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NON-LINEAR SEISMIC RESPONSE CHARACTERISTICS STUDY OF A RC BRIDGE COLUMN WITH SEISMIC ISOLATORS BY A SHAKING TABLE TEST

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SUMMARY

According to the present seismic isolation codes, the principal non-linearity expects to develop only at the seismic isolator so that the bridge column is designed so as not to yield under the design earthquake. However, when the bridge system is subjected to intensive earthquake ground motions, the non-linear response is expected both at the seismic isolators and the columns. Therefore, the bridge system response including the interaction of non-linear responses at both the seismic isolators and the columns must be clarified. In this study, a series of shaking table tests that tried to study the non-linear seismic response behavior of a seismic isolator and RC bridge column system, where the principal non-linear response was expected both at the seismic isolator and the column, was carried out. According to the test results, the global system response was dominated by the primary mode even if the non-linear behavior was found at both the seismic isolators and the column. The simulation results using ordinary models of the seismic isolators and the column can express the test result quite well. Furthermore, it was found that the global response was also simulated using an equivalent 1-DOF model with proper damping factor, even though the non-linear behavior was found at both the seismic isolators and the column.

INTRODUCTION

Seismic isolators can reduce seismic force acting to bridge systems by increase of energy dissipation and elongation of the natural period of the bridge system. According to the Japan Design Specifications for Highway Bridges [Japan Road Association, 1996] or the other specifications in Japan [Sugita, 1994], the bridge using seismic isolators should be designed in order that the bridge column may show no or slight non-linear response during design earthquake in order to ensure the seismic energy is dissipated principally at the seismic isolator. Calvi et al [Priestly, 1996] also proposed the displacement based design method for seismically isolated bridges where the bridge column may also show elastic response during design earthquakes. The bridge column and seismic isolator, however, may show non-linear response if an extremely intensive earthquake hit the bridge. Therefore, the system behavior characteristics of the seismically isolated bridge system where hysteretic response occurs more than one member in the bridge system must be clarified and the evaluation method of such bridge system response needs to be established and implemented in practical design.

The non-linear response of such bridge systems where principal non-linearity developed at the column and the isolators was mainly studied by analytical approach [Hayashi, 1997], [Yamashita, 1997], [Takahashi, 1997], [Adachi,1998]. The response characteristics of such bridge systems was studied based on the result of a series of time history analyses of seismically isolated bridges subjected to intensive earthquakes, and design methods were proposed based on the simulation results. Only one experimental approach [Iemura, 1993] was carried out using substructure hybrid experiment to study the effectiveness of seismic isolator under the condition where the column showed hysteretic response. Strong motion data of seismically isolated bridges have been accumulated gradually, including data of Hanshin Expressway Matsunohama viaduct during the 1995 Hyogo-ken Nanbu

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earthquake [Horie, 1995]. However, no record where both the column and the isolator showed hysteretic response has been obtained.

Considering above all recent studies, in order to obtain the actual response data of a seismically isolated bridge, the shaking table test using 1/4 scale seismically isolated bridge model was carried out. According to the test results, the response characteristics of such bridge system are examined. Finally, in order to verify the practical analytical approach, a comparison study was also carried out between the 1 DOF or 2 DOF analytical results and the experimental results.

SHAKING TABLE TEST SET UP

Shaking table test was performed at the laboratory of the Public Works Research Institute to examine how the bridge column with the seismic isolators behaved under intensive earthquake-type shaking. The test set up is shown in Figure 1 and Photo 1. The bridge column specimen, with placed the seismic isolator on its top, was anchored at the center of the shaking table, and two simply supported superstructure, which was 5m long and 395kN weigh, was placed on the isolator on the column specimen. The seismic isolators on the column specimen and the superstructures were pin-connected, and the other ends of superstructures were rested on low friction roller bearings on the end steel piers. This bridge model was only allowed to move in the longitudinal direction. All excitations were given along the longitudinal direction so that the column carries the all inertia force from the superstructure during the excitation.

