라커베어링 모델에 따른 교량의 지진거동

Seismic Performance of Bridges with the Modeling of Expansion Rocker Bearings

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요　　약 : 미국 중부 및 동남부에 위치한 많은 교량의 형식은 강거더와 콘트리트 슬래브의 복합 상부구조를 가지는 교량으로, 이들은 주로 라커베어링에 의해 상부구조가 지지 되어있다. 지진해석에서 이동식 라커베어링은 롤러나 마찰력으로 모델링 되는 것이 일반적이다. 그러나, 라커베어링은 일정 거리를 움직인 후 핀틀에 의해서 락킹되고, 이는 교량의 지진거동에 상당한 영향을 주리라고 판단된다. 본 연구는 이동식 라커베어링의 모델형식(롤러, 마찰력, 마찰력과 하드닝, 그리고 마찰력과 락킹)에 따른 다경간 단순지지 및 다경간 연속교에서의 지진거동을 고찰하였다. 락킹모델은 급격한 강성의 변화를 나타내는 요소를 포함하고 있어, 시간이력해석에서 발산의 위험이 있으므로 사용성이 떨어진다. 반면, 롤러나 마찰력은 모델이 간단하여 사용이 간편하고 수렴의 문제가 없으나, 지나치게 큰 지진응답을 발생할 우려가 있다. 본 연구의 목적은 이동식 라커베어링의 간단한 세 모델 중, 어느 모델이 실제에 가장 가까운 마찰력+락킹 모델에 유사한 응답을 발생시키는가를 살펴보고자 하는데 있다. 롤러모델은 락킹모델에 비해 큰 값을 나타내므로, 사용하는 것이 바람직하지 않다. 마찰모델은 약한 지진운동에서 상부구조의 변위가 작아 라커베어링에 락킹현상이 발생하지 않을 때 적합하다. 중 또는 강진운동에서는 락킹현상이 발생하므로, 마찰력과 하드닝을 고려한 모델이 실제 응답에 가장 유사한 것으로 판단되었다.

ABSTRACT : Multispan simply supported bridges and multispan continuous bridges take a large portion of bridges in Central and Southeastern United Sates. The superstructure of the bridges are supported by steel rocker bearings. In general, the rocker bearings are modeled with ideal rollers or Coulomb friction in seismic analysis. However, the rocker bearings have rocking action on pintles after rolling some distance. This rocking action may have considerable effect on the seismic performance of bridges. This study compares the effect of expansion rocker bearings models on a multispan simply supported and a multispan continuous bridge. Since the ideal roller model produces larger responses than the rocking model, its use is undesirable. However, the friction and hardening model does not have much difference from the responses of the rocking model. In addition, the use of the tow models is convenient in seismic analyses of bridges. Although the rocking model can obtain more exact responses, its behavior is complicated and it may induce the conversion problem in time history analysis because it includes the abrupt changing of stiffness . The friction and hardening model of expansion rocker bearings is therefore recommended in seismic analysis.

핵 심 용 어 : 라커 베어링, 교량, 마찰력, 락킹, 지진해석

KEYWORDS : Rocker Bearings, Bridges, Friction, Rocking, Seismic Analysis

1. Introduction

In Central and Southeastern United States (CSUS), the National Bridge Inventory Program (NBIP) shows that approximately 95% of the bridges are multispan simply supported, multispan continuous, or single span bridges. Approximately a third of these bridges consists of steel girder with reinforced concrete slab with reinforced concrete

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piers. These types of bridges are supported by hinged or rocker steel bearings at the ends of spans or at the middles of spans. As indicated by Iwasaki et al (1971), these types of bridges have deficiencies at hinged and rocker bearings; they played a major role in the collapse of many bridges during past earthquakes. Later studies indicated that hinge openings (relative displacement at expansion joints) in multispan simply supported bridges during earthquakes often approach the allowable displacement (Tseng and Penzien 1973; Zimmerman and Brittain 1979; Imbsen and Penzien 1986).

In general, the hinge opening is the function of several factors such as column stiffness, gap size at expansion joints, and the behavior of rocker bearings. Of the rocker bearings' behavior, many previous studies ignored the frictional force of the bearings and modeled rocker bearings as ideal rollers; in the case the seismic responses of bridges were conservative (Zimmerman and Brittain, 1979; Randall et al., 1999).

