3.70×10^{-3}

Table 2. Restraining of relative displacement between superstructure and substructure

Shoe Condition	Bridge Axis	Transverse	Vertical	Around Bridge Axis	Around Transverse	Around Vertical
Fixed Support	Restrained	Restrained	Restrained	Restrained	Free	Free
Movable Support	Free	Restrained	Restrained	Restrained	Free	Free

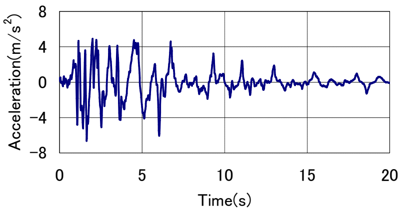


Figure 6. Takatori ground motion record (EW component)

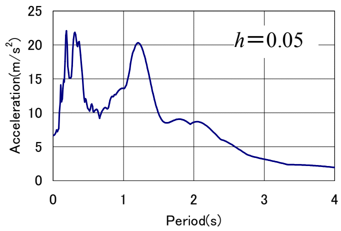


Figure 7. Acceleration response spectrum of Takatori record

three movable bearing conditions. The superstructure is assumed to have 3,000 t in mass. Three dimensional finite element model (hereafter, 3DFE model) are constructed for the longitudinal and transverse directions, respectively. Linear beam elements having their specifications (mass per unit length, flexural rigidity EI and torsional rigidity GJ) are assigned for the superstructure. Reinforced concrete columns corresponding to both fixed and movable bearings are idealized as a beam element with a tri-linear moment M and curvature ϕ relationship. 3DFE model properties are tabulated in Table 1. The fixed and movable bearings are modeled as just nodal in the 3DFE model and their freedoms are summarized in Table 2. The general purpose commercial code TDAPIII is used for the analysis. The first mode shape of the target bridge for the longitudinal and transverse directions is shown in Figure 5, respectively. The first natural period is 0.526 s and 0.440 s for the longitudinal and transverse directions, respectively.

The 3DFE model is then reduced to the 2DOF model for the longitudinal as well as the transverse directions as presented in Figure 3. In order to develop the 2DOF model, the analytical correlation between the 2DOF and the 3DFE model analyses is examined focusing on the maximum displacement response at the column top based on the dynamic analysis results. An EW component of the observed ground motion at Takatori-eki station of JR West during the 1995 Hyogo-ken Nanbu earthquake (hereafter, Takatori record for simplicity) is used for the dynamic analysis throughout this study. In reality, first twenty seconds of duration of Takatori record is used for analysis purpose. The acceleration time history and the acceleration response spectrum (h=5%; h represents

Table 3. Similitude rule used for the hybrid experiment

Quantity	Dimension	Scale Factor
Length	L	S
Mass	M	S^3
Time	T	S
Velocity	LT^{-1}	1
Acceleration	LT^{-2}	1/S
Force	MLT^{-2}	S^2
Rigidity	MT^{-2}	S

Table 4. Dynamic properties of 2DOF model

	Bridge Axis	Transverse
Superstructure Mass(t)	15.728	7.478
Pier Mass(t)	1.187	
Pier Stiffness(kN/m)	1.46×10^5	9.29×10^4
Damping Ratio	0.2086	0.2825
Natural Frequency(Hz)	1.140	1.269
Natural Period(s)	0.8773	0.7879

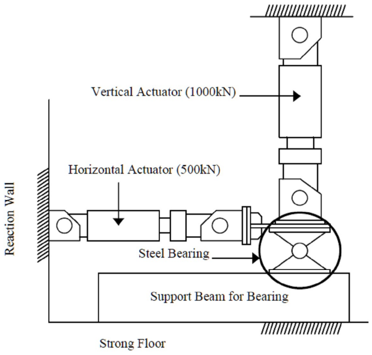


Figure 8. Illustrated view of experimental setup (longitudinal direction)

Figure 9. Photographed entire view of experimental setup (transverse direction)

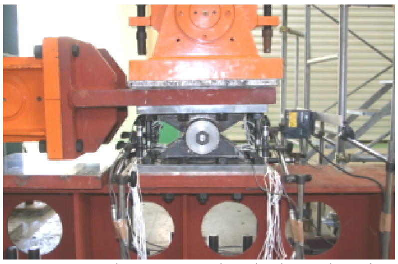


Figure 10. Photographed local view of experimental setup (longitudinal direction)

damping ratio) are presented in Figure 6 and Figure 7, respectively.