Figure 2 shows the dimension and the detail of bar arrangement of the tested column specimen as well as the detail of the seismic isolator. The tested column specimen was made of reinforced concrete. Based on the facility capacity, the bridge column was 1/4 scaled down of the general dimension of the viaduct in urban area in Japan. The dimension of the RC column specimen was 60(B)×60(D)×270(H) cm. The longitudinal reinforcement and the volumetric hoop reinforcement ratio were set to both about 1% that are equivalent to those in common practice in urban areas in Japan. Consequently, the yield capacity of RC column model was about 0.35×W (W:

Photo 1: Shaking Table and Specimen

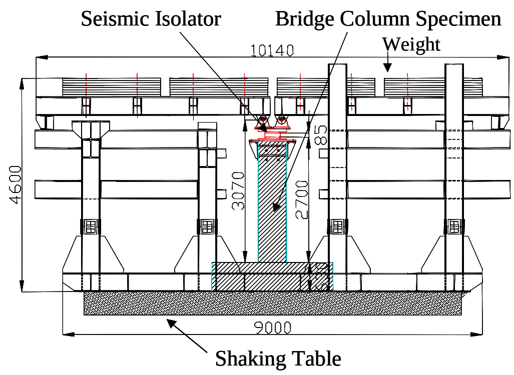
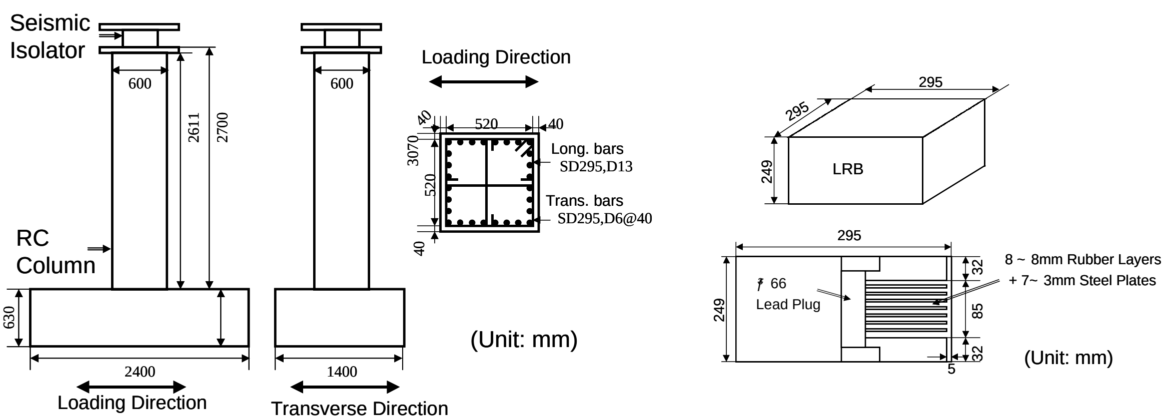


Figure 1: Shaking Table Set Up



(a) Column Specimen **(b) Seismic Isolator Specimen**

Figure 2: Column and Seismic Isolator Specimen

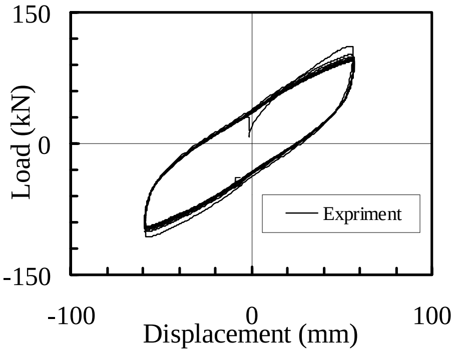


Figure 3. Load-Displacement Test Result of the Seismic Isolator

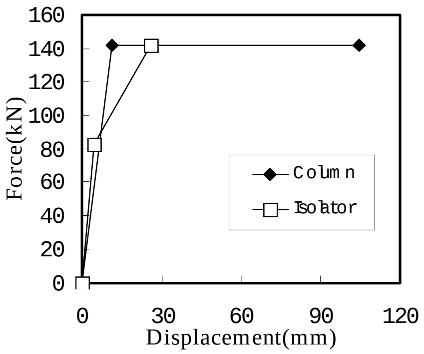


Figure 4. Force-Displacement Relation of the Seismic Isolator and the Column Specimen

