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STUDY ON THE DAMAGES OF STEEL GIRDERS BY HYOGO-KEN NANBU EARTHQUAKE USING NONLINEAR SEISMIC RESPONSE ANALYSIS

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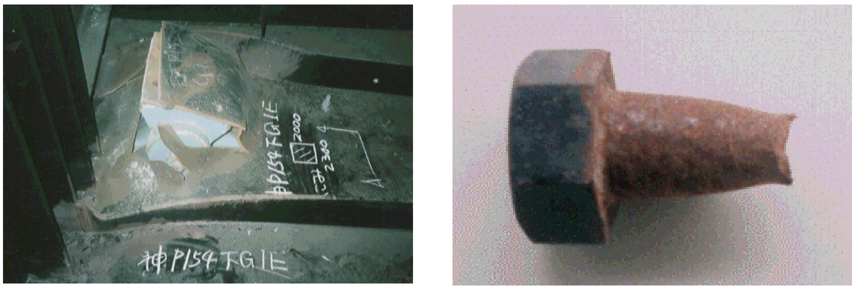
SUMMARY

Many highway bridges were damaged by Hyogoken Nanbu Earthquake (January 17,1995, M=7.2). Damages to girders almost occurred around bearings. The failure of set-bolts of bearings caused damages to girders, bearings and beams of piers. In this study, nonlinear seismic response analyses for two different steel girder bridge systems are carried out using three-dimensional models. Acceleration waves recorded at Kobe during the Hyogoken Nanbu Earthquake are used. The nonlinearity of members is prescribed by the relationship between bending moment and curvature. Skeleton of moment-curvature relationship is modeled as bi-linear for steel members, and as tri-linear for RC members. This paper reports the results of these analyses that show tensile axial force act on bearings excessively by transverse horizontal seismic excitation. The axial force is found to be large enough for tensile cutting of set-bolts. And both bridge total systems with single-column bents or multi-column bents show almost same dynamic behaviors. In the case of using isolation bearings, tensile axial force is decreased. According to these results new design force for bearing systems should be presented.

INTRODUCTION

About urban viaduct that received large damages by Hyogo-ken Nanbu Earthquake, the damages were mainly occurred around support bearings (**Photograph 1**). According to the observation about the cutting of set-bolts in damaged bearing support, it comes to light that the tensile force affects the bolts, as it is shown in **Photograph 1(b)**. That is to say, when the girders were damaged, the set-bolts of the bearing supports had already been broken by the tensile force. After steel girders once separated from the supports, it collided again, and steel girders and supports were damaged each other (**Photograph 1(a), (c)**). Under certain circumstances extreme residual deformation remained (**Photographs 1(d)**). In this study, in order to clarify the process that made damage of steel bridges, the nonlinear seismic response analyses are carried out for two bridge systems that are consisted of girder, bearing supports, piers and foundation, and that was damaged in Hyogo-ken Nanbu Earthquake. The one of two cases is a system with single-column bents, and the other case is that with multi-column bents. By examining for resultant displacements and internal forces, it is clarified that the excessive axial tensile force acted and tensile cutting of set-bolts occurred by longitudinal excitation. Furthermore the response analyses of the system with isolation bearings which are adopted in retrofit works are carried out. It is investigated how internal force of bents and girders and axial force of bearing have been improved. The influences that the differences of the type of bents bring about are examined.



(a) Bearing's penetration into lower flange **(b) Ruptured set-bolts**

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(c) Broken bearing **(d) Respective deformation of girders in transverse direction**

Photograph 1: Damages of steel girders

2. THE ANALYSIS OF 3-SPAN CONTINUOUS STEEL BOX GIRDER WITH SINGLE-COLUMN BENTS

2 .1 Object of analyses

General view of the 3-span continuous steel box girder with single-column bents (K Bridge) analyzed in this paper is shown in **Figure 1**. The structure was composed of three spans continuous steel girder, bearing supports, steel bents of a reverse L shape (KS10, 11, 12), T-type concrete bents (KS13), pile foundation and caisson foundation. And it has been constructed on the second type ground (moderate) in Japanese standard.