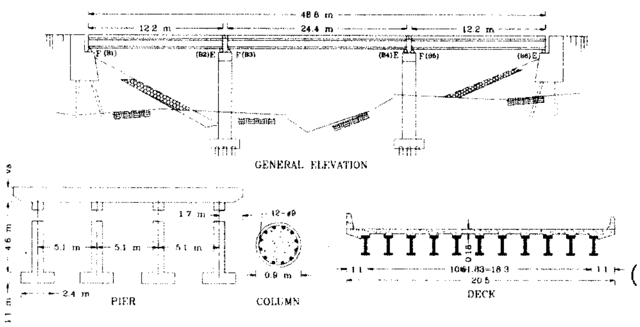
Mander et al. (1996) conducted the experiment of rocker bearings and developed an analytical model of the bearing considering the frictional force, and Choi (2002) used the bearing model to evaluate the seismic response of the three types of bridges in the CSUS. Barker and Hartnagel (1997), however, showed that rocker bearings have a very stiff hardening due to the rocking action of rocker plate to pintles before being unstable. The rocking force was approximately 65 kN which is about 33% of the strength of the fixed steel bearing tested by Mander (1996). When including the frictional force of rocker bearings, the total force (frictional and rocking) becomes larger than 33% of the fixed bearing's strength. Therefore, it may say that an expansion rocker bearing acts like a fixed bearing after activation of the rocking action.

The principle objectives of this study is the understanding how the modeling of expansion rocker bearings has an effect on the seismic responses of the bridges. The effect of four types of modeling of expansion rocker bearings, such as 1) without friction and rocking (Type I, ideal roller), 2) with friction only (Type II), 3) with friction and hardening (Type III), and 4) with friction and rocking action (Type IV), will be discussed in this study. The single span bridges will be excluded in this study because the behavior of single span bridges is governed by fixed bearings (Choi, 2002).

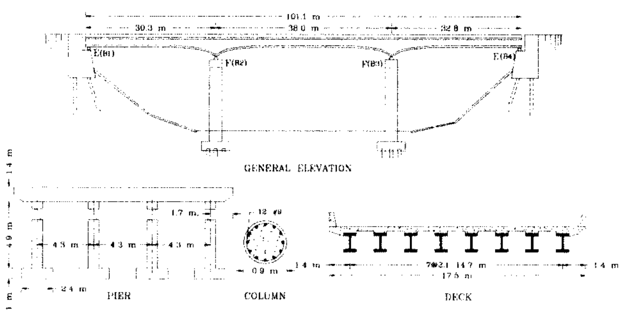
2. Bridge Description and Analytical Model

The multispan simply supported (MSSS) and the multispan continuous (MSC) bridge have three spans, two multi-column bents with four columns, and pile-bent abutments as shown in Fig. 1. The MSSS bridge has 38 mm gaps on abutments and 25 mm gaps on piers. The MSC bridge has 76 mm gaps on abutments. Each span of the MSSS bridge is supported by fixed and expansion bearings at the ends. In the MCS bridge, the array of fixed bearings supports the deck on the first pier from left, and there are expansion bearings on the other supports, the second pier and abutments.

The two-dimensional analytical models of the two bridges are developed in longitudinal direction using DRAIN-2DX (Prakash et al. 1992). The superstructure is modeled using a linear element to represent the stiffness and mass properties of the composite deck. The columns are modeled with fiber elements which represent the stress-strain relationship of unconfined and confined concrete and steel reinforced bars. The abutment properties used in this model are modified from Caltrans (1990) recommendations based on the results of recent experimental studies (Maroney et al., 1994; Goel and Chopra, 1997). The behavior of the abutments shows the multi-linear inelastic in both active action (tension) and passive action (compression). The pile foundation is modeled using linear springs in the horizontal and rotational direction considering small deformation of soil. The impact between decks and at the abutments are modeled with a trilinear element following the contact element approach (Maison and Kasai, 1992). Previous studies have shown that a linear element with very high stiffness is not appropriate since it can produce unrealistically high pounding forces and accelerations (DesRoches and Fenves, 1997).