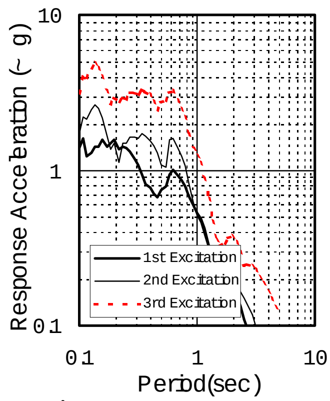
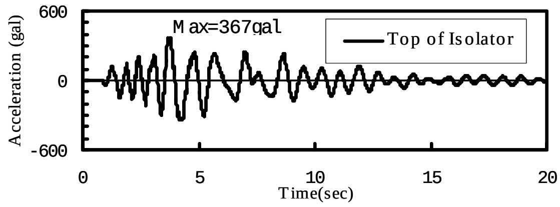
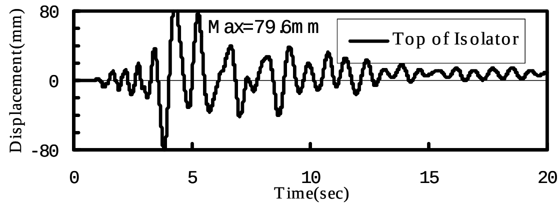


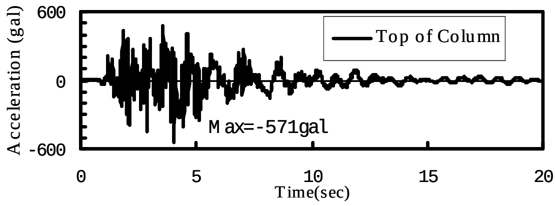
Figure 5. Response Acceleration of Input Shaking Motion (5%)



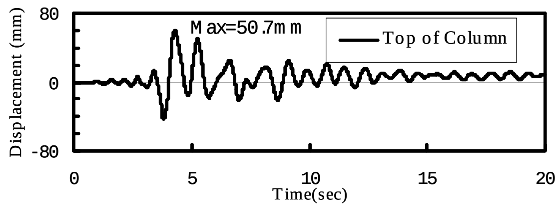
(a) Top of Seismic Isolator



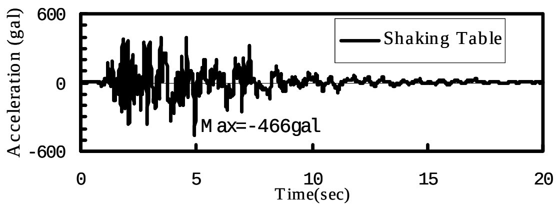
(a) Top of Seismic Isolator



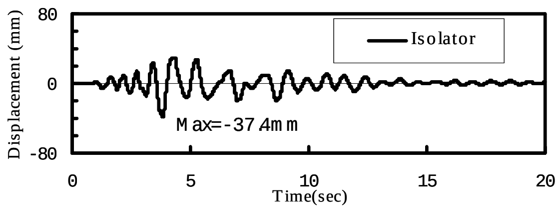
(b) Top of RC Column



(b) Top of RC Column



(c) Shaking Table



(c) Relative Displacement of Seismic Isolator

Figure 6. Time History of Response Acceleration of the First Excitation

Figure 7. Time History of Response Displacement of the First Excitation

the weight of the superstructure) computed by using actual material strength. Lead rubber bearings (LRB) were

used for the isolation and damping device. The ratio between the yield strength of the seismic isolator (Qy) and the yield capacity of the RC column (Py) was set to about 0.4. The equivalent natural period of the RC column with the isolators was 0.73sec that is almost twice of 0.34sec that is the period of the non-isolated bridge. The equivalent period of the isolated bridge was computed using the yield stiffness of the column and the secant stiffness of the isolator where the strength of the isolator is equal to the yield strength of the column.