2.2 Analytical Model

In the K bridge steel fixed-movable bearing supports had been used before Hyogo-ken Nanbu Earthquake occurred, and it has been replaced with high damping rubber bearing for the reason of having the damages as shown in the above photographs. Two kinds of models are used as the analytical models. Model 1 having fixed-movable bearing is the type before earthquake disaster, and Model 2 having isolation bearing is the type after that. The elements that have nonlinear restoring characteristics are steel bents (bilinear type), concrete bent (trilinear type), isolation bearing (bilinear type) and movable bearing (nonlinear elasticity type). The ground, pile foundations and caisson foundation are modeled as a linear spring (**Figure 2**). JR-Takatori's 3-component of wave forms are used as input seismic waves which were observed in Hyogo-ken Nanbu Earthquake at Japan Railroad Takatori station (second type of ground), the maximum acceleration is adjusted at 686.831gal.

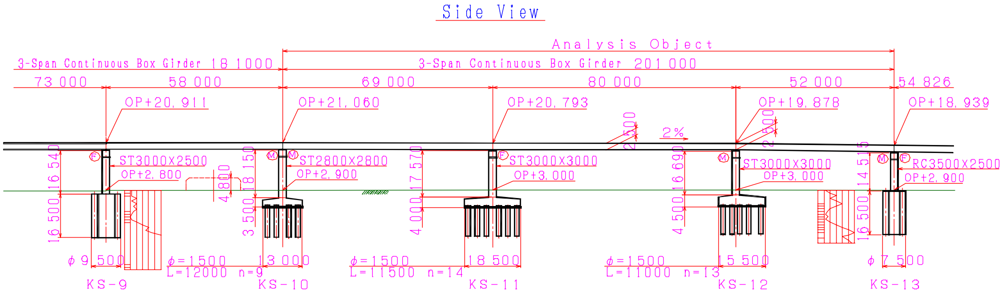


Figure 1: K Bridge general view

Rayleigh damping is used, in which first and second natural frequency and damping coefficient h=0.03 are adapted. The nonlinear moment-curvature relation of bents are calculated using stress-strain curve of Design Specifications of Highway Bridges Part V Seismic Design.$^{1)}$ The nonlinear characteristic of the high damping rubber bearing (HDR) is calculated after static design was carried out using dead load and stiffness of bents etc.. Four kind of seismic excitations i.e. independent each direction and 3-direction simultaneous excitation were adopted for the analyses of both models.

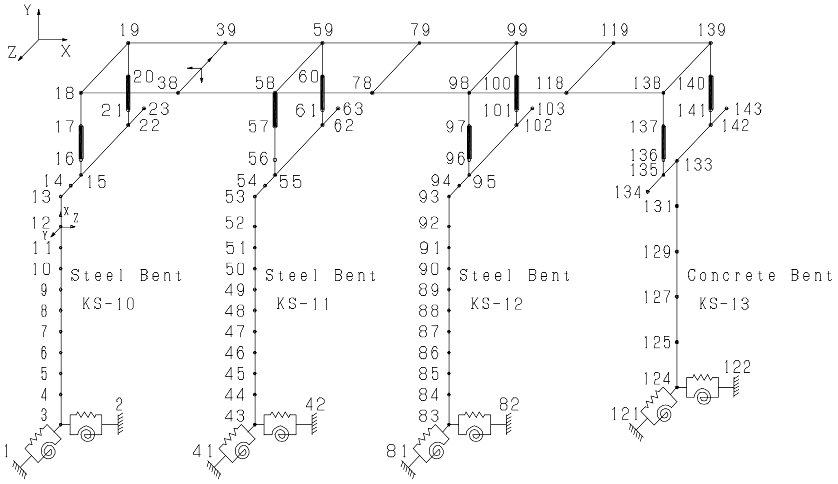


Figure 2: K Bridge total system analytical model

2.3 Analytical result

In the analytical result of the K Bridge, there is not large difference at the maximum response values between three-direction simultaneous excitation and other one-direction excitation, therefore response values of longitudinal and transverse excitations are shown in **Figure 3, 4 and 5**.

Displacement

Figure 3 shows the maximum displacement of the bents and girder. The response displacement of the Model 2 at the column-beam joint of bents (nodal point 13, 53, 93, 133) decreases in about 1/2 of the values of the Model 1. Those of Model 2 increases in comparison with Model 1 at the center of box girder (nodal point 18, 19, 58, 59, 98, 99, 138, 139). In the case of using isolation bearings, the values of displacement are the same at every nodal point of the girder in longitudinal excitation, but that of the end supports become double of the intermediate supports in transverse excitation.