(a) Layout of MSSS Bridge



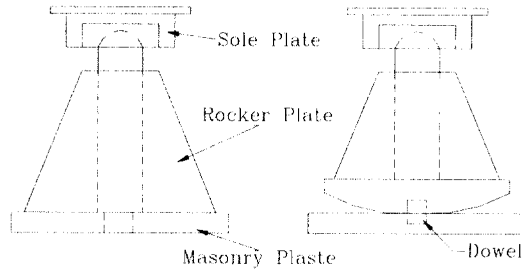
(b) Layout of MSC Bridge

Fig. 1. General Shape of MSSS and MSC Bridge

3. Rocker Bearings

Fig. 2 shows the shape of the two rocker bearings; fixed and expansion type. The fixed type permits only rotation on the sole plate. However, the expansion type allows rotation as well as movement with the rolling of rocker plate on masonry plate.

Mander et al. (1996) conducted an experiment of a fixed bearing on concrete pedestal and developed an analytical model of the bearing whose hysteretic loops are shown in Fig. 3.. Mander and his colleagues (1996) also suggested the frictional coefficient of 0.04 for expansion bearings and recommended the hardening ratio of 0.018 for the corroded bearings.



(a) Fixed Type (b) Expansion Type

Fig. 2. Fixed and Expansion Type of Rocker Bearings

The experiments performed by Barker and Hartnagel (1997) showed that the frictional coefficients are approximately 8.8% and 3.2% for the heavy and mild deteriorated expansion bearings, respectively; theses values are estimated by the subtracting the frictional coefficient of test apparatus, 1.55%, from the total frictional coefficient. In addition, they showed the rocking action of the bearing through large displacement test as illustrated in Fig. 4.

Based on the results of Barker and Hartnagel's test, this study used the frictional coefficient of 0.03 and the hardening ratio is 0.018 following Mander's suggestion for the hardening model. The developed rocking model whose hysteresis curves are shown in Fig. 5 has one truss element and three link elements in DRAIN-2DX. The truss element represents for the frictional force and the link elements are used for the hardening and softening as shown in Fig. 5.

In reviewing Mander's and Barker's test, the

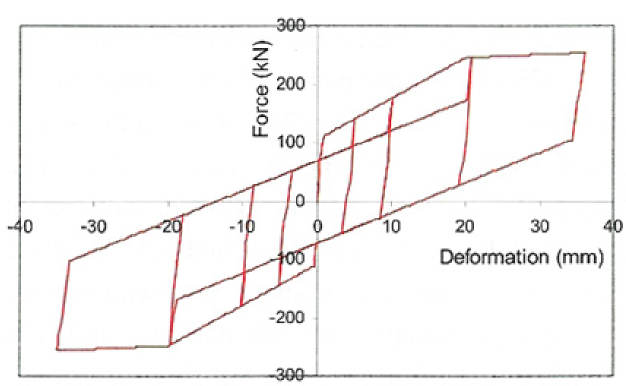


Fig. 3. Hysteresis Curves of Fixed Bearing

limitation of movable range before the rocking action is assumed to be 51 mm. The rocking model does not have any resistance after failure.