Figure 3 shows the force-displacement relationship of the seismic isolator obtained by the loading test conducted before the shaking table test. Figure 4 shows the force-displacement relationship between the column and the isolator used in this experiment. The force-displacement relationship of the isolator was modeled by the bi-linear rule.

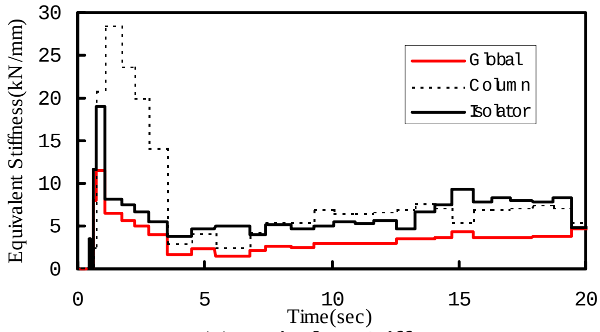
The shaking table test was performed only in the longitudinal direction. The generated earthquake ground motion was used for the excitation. The generated ground motion data [Japan Road Association, 1997] was made to fit the response acceleration spectrum of intensive near-fault-type earthquake for intermediate soil site specified in the Japanese Specification for Highway Bridges, Part□, Seismic Design. The original earthquake record was obtained at the JR Takatori Station during the Hyogo-ken Nanbu earthquake, and the maximum ground acceleration was 642gals.

The geometric scale factor was already determined to 1/4. Dimension analysis was carried out to determine the input acceleration and the scale down of the time axis. According to the results, the time axis needs to be reduced to $1/\sqrt{4} = 1/2$ when the scale factor of acceleration needs to be set to 1.

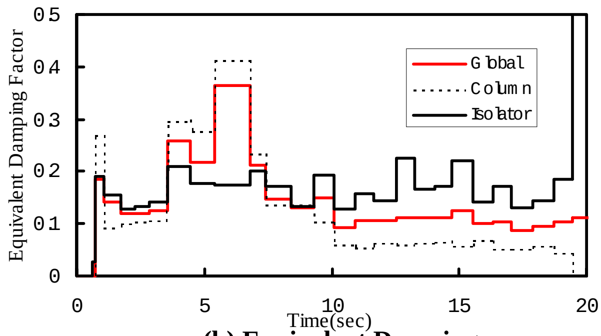
The excitation was carried out three times. The acceleration of the first two excitations was not amplified but the acceleration of the third excitation was amplified twice. The response acceleration spectrum of each input motion is shown in Figure 5. The first two excitations were intended to do in the same intensity but the actual shaking acceleration was different because of the shake control problem. Consequently, as the number of the excitation increased, the level of the intensity was also increased around the equivalent period of this bridge model.

DYNAMIC BEHAVIOR OF THE RC COLUMN SPECIMEN AND THE SEISMIC ISOLATOR

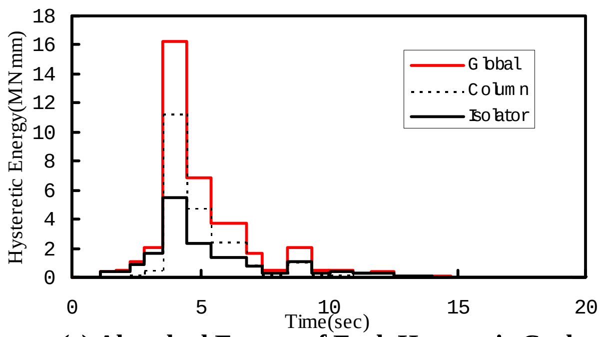
Figure 6 shows the response acceleration record measured at the table, the top of the RC column specimen, and the seismic isolator of the first excitation. The records were band pass filtered from 0.1 Hz to 10 Hz. The maximum acceleration obtained were 571 gals at the top of the column, 367 gals at the seismic isolator, and the 466 gals at the shaking table. The maximum acceleration at the top of the column was amplified by 1.22 comparing to that of the table, but the acceleration at the top of the seismic isolator was amplified only by 0.78.