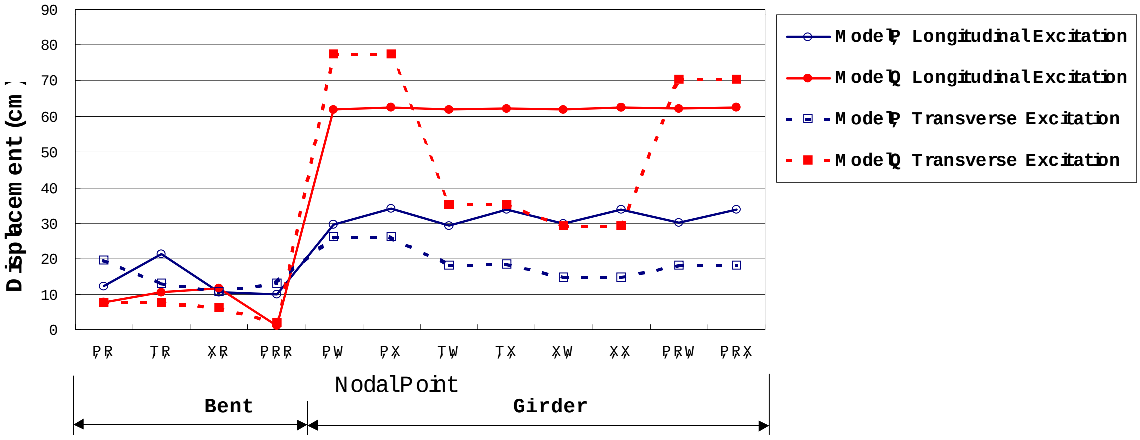


Figure 3: Maximum displacement of the bents and girder

Bending moment

Figure 4 shows maximum bending moments of the bents. It is distinct that the response bending moment of Model 2 decrease about 1/2 compared to Model 1. This is a effect of isolation bearings. The only exception is that of the longitudinal direction in nodal point 83 (bottom of the pier of intermediate support), it slightly becomes large value in Model 2. This shows that it may not be able to say that the internal forces of all bents decrease in the bridge with isolation bearing supports.

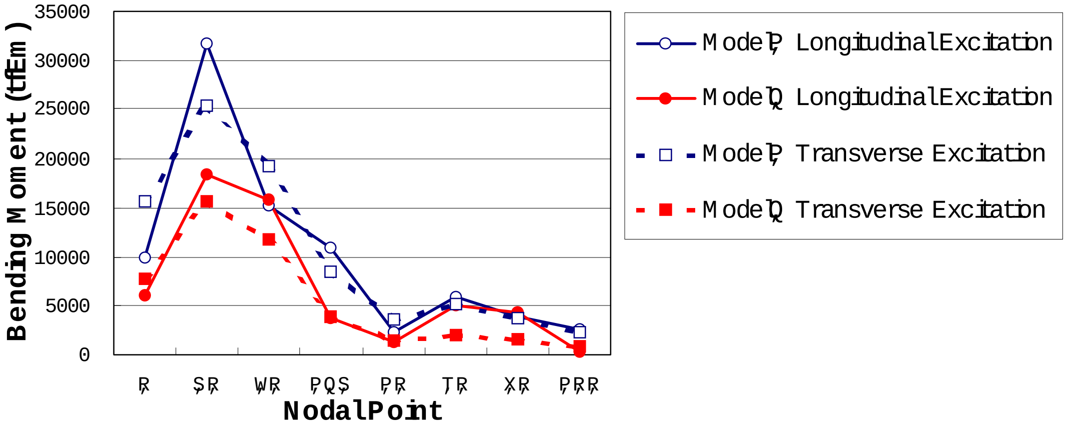


Figure 4: Maximum bending moment of the bents

2.3.1 Axial force

Maximum response axial forces of bearings for seismic excitation are shown in **Figure 5**. It is reasonable result that the set-bolt broke by tensile force, because the response axial forces of the bearings considerably exceed axial force obtained by dead load and rupture axial force of the set-bolts in transverse excitation (Model 1). In the case of Model 2 (isolation bearing), the response value surpass dead load axial force at end supports in transverse excitation. This means that uplift affect the bearings during the earthquake.