As far as the column stiffness is discussed, values of equivalent stiffness (secant stiffness) and damping ratio (consumption energy in the hysteresis loop) for the column correspond to nonlinear load and displacement relationship listed in Table 1.

To assess seismic response of the target bridge, a similitude rule must be applied. The similitude rule widely used among many hybrid seismic response experiments for a bridge structure is employed as presented in Table 3. The scale factor is determined on the ground that dimensions of the model bearing can be scaled down from a so-called ‘300 t class bearing’ whose narrowed part diameter size is equal to 60 mm by referring one of the practical design examples. As a result, the scale factor is determined to be 3.2. In this respect, five bearings are assumed being installed on the pier. The 2DOF model properties identified based on the seismic analysis results are tabulated in Table 4.

2.3. Experiment Appearance

The schematic view of the hybrid experiment setup is depicted in Figure 8. Photographs of the transverse and longitudinal directions setups are also shown Figure 9 and Figure 10, respectively. The horizontal and vertical loads are applied to the bearing specimen by 500 kN and 1,000 kN actuators, respectively. The 500 kN actuator play a role on response displacement loading from the computed superstructure response, while the 1,000 kN actuator load the dead weight of the superstructure.

The horizontal loading is applied to the bearing specimen as a computed response under Takatori record for the longitudinal and transverse directions. In other words, for an example, the pin axis is placed perpendicular to the 500 kN actuator axis for representing the longitudinal excitation.

3. RESULTS AND DISCUSSION FOR HYBRID TEST

3.1. Excitation Cases

Peak ground acceleration (PGA) value equal to 6.66 m/s^2 in Takatori record is adjusted like 1.11 m/s^2, 3.33 m/s^2, 6.66 m/s^2 and 8.00 m/s^2. Then, four sets of excitation cases are applied for the longitudinal direction.

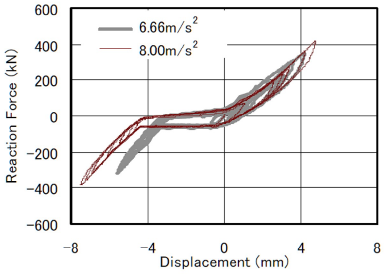


Figure 11. Hysteresis behavior on load and displacement relationship of the bearing in the longitudinal direction

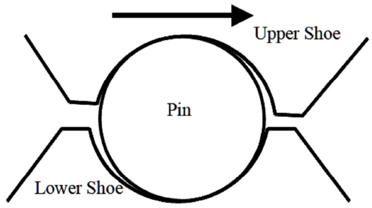


Figure 12. Translation movement around the pin

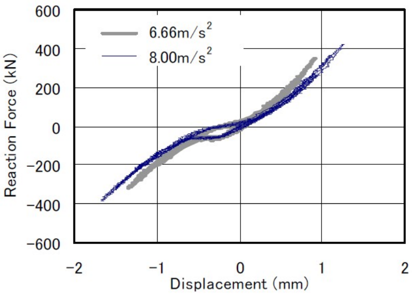


Figure 13. Hysteresis behavior on load and displacement relationship of the bearing using corrected displacement in the longitudinal direction

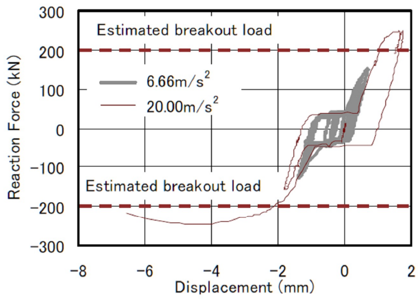


Figure 14. Hysteresis behavior on load and displacement relationship of the bearing in the transverse direction

According to the similar manner with the case of the longitudinal direction, 1.11 m/s^2, 3.33 m/s^2, 6.66 m/s^2, 10.00 m/s^2 and 20.00 m/s^2 in PGA are applied for the transverse direction case.