(a)Equivalent Stiffness

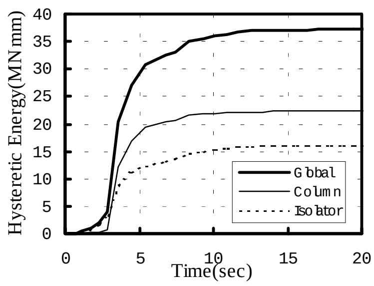


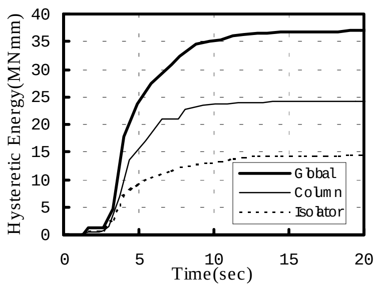
(b) Equivalent Damping

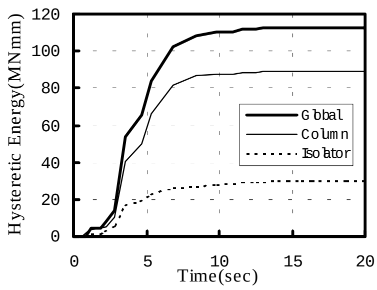


(c) Absorbed Energy of Each Hysteretic Cycle

Figure 8. Time History of Equivalent Stiffness, Equivalent Damping, and Absorbed Energy of Each Cycle of the 1st Excitation







(a)1st Excitation **(b)2nd Excitation** **(c)3rd Excitation**

Figure 9. The Time History of the Accumulated Hysteretic Energy of each Excitation

The shorter period wave comparing to the period of the isolated or non-isolated bridge model seemed amplified in the record at the top of the RC column specimen, whereas the shorter period wave was seemed filtered out in the record at the top of the seismic isolator.

Figure 7 shows the response displacement record measured at the top of the column and the seismic isolator of the first excitation. The maximum measured displacement were 80mm at the top of the isolator, 50mm at the top of the column. The maximum relative displacement of the seismic isolator was 38mm. During 0sec to 3 sec where the column did not yield, the relative displacement of the seismic isolator was relatively larger than that of the column. During 3 sec to 7 sec where the column showed non-linear response, the displacement response of the column was much larger than that of the seismic isolator. After the principal motion went by, the RC column specimen was still shaking whereas the shaking of the seismic isolator was almost damped out. Therefore it was found that the non-linear response was concentrated to the isolator when the column did not yield, and to the column when the column yielded. However, the displacement record shows that the primary mode was dominant and the seismic isolator and the column was shaken with almost the same phase and almost the same period even if both the column and the isolator showed non-linear response.

Figure 8 shows that the time history of the equivalent stiffness, equivalent damping, and hysteretic absorbed energy at each hysteretic loop. The equivalent stiffness defined here was computed from the maximum and minimum displacement and the corresponding force. The equivalent damping defined here was calculated by the hysteretic absorbed energy divided by the elastic energy. During 0 sec to 3 sec, the RC column specimen responded elastic so that the equivalent stiffness of the column specimen was greater than that of the global system or the seismic isolators. After that, the stiffness of the column specimen was decreased and convergent to 6-7 kN/mm. The equivalent stiffness of the seismic isolator was almost stable after 3 or 4 sec, but the equivalent stiffness of the isolator showed greater values during 0sec to 3 sec because seismic isolators showed larger stiffness at the first cycle of loading than that of second or more cycles. The equivalent damping ratio of the seismic isolator seemed almost stable during the excitation whereas the global damping showed around 15% damping ratio or so observed during 0sec to 3sec but decreased to 10% or less damping observed after 10sec.

The hysteretic absorbed energy was dissipated at the seismic isolator before the RC column specimen yielded, but the almost all of the hysteretic energy was dissipated at the column during 4sec to 7sec when the RC column specimen was yielded. According to those findings, the stiffness and damping of the global system was changed around the column yield, and the member that primarily dissipated the energy was also changed. However, the global response was dominated by primary mode and showed only slight phase delay.