These analytical results show that set-bolts of fixed-movable bearings are broken by either longitudinal or transverse excitation. And it is meant that the rupture of the set-bolts are generated by transverse excitation, when the same set-bolts are used, even if they are changed in seismic isolation bearings.

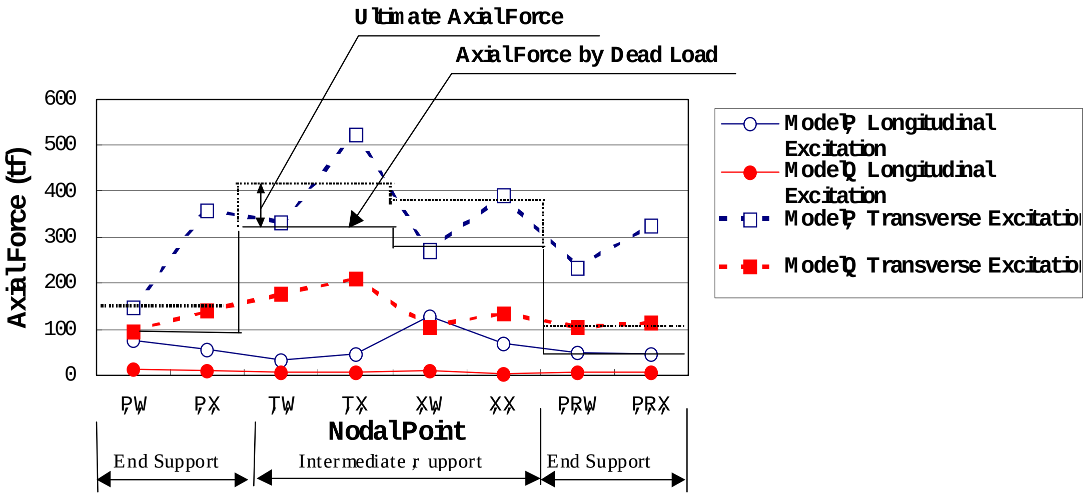


Figure 5: Maximum axial force of bearings

THE ANALYSIS OF 3-SPAN CONTINUOUS STEEL BOX GIRDER WITH MULTI-COLUMN BENTS

3. 1 Object of analyses

General view of the analytical object (H Bridge) is shown in **Figure 6**. The H Bridge is composed of double deck 3-span continuous steel box girder, four of racket shape steel bents and caisson foundation. Two spans of this bridge have been spanned over the sea.

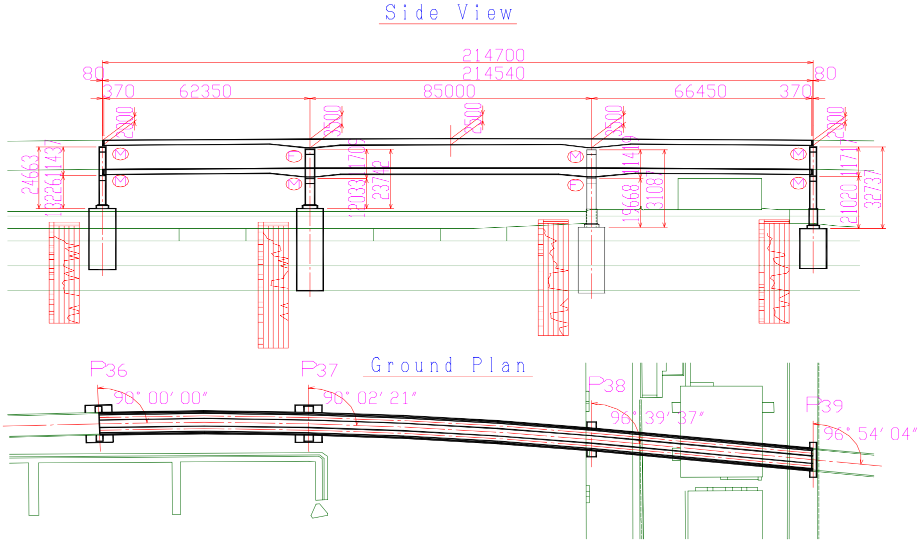


Figure 6: H Bridge general view

3.2 Analytical model

Total analytical model of the H Bridge is shown in **Figures 7**. The H bridge also received the damage by Hyogo-ken Nanbu Earthquake, and it was replaced to the isolation bearings from steel fixed-movable bearings. Two types of models are used as an analytical models, one of which using fixed-movable bearings is the before earthquake disaster type (Model 3), and the other model using the isolation bearings is after earthquake disaster type (Model 4).