3.2. Bearing Behavior

3.2.1 Longitudinal Direction

Figure 11 shows the load and displacement relationship under 6.66 m/s^2 and 8.00 m/s^2 in PGA excitation cases. A slip-type hysteresis loop is clearly observed in the respective case. The slip is probably due to rotation of the bearing around the pin axis, which simultaneously occurs when the applied load exceed the maximum static friction force between the upper and lower shoes. The positive and negative reaction forces correspond to the slip stays almost at constant values regardless of the magnitude of PGA. These absolute values are, however, unequal between positive and negative movement. This may depend on intact inclination of the bearing seating.

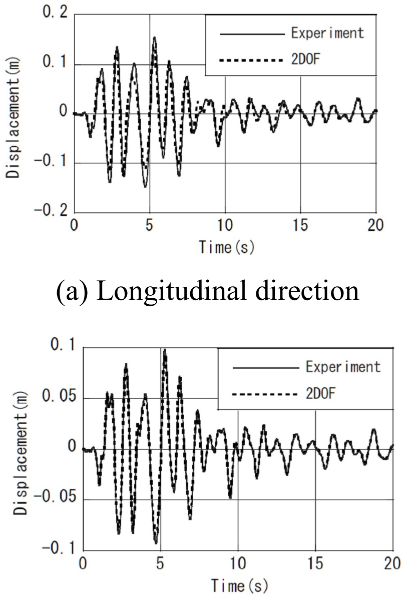
The cause of relatively large stiffness as observed in Figure 11 can be explained as follows: When the shoe rotates around the pin axis, a slight translation of the pin occurs due to existing gap as illustrated in Figure 12. After the translation reaches the pin-support surface between upper and lower shoes, like a mechanical key appears, resulting in essential stiffness of bearing body.

Figure 13 also presents load and displacement hysteresis under 6.66 m/s^2 and 8.00 m/s^2 in PGA excitations, in which rotation-induced displacement is extracted. Then, slip length is obtained as about 0.5 mm. In addition, the difference between the pin diameter and the pin-support diameter is 0.5 mm, which indicates that the maximum translation should be equal to 0.5 mm and meets the slip length as shown in Figure 13. This observation demonstrates the above-mentioned discussion.

3.2.2 Transverse Direction

Figure 14 indicates load and displacement relationship under 6.66 m/s^2 and 20.00 m/s^2 in PGA excitations, in which significant slip-type hysteresis loops are also obtained. Note that pin breakout at the narrowed part occurred during the 20.00 m/s^2 excitation; subsequently the hybrid experiment is terminated due to the limiting values of displacement and force of the 500 kN actuator. The degree of the reaction force at which the slip occurs is roughly constant under respective excitation, indicating that the pin moves along with the gap around

Figure 15. Breakout of the pin



(a) Longitudinal direction

(b) Transverse direction

Figure 16. Comparison of superstructure displacement time history (2DOF vs. experiment; 6.66m/s^2 excitation)

the shear key (See Figure 2) of the bearing when the applied force becomes larger than the static friction force. The magnitude of the slip movement is further intensified arising from the enlargement of the narrowed part brought by cyclic stress-induced plastic deformation.

Figure 15 presents the pin breakout occurred during the 20.00 m/s^2 excitation. One can observe that the failure surface deviates 45 degrees from the pin axis. However, this seems to be still brought by a tensile force. The tensile strength of the narrowed part of the pin is calculated about 160 kN, this value virtually becomes about 200 kN because of additional static friction force of 40 kN. On the other hand, the breakout load is identified as 247 kN as shown in Figure 14, which indicates a twenty percent increase to the above-mentioned value.