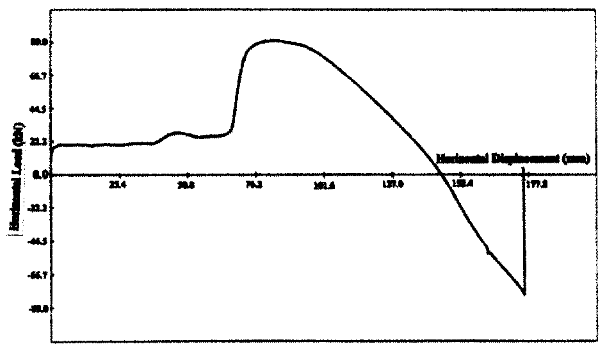


Fig 4. Rocking Behavior of Expansion Rocker Bearing

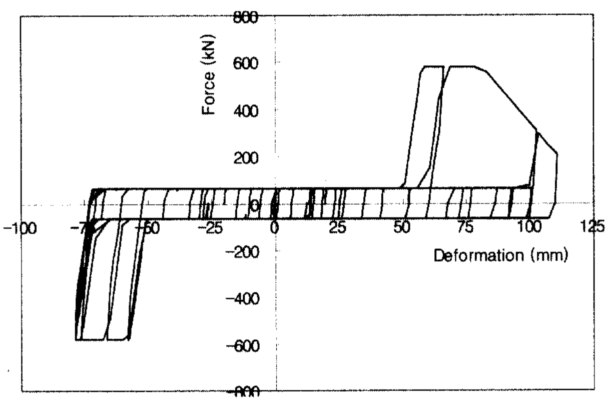
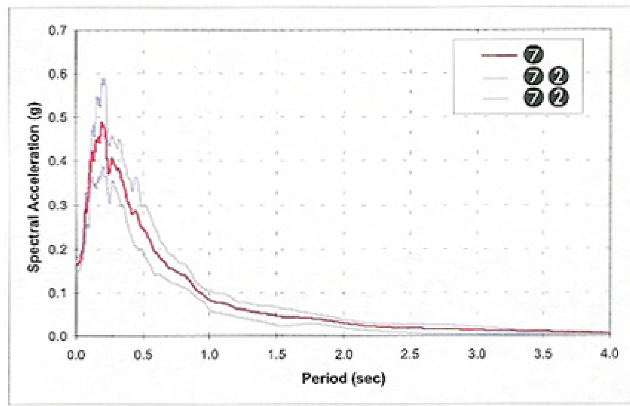


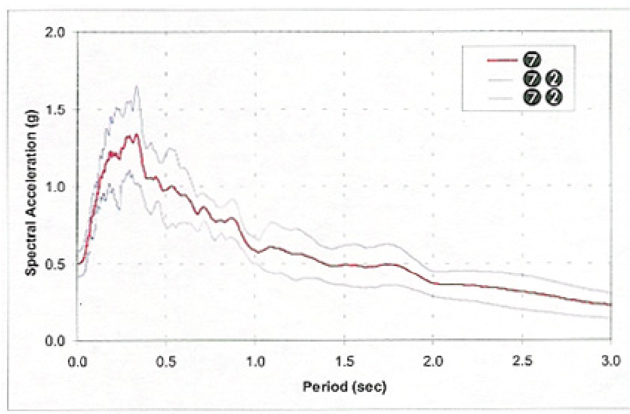
Fig. 5. Hysteresis Curves of Expansion Rocker Bearing

4. Ground Motions

The two suites of ground motions were developed by Wen and Wu (2001) for the CSUS; one is for the 475-year earthquakes (10% probability of exceedance in 50 years, G1) and the other is for the 2475-year earthquakes (2% probability of exceedance in 50 years, G2). Each suite has 10 ground motions, and the averaged PGAs (Peak Ground Acceleration) of the ground motions are 0.17g and 0.51g for the 10% and 2% PE in 50 years, respectively. Fig. 6 shows the mean response spectral accelerations with 5% damping and mean (μ)±one standard deviation(σ) of the two suites.