Steel bents (bilinear type), movable bearing with the restriction equipment in the transform direction (nonlinear elasticity type) and isolation bearing including the lead plug (bilinear type) are given the nonlinear restoring characteristics. It were made to be fixed at the bottom of bents, because the caisson foundation is used in the H Bridge. Time history seismic response analyses are carried out using the Rayleigh damping. The seismic waves used here are the same waves used for K Bridge. The four case analyses were carried out for both models, in which seismic excitation was made in the each direction and 3-direction simultaneous excitation.

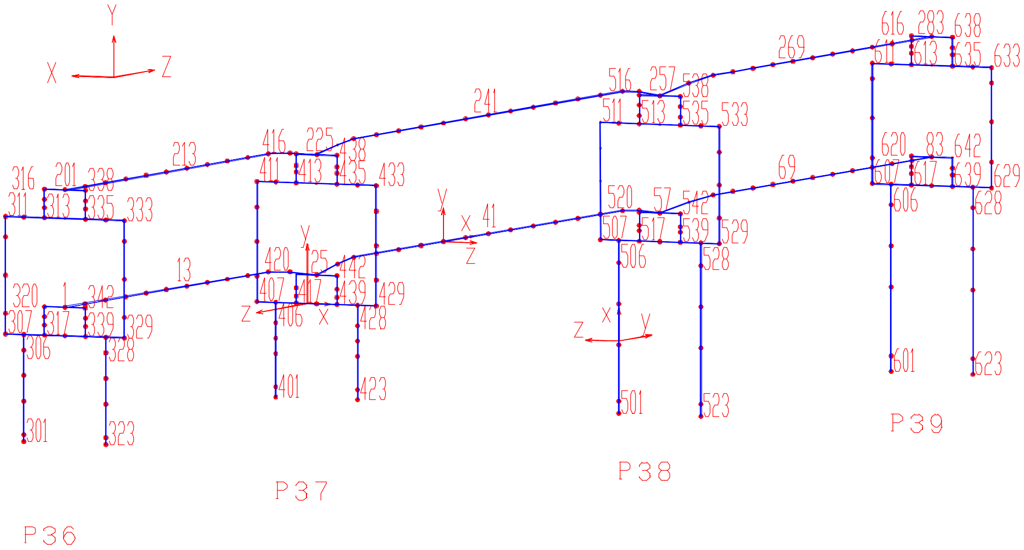


Figure 7: H bridge total system analytical model

2.4 Analytical result

Displacement

The displacements of girder are shown in the **Figure 8**. At nodal points 57 and 257 located on P38 bents, the values of Model 3 increase due to transverse excitation. That is to say, large displacements of transverse direction are occurred around P38 bent which height is relatively high. Isolation bearings are evidently effective for reducing these extreme large responses due to transverse excitation. The response values of the lower layer girder in Model 4 increase in about the double for the longitudinal excitation, and become almost same values in every nodal point.