3.3. Effects On Superstructure Response

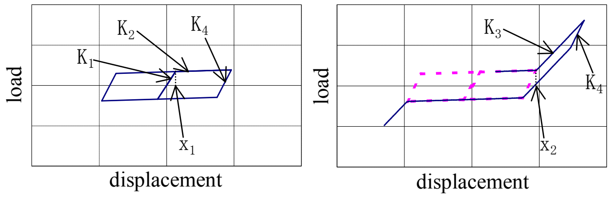
Experimental results discussed here are enlarged to a real size and correlated with the 2DOF analysis results. In this respect, the 2DOF model excludes the relative displacement of the bearing to investigate clearly the effect of the bearing performance. The superstructure displacement time histories in the longitudinal direction and the transverse direction are plotted in Figure 16, respectively.

In the longitudinal direction, the duration patterns are similar to each other, especially peak response are almost identical in the duration of 10 s and more. On the other hand, the magnitude of the peak response in the experiment result is relatively larger than those of in the analysis result. Thus, the effect of the nonlinear hysteresis characteristics of the bearing on the superstructure response is observed. The maximum displacement obtained by the experiment is 18.4 mm or about 14% larger than that of the 2DOF analysis result. This suggests that essential response of a bridge superstructure needs to be estimated taking the bearing hysteresis into account. The slip-type hysteresis as shown in Figure 11 undoubtedly contributes to such a response. As a result, relatively larger peak responses occur in negative value in the reflection of negatively biased hysteresis loop.

In the transverse direction, peak responses as well as duration characteristics are almost identical. The maximum displacement is 98.2 mm and 94.2 mm for the experiment and the 2DOF analysis, respectively. This comparison indicates that the experimental maximum response is about 4 % larger than that of the 2DOF analysis and therefore the effect of the slip-induced displacement on the superstructure is insignificant.

4. NUMERICAL MODEL DEVELOPMENT FOR BEARING

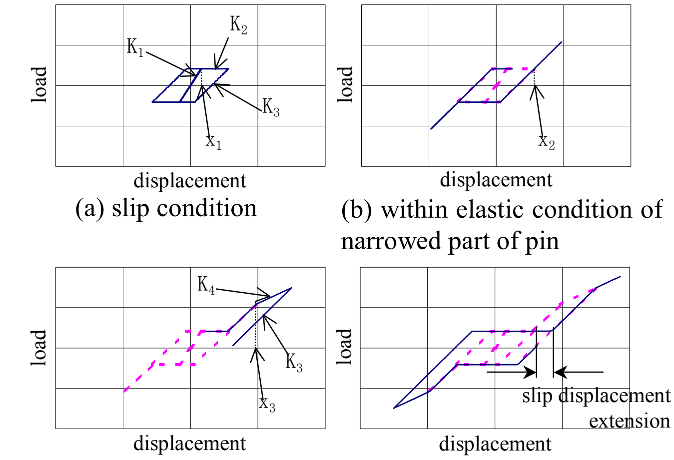
Based on the hybrid experiment results, numerical models for the bearing are developed for the longitudinal direction and the transverse direction using a multiple linear characterization, respectively. Also, effects for the superstructure are more quantitatively investigated using the devised numerical pin bearing models.



(a) slip condition (b) after contact between shoe and pin

x_i: ith point, K_i: ith stiffness between each point

Figure 17. Developed numerical hysteresis model for steel pin bearing for the longitudinal direction



(a) slip condition (b) within elastic condition of narrowed part of pin

(c) after plastic deformation of narrowed part of pin (d) slip displacement extension

x_i: ith point, K_i: ith stiffness between each point

Figure 18. Developed numerical hysteresis model for steel pin bearing for the transverse direction

4.1. Numerical Model For Steel Pin Bearing

Figure 17 shows the hysteresis model of the bearing for the longitudinal direction. The numerical model has two characteristics. One is a slip-type hysteresis. The other is a stiffness increase after the slip.

The numerical hysteresis model for the transverse direction is shown in Figure 18. The numerical model has a slip type hysteresis and a stiffness increase after the slip as well as the numerical model for the longitudinal direction. Also, the numerical model for the transverse direction has slip displacement extension due to a plastic deformation of the narrowed part of the pin.

Parameters for the hysteresis model are determined based on the hybrid test results.