(a) 10% PE in 50 Years



(b) 2% PE in 50 Years

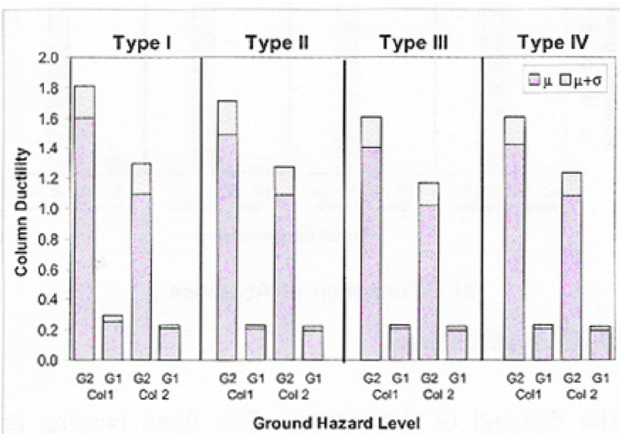
Fig. 6. Mean Response Spectra

5. Statistical Seismic Analysis

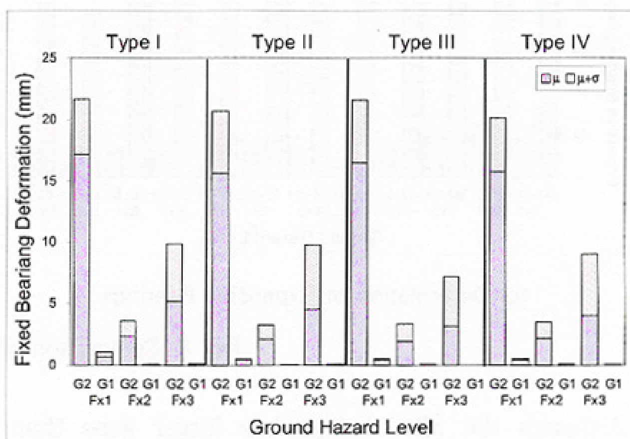
Figs. 7 and 8 show the mean responses and one standard deviation for the MSSS and MSC bridge, respectively.

Of the responses with the weak ground motions (10% PE in 50 years, G1), the expansion bearings of Types II & IV produce the same results since the deformation of the expansion bearings is less than the limitation of movable range in Type IV. However, not having any frictional force, Type I generates larger mean responses than Type II or IV; for example, the maximum column ductility of Type I is 88% of the ductility of Type II or IV in the MSSS bridge. Even with the hardening, Type III produces almost similar results to those of Type IV with the weak ground motions; the ductility of the first column in the MSC bridge with Type III is 98% of the ductility with Type IV.

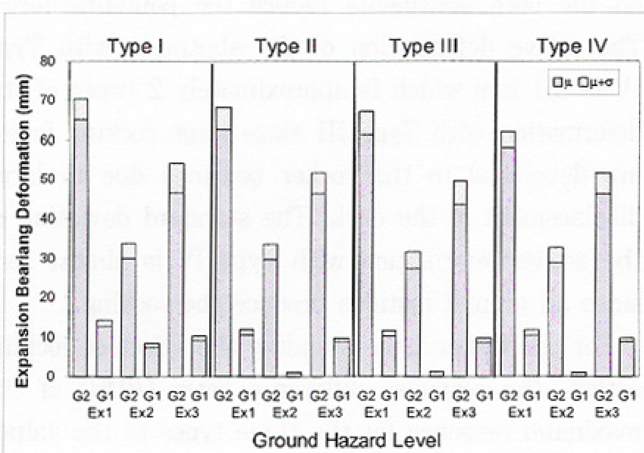
Different from the ground motions of 10% PE in 50 years, the moderate ground motions (2% PE in 50 years, G2) can produce enough large deformation on expansion rocker bearings to activate the rocking action. In the MSSS bridge, the models of friction, friction and hardening, and friction and rocking action reduce the response of column ductilities and expansion bearing deformations compared with those of ideal roller model. In reviewing the ductility of the first column of the MSSS bridge, the response ratios to Type IV are 1.13, 1.05, and 0.99 for Type I, II, and III, respectively. The maximum deformation of fixed bearings is observed at the first bearing on the left abutment. The relative large deformation of the bearing is due to the pounding force of the second deck to the first one. The pounding occurs before the rocking, and thus Types II and IV have the same deformation of the bearing. The same phenomenon occurs on the passive (pushing) deformation of the right abutment having expansion bearings, and thus Types II and IV have the same passive deformation of the abutment. In active (pulling) deformation of the abutment, Types I and II have no or small deformation. In Types III and IV, the hardening and the rocking produce relatively large deformation; the active deformations of the abutment are 0.65 mm and 0.47 mm for Types III and IV, respectively. Type IV has much large standard deviation since some ground motions generate the rocking but the others do not.