Figure 9 shows the relation between the accumulated hysteretic absorbed energy and the time of each excitation. As the number of excitation was increased, the stiffness of the column was decreased. This means that the stiffness of the column became smaller than that of the isolator. Consequently, the total dissipated energy at the seismic isolator was decreased and the total dissipated energy at the RC column specimen was increased, as the number of the excitation increased. Furthermore, by comparing the result of the third excitation to those of the first and second excitation, the ratio of the hysteretic energy absorbed at the isolator to the global one was decreased. This is because the nonlinear response was concentrated to the column. According to those findings, as the number of the excitations increased or the intensity of the excitations increased, the stiffness of the RC column specimen was decreased so that the nonlinear response was concentrated to the RC column specimen.

SIMULATED RESULTS

Analysis using 2-DOF Model:

In order to analyze the behavior of the bridge model and to verify the accuracy of practically used dynamic analysis, time history analysis was performed and the analytical result was compared to that of the first excitation. The tested bridge model was modeled using a 2 mass and 2 non-linear spring system. The 2 masses represented the mass of the superstructure and the mass of the column. Takeda model was assumed to represent the non-linear flexural hysteretic behavior of the RC column specimen, but neglecting the crack behavior. The bi-linear hysteretic model was assumed to represent the non-linear behavior of the seismic isolators. The first and second stiffness was determined by using the pre-loading test result. The stiffness was determined to go through the maximum displacement and the maximum force point.

When modeling the hysteretic response characteristics of the seismic isolator, the influence of the rotation behavior of itself was also considered. The reason is the followings. The superstructure and the seismic isolators were usually rigid connected between the lower flange of the girder and the upper flange of the isolator in the

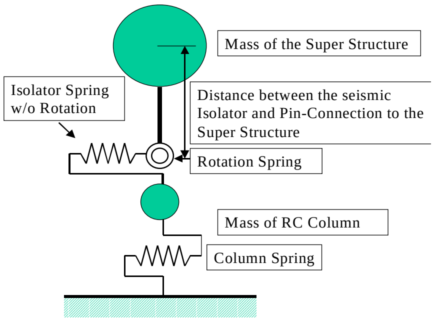
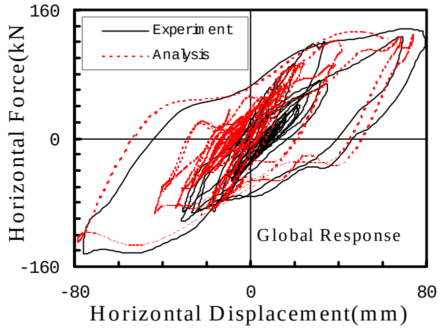
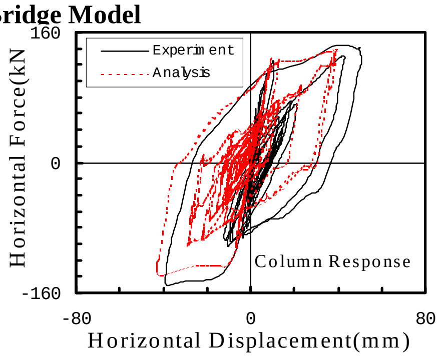


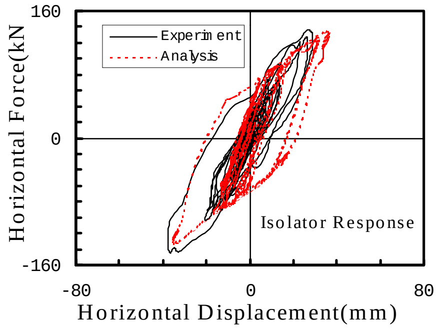
Figure 10. Schematic Image of the Tested Bridge Model



(a) Global Response (Top of Isolator)



(b) RC Column



(c) Seismic Isolator

Figure 11. Comparison between the Experimental and Analytical Results (2DOF

general practice. However, this bridge model that was subjected to the shaking test used pin-connection so that the additional rotational moment was occurred to the isolator due to the large displacement of the superstructure. This is the similar effect as the P-□ effect, not in the vertical but in the horizontal direction. Therefore, the modeling of the bridge was considered as shown in Figure10. The rotation stiffness of characteristics of the bearing is expressed using the following formula.