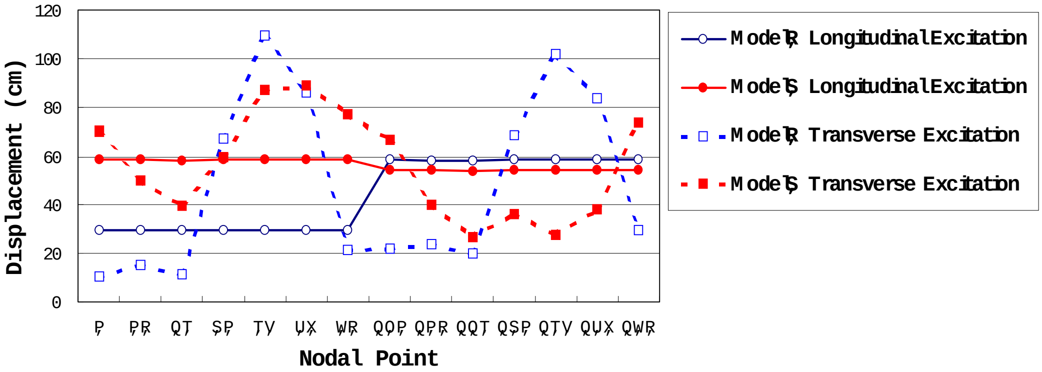
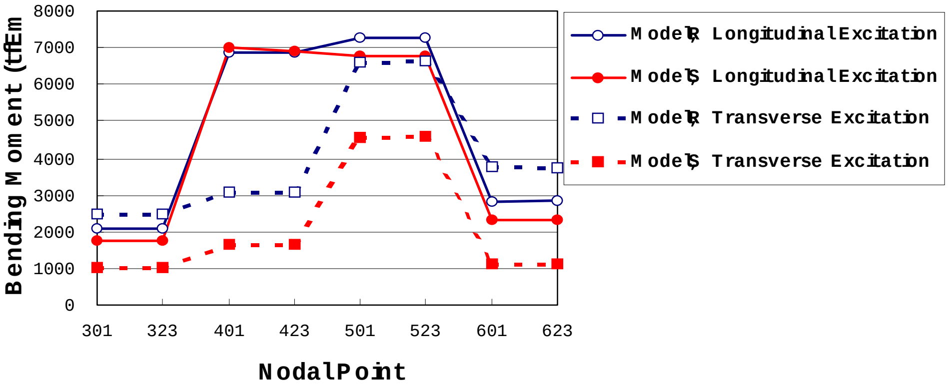


Figure 8: Maximum response displacement of girders

3.3.2 Bending moment

Figure 9 shows bending moments of the bents. Comparing Model 3 with Model 4 about the values of response bending moment due to longitudinal and transverse excitations, there is almost no difference of that for longitudinal excitation, though some response values slightly decrease by using isolation bearing. On the other hand about transverse excitation, bending moment decrease 1500•2500tfm in each bents and the effect of isolation bearing is clear.



Figures 9: Maximum bending moment of bents

3.3.3 Axial force

The response axial forces in seismic excitation are shown in **Figure 10** (for the case of fixed-movable bearing) and **Figure 11** (for the case of isolation bearing).