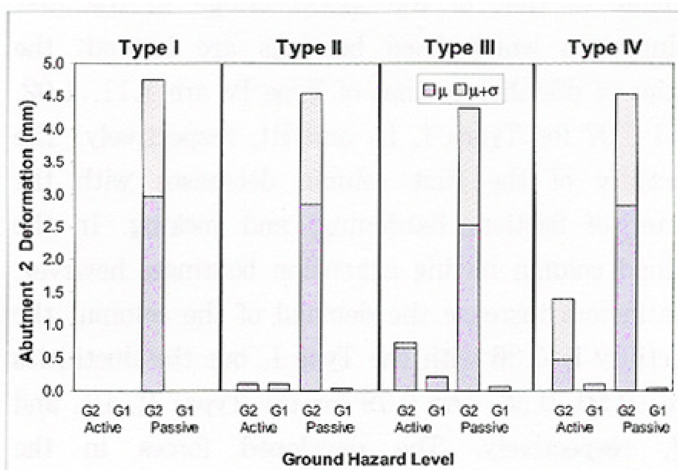
(a) Column Ductility



(b) Deformation of Fixed Bearings

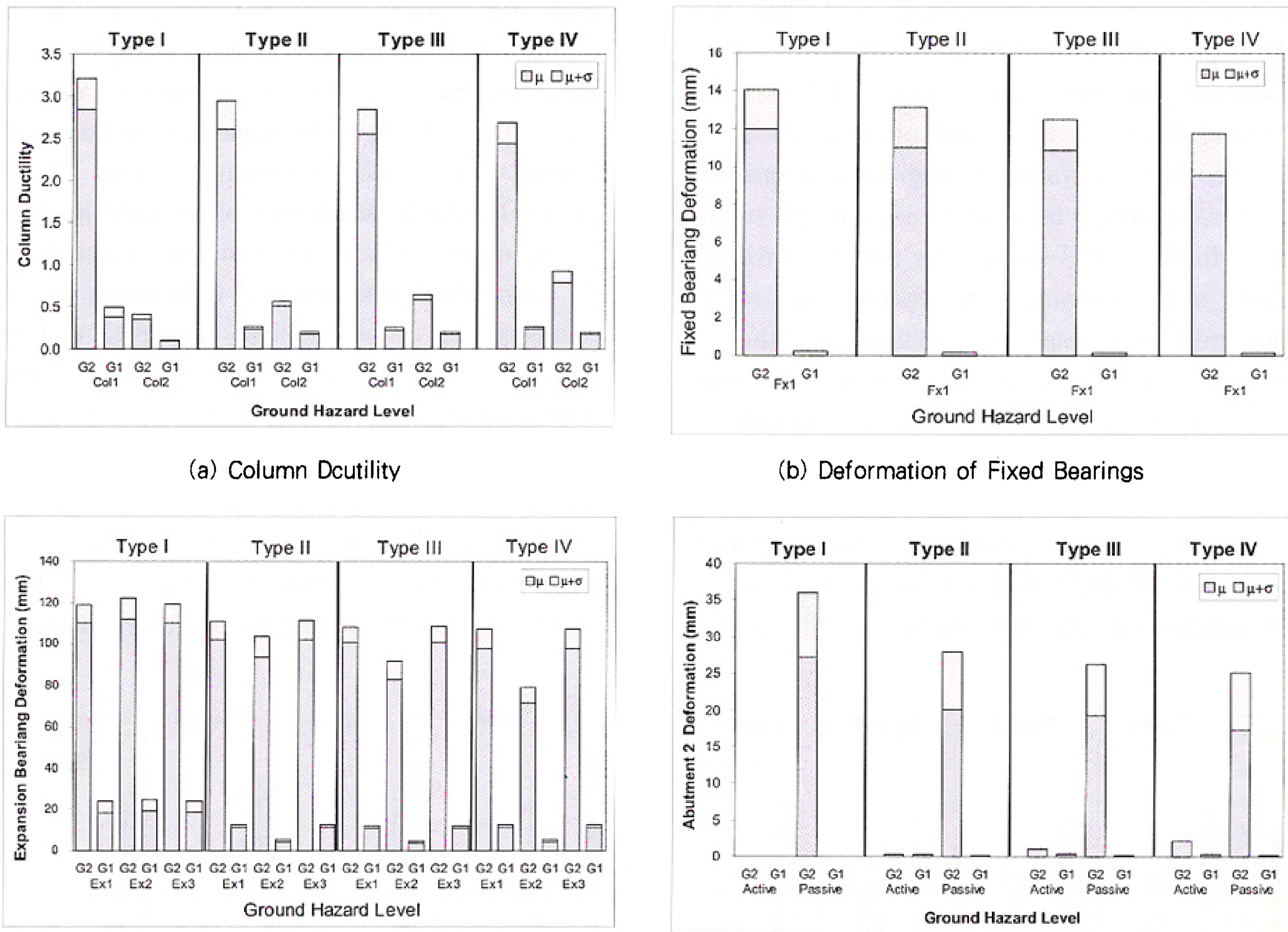


(c) Deformation of Expansion Bearings



(d) Deformation of Abutment 2

Fig 7. Comparison of Responses of MSSS Bridge



(a) Column Dcutility

(b) Deformation of Fixed Bearings

(c) Deformation of Expansion Bearings

(d) Deformation of Abutment 2

Fig 8. Comparison of Responses of MSC Bridge

Although the MSC bridge has larger gaps than the limitation of movable range, the response trend of column ductility and expansion bearing deformation is similar to that of the MSSS bridge in the first column on which fixed bearings are located; the ratios of ductility to that of Type IV are 1.11, 1.02, and 0.97 for Types I, II, and III, respectively. The ductility of the first column decreases with the factor of friction, hardening, and rocking. In the second column having expansion bearings, however, the factors increase the demand of the column; the ductility is 0.36 with the Type I, but the ductilities are 0.50, 0.58, and 0.79 for the Types II, III, and IV, respectively. The developed forces in the expansion bearings on the abutments reduce the demand of the first column, however, the forces on the expansion bearings on the second column raises the demand of the column. The fixed bearing and the abutment in passive action have the smallest deformation with Type IV since the rocking action on the both abutments reduce the pounding force. The active deformation of the abutment with Type IV is 2.1 mm which is approximately 2 times of the deformation with Type III since large rocking forces are developed in the rocker bearings due to large displacement of the deck. The standard deviation of the active deformation with Type IV is almost zero since all ground motions produce the rocking.