$$K_{bR} = C_M \cdot G \cdot \frac{a^5 \cdot b}{ne \cdot te} \qquad (1)$$

where K_{bR} Rotation Stiffness of the Seismic Isolator[Rejcha, 1984]

C_M Coefficient determined by b/a C_M =0.01157 where b/a =1

G Shear Modulus

a,b Dimension of Seismic Isolator in Rotation and its Perpendicular Axis

te, ne Rubber Thickness of Each Layer and the Total Number of Rubber Layer

2% damping was assumed to the column specimen and 0% damping was assumed to the isolator. Newmark βmethod was used for integrating method and the time step was set to 1/2000sec.

Figure 11 shows the force-displacement relationship at the top of the isolators, at the top of the column, and of the seismic isolator itself. According to the Figure 11(c) that shows the force-displacement relation of the isolator, the analytical and experimental results show quite good correlation, especially the outer hysteretic loop. The stiffness of the inner loops seems smaller than that of the analysis. The stiffness of the seismic isolator is usually small under shear strain of 50% or less according to the previous study [LRB Research Group, 1996]. The maximum shear stain of the isolator in this excitation was around 50%. This must be one of the reasons the only outside loops shows good correlation. Further studies are needed on this matter, but present practical assumption to use bi-linear model for the hysteretic of the isolator is good enough to obtain the maximum response of the isolator. Figure 11(b) that is the force-displacement relation of the column specimen also shows that the correlation of the analytical and experimental results are quite good when looking at the outer loops, but need improvement to simulate the inside loops. Improvement of modeling of the isolator will improve the correlation of inner hysteretic loops of the RC column specimen. Over all response shown in Figure 11(a) shows that the analytical result agree well to the experimental results and good enough to obtain the maximum response that are quite important when designing bridges, even if simple 2-DOF model was used.

Analysis using Equivalent Non-Linear 1-DOF Model:

As the result of shaking table test, it was found that the response characteristics of the seismically isolated bridge were dominated by the primary mode even though significant non-linearity was found at both the column and the isolator. In this section, another try to simulate the experimental results was conducted using the equivalent 1DOF model.

The modeling of the bridge to the equivalent 1DOF system was carried out using following equations [Adachi, 1998].

$$\frac{1}{K_{eq}} = \frac{1}{K_{beq}(1+W_p/W_u)} + \frac{1}{K_{p1}} \quad (2)$$

$$h_{eq} = \frac{K_{p1}\cdot h_{beq} + K_{beq}\cdot (W/W_u)^2 \cdot h_p}{k_{p1} + K_{beq}\cdot (W/W_u)^2} \quad (3)$$

Where

- K_{eq} Yield Stiffness of the Equivalent 1DOF Model
- K_{p1} Yield Stiffness of the RC Column Specimen
- K_{beq} Scant Stiffness of the Seismic Isolator where the RC Column Specimen Yields
- W_u Mass of the Superstructure
- W_u Mass of the RC Column Specimen
- h_{eq} Equivalent Damping Ratio of Equivalent 1DOF System
- h_{beq} Equivalent Damping Ratio of Seismic Isolator where the RC Column Specimen Yields
- h_p Damping Factor of the RC Column Specimen ($h_p = 0.02$)

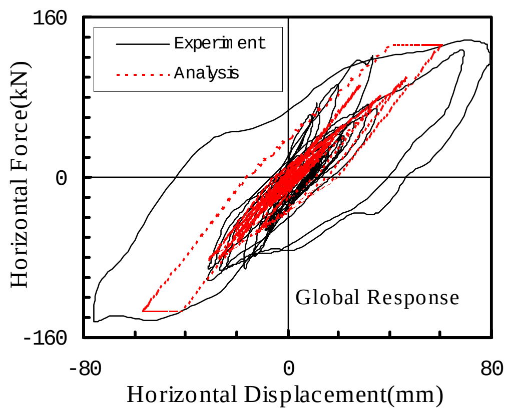


Figure 12. Comparison between the Experimental and Analytical Results (Equivalent 1DOF Analysis: Equivalent damping was computed using equation (3))