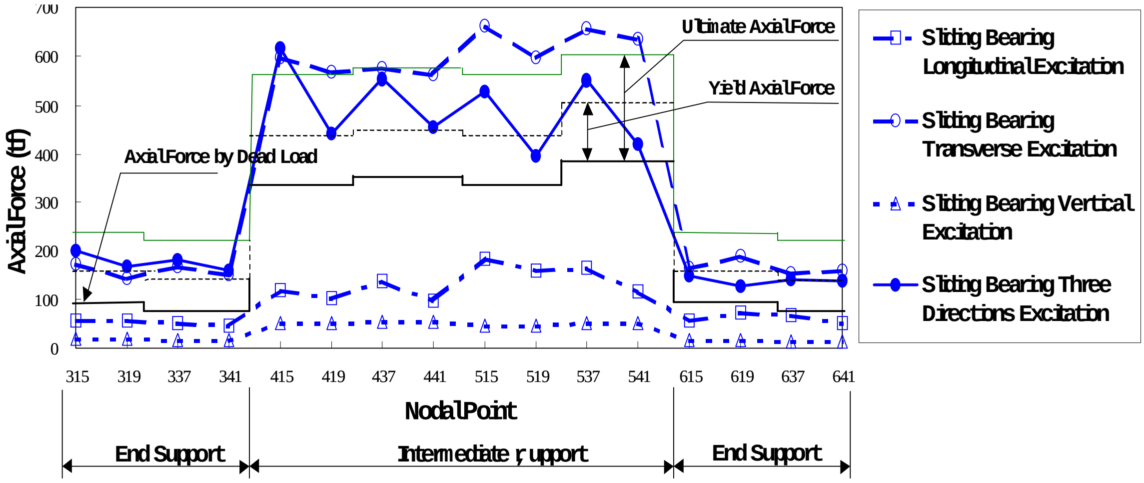


Figure 10: Virtual axial force of fixed-movable bearings

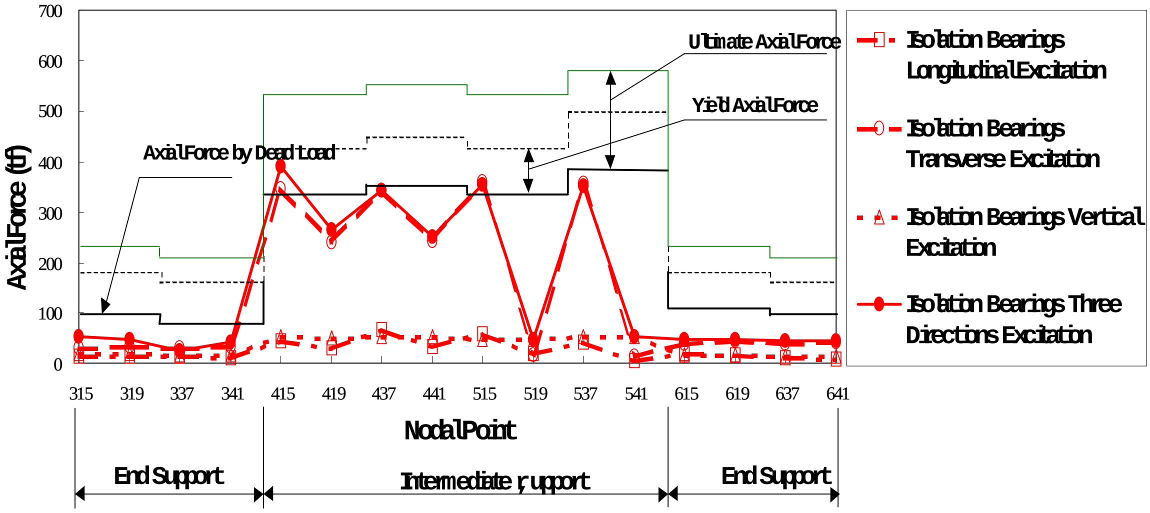


Figure 11: Virtual axial force of isolation bearings

The set-bolts of fixed-movable bearings had been designed as vertical seismic intensity of 0.1 by seismic coefficient method. And four M30(S35CN) bolts for an end support and four M42(SS400) bolts for an intermediate support had used. These yield axial forces are 75tf and 115tf, and rupture axial forces are 126tf and 197tf respectively. Vertical axial forces at the bearing support by transverse excitation are 129tf to 201tf in end support, 396tf to 661tf in intermediate support in case of fixed-movable bearing. The axial force has been far exceeded the yield strength, and exceeded tensile strength even if the dead load reaction is deducted on intermediate support. In case of isolation bearings, the response axial forces decrease between 26tf and 54tf on the end support, and between 47tf and 393tf on the intermediate support. It seems that the tension has already affected the set-bolts in dead load condition before the seismic excitation, because the set-bolts are tightened under the condition that the dead load has affected in actual construction. If one of these set-bolt breaks, the burden rate of tensile force in remained bolts increase, and the bolts will rupture one after another. As a fact, all set-bolts of every bearing support had broken in the bridge analyzed in this paper.

CONCLUSION

By the knowledge got from above analytical result, the damage mechanism of steel bridge in Hyogo-ken Nanbu Earthquake is arranged like the following. The vertical axial force which mainly surpass the conventional design reaction force, acts on bearing supports by the response of structure total system in transverse excitation. Especially the tensile axial forces that exceed tensile strength of set-bolts act on that of bearings and the tensile ruptures happened. This is first damage. The girder freely vibrates without receiving the restraint of the bearings after the set-bolts rupture. And penetration of the bearing support to the bottom flange (**Photograph 1(a)**) and support destruction (**Photograph 1 (c)**) are generated by the collision of bearing support and girder.

These are secondary damages. On occasion large relative displacement occurs between the adjacent girder (**Photograph 1(d)**).

The response displacement increases, when the support was replaced with isolation bearings from the steel fixed-movable bearings, however the seismic capacity for the whole bridge system is improved, because bending moment which affect bents and axial force which affect the bearing support considerably decrease. This improvement effect of seismic capacity is get beyond bent type (single column bent or multi column bents), if the bearings are not destroyed.

The result of this study shows there is possibility that the tensile force which surpasses uplift calculated in static design act, and that it may cause the damage to the bearing supports and girders. For improvement of seismic capacity of structures showing the complicated seismic behavior such as urban viaducts, it is necessary that the bearings are designed with accurate internal forces based on seismic response analysis of bridge total system and that each parts of those have the sufficient proof strength.

REFERENCES

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