For the better understanding the effect of rocking action, the response difference ratio (RDR) of the maximum response for the three types to the values of Type IV are calculated for the moderate ground motions following the below equation;

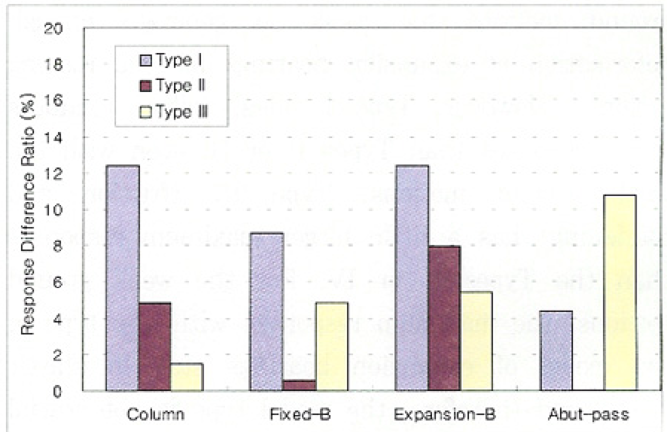
$$RDR = abs(\frac{R_i}{R_4} - 1) \times 100 \quad i = 1, 2, 3 \qquad (1)$$

where R_4 is the maximum responses of Type IV, R_i is the maximum for the other types, Types I, II, or III, and the abs menas absolute. In the equation, the value in the parenthesis can be negative, and thus the absolute value is used. Fig. 9 shows the RDRs for the MSSS and the MSC bridge.

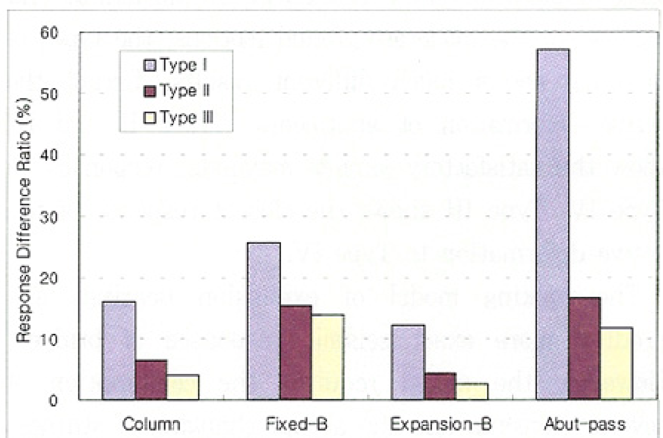
In the figure, Type I has more than 10% differences from Type IV for the demand of the column and the expansion bearing. However, Type III has 4% RDR for the column in the MSC bridge and 6% RDR for the expansion bearing in the MSSS bridge. Type II has much low RDRs for the deformations of the fixed bearing (0.6 %) and the abutment in passive action (0.1 %) in the MSSS bridge since the pounding is critical on the deformations and occurs before the rocking action as mentioned above. In the MSC bridge, Type III has less RDRs for the deformations of the fixed bearing and the abutment than Type II since the rocking occurs before the pounding and the hardening in Type III can resist the deck movement more effectively than the Type II. The RDR of Type I reaches 57% for the passive deformation of the abutment; the difference is to large to accept.