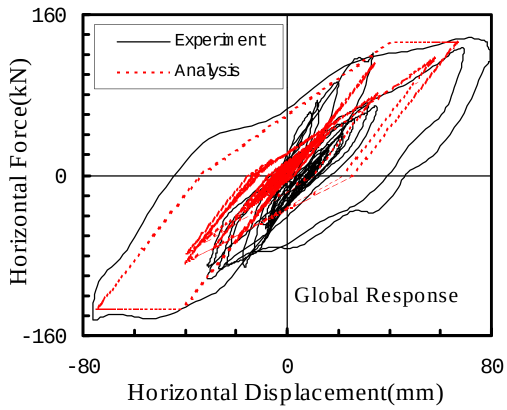


Figure 13. Comparison between the Experimental and Analytical Results (Equivalent 1DOF Analysis: Equivalent damping was computed using equation (4))

The effective primary stiffness of the equivalent 1DOF system was computed from using equation (2). This means that the effective stiffness was calculated using the yield stiffness of the column and the secant stiffness of the isolator where the strength of the isolator is equal to the yield strength of the column. The global damping is considered in two ways. One is structural damping and the hysteretic damping. The equivalent structural damping of the 1DOF system can be obtained from equation (4) that is the composite damping computed by assuming the stiffness proportional damping of the isolator damping and the column damping where the column just yield. The hysteretic damping of the system was assumed Takeda model because the global hysteretic behavior was similar to the hysteretic behavior of the column. Figure 12 shows the relation between the force-displacement relationship of the experimental result and the analytical result of equivalent 1DOF system obtained using the equation (2)-(5). The structural damping obtained from equation (3) is 16.8%. In this case, the analytical result show smaller results compared to the experiment, but the global stiffness was good enough to express the experimental response. The reason why the analytical response gives the smaller solution is the over estimate of the global structural damping. The estimation of the equivalent global structural damping used here is the same as seismic isolated bridge where the column responds elastic.

According to the reasons described above, the global structural damping was computed using the following equation, and another computation was performed.

$$h_{eq} = \frac{K_{peq} \cdot h_{beq} + K_{beq} \cdot (W/W_u)^2 \cdot h_p}{k_{peq} + K_{beq} \cdot (W/W_u)^2} \quad (4)$$

Where

K_{peq} : Secant Stiffness of the Column Specimen at the Maximum Response

Equation (4) assume the global structural damping of the 1DOF system can be computed by the stiffness proportional damping of the isolator damping and the column damping where the column specimen just has the maximum response. Using the equation (4), the computed structural damping was 9.5% that is almost the half of the damping computed from equation (3). Figure 13 shows the result where the computed damping was reduced to half of the results of equation (4). The correlation of the analytical and experimental results is quite better than that of Figure 12. This means that the global damping enhanced by the seismic isolator is different in the system where the column shows elastic response or the non-linear response. Additional research is needed to develop the structural damping of seismically isolated bridge, when the system response may estimate by using equivalent non-linear 1DOF approach.

CONCLUSIONS

The purpose of this study was to obtain the actual response behavior of a seismically isolated bridge model and to verify the accuracy of the practical time history analysis. Based on the experimental observation and analysis of test data, the following conclusions were obtained.

1) The response characteristics of the seismically isolated bridge was dominated by the primary mode even though significant non-linearity was found at both the column and the isolator, according to the experimental data of shaking table test using a scale model.
2) The most of the energy was dissipated at the isolator before the column did not yield. Once the column yielded, the seismic energy was dissipated mostly at the column specimen and only some at the isolator.
3) The modeling to 2 DOF system from the actual structure was good enough to simulate the maximum bridge response. Further research is needed for developing the hysteretic rule of the isolators especially small shear strain region such as 50% strain or the less.
4) The global response can be expressed using non-linear 1 DOF model. According to this study, the global damping calculated by stiffness proportional damping using equivalent stiffness of the seismic isolator and scant stiffness at the maximum response of the column yields quite good agreement to the response of the experiment.

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