4.2. Seismic Response Analysis

A nonlinear seismic analysis is implemented to investigate effects of the developed numerical model on the global seismic response of a bridge. The equation of motion is solved by numerical direct time integration scheme, or Newmark's method (β=0.25) is employed with time increment of 0.0007812 s. Rayleigh type damping is used to express viscous damping constants involved in the equation of motion. Modal damping ratio of 2 % is assumed to be valid on the first and the third natural periods for both the longitudinal and transverse directions.

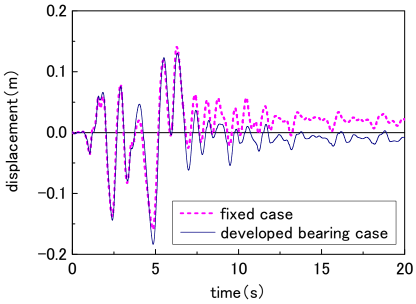
Two bearing models are used as the fixed bearing model in 3DFE model. One is the model whose freedoms are summarized in Table 3. The other is the devised numerical model. Hereafter, the case used the nodal fixed model is called 'fixed case', and the case used the developed numerical model is called 'developed bearing case', respectively. The responses of 3DFE models that are attached two bearing models under Takatori record are examined, respectively.

4.3 Results and Discussion

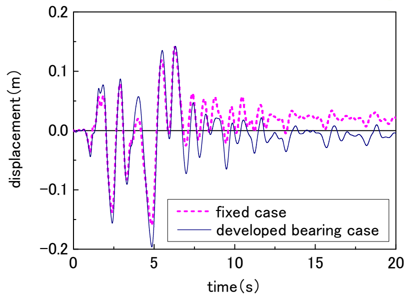
Figure 19 shows the superstructure displacement histories in the longitudinal direction and the transverse direction obtained by analysis, respectively.

The maximum response displacement is 159 mm and 196 mm for the fixed case and the developed bearing case in the longitudinal direction, relatively. This comparison indicates that the maximum response of the developed bearing case is about 23.5 % larger than that of the fixed case.

In the transverse direction, the fixed shoe column is used as the 3DFE model for analysis in order to avoid the effect of the movable bearing. According to the way included in Design Specification for Highway Bridges, the superstructure mass for analysis corresponds to the contributing superstructure mass of the target pier. As a result, the developed bearing case is larger than the fixed case in the aspect of maximum response. The maximum superstructure displacement of the developed bearing case is about 1.2 % larger than that of the fixed case. The difference between the fixed case and the developed bearing case in the transverse direction is smaller than that in the longitudinal direction. This result is similar to the hybrid test results.



(a) Longitudinal direction



(b) Transverse direction

Figure 19. Comparison of superstructure displacement time history (fixed case vs. developed bearing case)

5. CONCLUSIONS

The present study examine the effects of the pin bearing performance on a superstructure based on the hybrid seismic response experiment and the dynamic analysis using the developed numerical bearing model From the hybrid experiment and the numerical analysis results, the following conclusions can be addressed:

(1) Load and displacement characteristics are identified as a slip-type hysteresis for the longitudinal as well as transverse directions. In the longitudinal direction, rotation of the upper and lower shoes around the pin contributed to develop such a specific loop. On the other hand, the pin movement in the gap distance around the shear key plays a role on the slip-type hysteresis characteristics for the transverse direction. The magnitude of the slip is further intensified under accumulated cyclic loading.

(2) The slip-type hysteresis indeed affects the superstructure response. The maximum horizontal displacements at the superstructure for the longitudinal and transverse directions in the hybrid experiment are larger than those of the 2DOF analyses that use a prescribed condition at the bearing to represent the bearing behavior. Namely, 14 % and 4 % increases for the longitudinal transverse directions respectively are recognized. In particular, the 14 % increase may have a serious consequence on the design of the gap allowance between adjacent decks.

(3) Based on hybrid test results, the numerical pin bearing model for the longitudinal and transverse directions are developed using a multiple linearization, respectively. In the analysis to investigate effects of the devised numerical bearing model, the increasing quantity of the superstructure displacement in the longitudinal direction is more than that in the transverse direction.

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