In the active deformation of abutments, the RDRs for Types I and II are over than 80%. Type I (ideal roller) can not make any active deformation on abutment and Type II (friction) can make small deformation on abutment in active action. Even Type III (friction and hardening) produces much smaller deformation of the abutment in active action than Type IV (friction and rocking). In the passive action of abutments, impacts governs the passive deformation and the rocking happening before the pounding can transfer large forces to abutments. However, in the active action, friction and hardening can generate much smaller forces than the rocking, and thus the RDRs in the active deformation are much large generally.

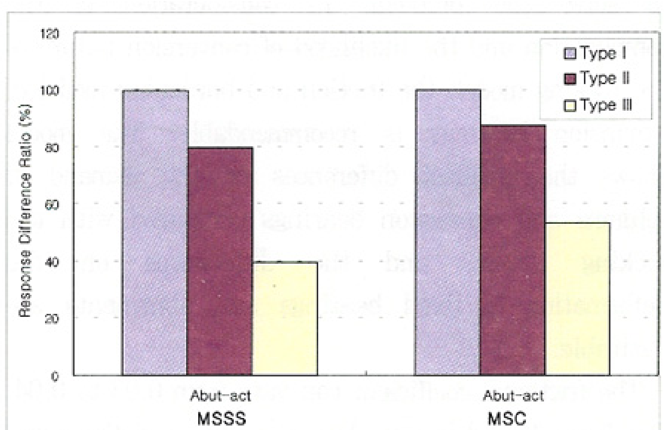
In the active deformation of abutment, Type IV has 10 times larger deformation than Type III in the MSC bridge. However, the maximum deformation of 2 mm in active action is in elastic range, thus it does not make any damage on the abutment.



(a) MSSS Bridge



(b) MSC Bridge



(c) Active Deformation of Abutments

Fig. 9. Responses Difference Ratios

6. Conclusions

For the weak ground motions, there is not any difference between the models of Type II (friction only) and Type IV (friction and rocking). The ground motions too weak to generate enough deformation of expansion bearings for the rocking action. However, Type I (ideal roller) produces larger reponses than Types II or IV even with the weak ground motions. Type III (friction and hardening) has a little larger maximum responses than the Types II or IV. For the weak ground motions, the maximum responses with any type of the model of expansion bearings stay in elastic range, and therefore, the model type is not crucial to assess the seismic damage of bridges.

Since the deformation of expansion bearings are large enough to show the effect of hardening and rocking for the moderate ground motions, the types of modeling shows much different results. Except the active deformation of abutments, Types II and III show the satisfactory similar maximum responses to Type IV. Type III shows the closest response of the active deformation to Type IV.

The rocking model of expansion bearings can produce more exact seismic responses of bridges. However, the model requires the combination of several elements and the abrupt changing of stiffness which may induce the conversion problem in time history analysis, and it is needed very short time step to solve the problem. In consideration of the complication and the likelihood of conversion failure of the rocking model, the friction and hardening model of expansion bearings is recommendable. The model shows the smallest differences on the demand of columns and expansion bearings compared with the rocking model, and the differences on the deformation of fixed bearings and abutments are desirable.

The frictional coefficient can vary from 0.03 to 0.04. The lower bound is from Barker's test, and the upper one is from Mander's test. The hardening ratio of 0.018 is recommended following Mander's test.

A lot of researchers have used the ideal roller for expansion rocker bearings to obtain the conservative responses in seismic analyses of bridges. However, the difference between the ideal roller and the rocking action model is not ignorable. Therefore, the roller model is not recommended.

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