Effect of variation of normal force on seismic performance of resilient sliding isolation systems in highway bridges

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SUMMARY

In this study, a series of shaking table tests are carried out on scaled models of two seismically isolated highway bridges to investigate the effect of rocking motion and vertical acceleration on seismic performance of resilient sliding isolators. In addition, performance of RSI is compared with system having solely natural rubber bearings. Test results show that variation of normal force on sliders due to rocking effect and vertical acceleration makes no significant difference in response of RSI systems. In addition, analytical response of prototype isolated bridge and the model used in experiments is obtained analytically by using non-linear model for isolation systems. It is observed that for seismically isolated bridges, dynamic response of full-scale complex structures can be predicted with acceptable accuracy by experiments using a simple model of the structure. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: highway bridge; seismic isolation; RSI system; shaking table test; rocking effect; vertical acceleration

1. INTRODUCTION

In most cases, bridges are strategic structures providing an important link in road network. Failure of these structures during an earthquake may seriously affect the relief and rehabilitation work. As a matter of fact the fundamental period of vibration of majority of bridges falls in the range of 0.2–1.2 s, which unfortunately matches with predominant periods of most of the earthquake-induced motions [1]. Isolation systems help in elongating the fundamental period of the bridge beyond the predominant periods of base motion and dissipation of seismic energy transmitted to the superstructure. However, long period may result in undesirable large
displacement at isolation level accompanied by increase of noise and vibrations. Therefore, in Japan, menshin design is commonly followed for design of bridges. Instead of elongating the period to high values, emphasis in the menshin design is given on increasing energy dissipating capability and distribution of lateral forces to as many substructures as possible in order to decrease the lateral forces for design of substructures [2]. There has been number of devices proposed for seismic isolation of bridges [3]. Sliding bearings in combination with a restoring spring are mostly used for this purpose. The system is called resilient sliding isolation (RSI) system, if the two elements are used in parallel (Figure 1). In RSI system, force transmitted to structure is equal to restoring force of spring plus friction force at sliding interface. In recent years FPS bearings, one of the most popular RSI systems, has been employed in several long span bridges in United States and Canada [4]. Since Hyogo-Ken Nanbu Earthquake of year 1995, RSI system comprising of rubber buffer and PTFE bearing has been commonly used for seismic protection of highway bridges in Japan.

It was felt for RSI systems that variation in normal pressure may change the frictional force and affect the seismic performance of the structure. Variation of normal pressure in RSI systems used in highway bridges is mainly due to (i) seismic acceleration in vertical direction and (ii) rocking motion due to overturning effect of horizontal acceleration. Moreover, in long span bridges with flexible girders, variation of normal reaction on sliders may be affected by vertical oscillation of these girders.

A number of studies have been carried out to assess the effect of variation of normal pressure on behaviour of pure sliding type isolation system and it was observed that due to increase in normal pressure, the coefficient of friction gets reduced [5–7]. Further, number of experimental studies on RSI system and on bridge seismically isolated by RSI system has been carried out [1]. Tsopelas et al. [8, 9] carried out shaking table tests on a bridge model isolated by RSI system. For Japanese level 2 bridge design, they used additional fluid viscous damper. The response was compared with that of non-isolated bridge and the isolated bridge was found to perform much better. Moreover their tests determined that the vertical acceleration has minor effect and it appeared as waviness in the force–displacement loops

Figure 1. Resilient sliding isolation (RSI) system.
Al-Hussaini et al. [10] conducted experiments on seven-storied building model isolated with friction pendulum system. They reported that local variation of vertical load and local uplift does not have any measurable effect on overall response of the isolation system or the upper structure. In another study made by Feng and Okamoto [11], shaking table tests were carried out on a model bridge isolated by sliding system combined with rubber restoring device. They observed that the deck acceleration was limited to a constant value regardless of input acceleration. For large earthquake motions, sliding system shows better isolation performance for response acceleration when compared with laminated rubber bearing system. Izuka et al. [12] conducted a series of shaking table tests on a five-storey concrete structure model seismically isolated by combination of friction slider and rubber buffer. The model was excited under simultaneous vertical and horizontal acceleration. They reported that maximum response acceleration was increased due to presence of vertical acceleration whereas there was no significant effect on maximum response displacement. Nakajima et al. [13] carried out a hybrid on-line earthquake response test on isolation system comprising of slider and rubber bearing. They tested the system for time histories, recorded during Kobe earthquake of 1995. In order to study the behaviour of the system for the worst case of simultaneous horizontal and vertical excitation, they also tested the system for horizontal and vertical sine waves that were in phase. It was observed that the vertical motion does not have much affect on the behaviour of the isolation system. However, for harmonic motions, sliding bearings had a large earthquake response when the peaks of the vertical and horizontal motions coincide. In another investigation on RSI system, Iemura et al. [14] used substructure hybrid tests to investigate the effect of vertical motion on the response of seismically isolated bridge structure. They observed that deformation of the isolator becomes larger for smaller axial loads. However, the difference was insignificant and the overall response was almost the same.

The main objective of this study is to investigate the effects of variation of normal forces on the seismic performance of highway bridges isolated with RSI systems. In this regard, two series of shaking table tests are carried out on scaled models of two proposed bridges to investigate the effects of rocking motion and vertical acceleration. Rigidity of bridge deck in test-1 is much higher than that of the bridge considered for test-2. It is further aimed to observe the relative performance of RSI systems to laminated natural rubber (NR) bearings.

# 2. SHAKING TABLE TEST—1: EFFECT OF ROCKING MOTION

## 2.1. The structure

The structure considered is a steel highway bridge (Abora Ko Ji Bridge) located in south of Kyoto city, Japan. The bridge has steel girders supported by reinforced concrete piers. Part of this bridge between piers number 89—97 with total length of 314.54 m is considered in this study. Details of the structure are shown in Figure 2. Total weight of deck is 11 192 kN and the height of centre of gravity of deck from sliding interface level \( h_G \) is equal to 2100 mm.

Total stiffness of buffers for each span is 18,496 kN/mm, which results into a period of 1.10 s for isolated deck. Normal pressure on sliders under static load is 16.3 N/mm².
2.2. Design of the test model

Portion of the bridge between two piers is considered as test model to simulate the behaviour of prototype bridge structure. The span between the selected piers is 40.1 m. Considering the limitations of the shaking table, the geometrical scale ($S$) for the model is selected as 1:10.69. Table I summarizes the scale transformations for relevant indices. In non-flexible girder bridge, variation of normal pressure on sliders is function of vertical acceleration and rocking motion. Therefore, to simulate the effect of variation of normal force, ratio of vertical force induced by vertical acceleration and rocking effect should be equal for model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scaling factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>$S$</td>
</tr>
<tr>
<td>Acceleration</td>
<td>1</td>
</tr>
<tr>
<td>Force</td>
<td>$S^2$</td>
</tr>
<tr>
<td>Mass</td>
<td>$S^2$</td>
</tr>
<tr>
<td>Time</td>
<td>$S^{0.5}$</td>
</tr>
<tr>
<td>Frequency</td>
<td>$S^{-0.5}$</td>
</tr>
</tbody>
</table>

Table I. Scaling factors for simulation.
and prototype

\[
\frac{1/2Ma_v}{Ma_h h_G b_W} = \frac{1/2Ma_v}{Ma_h h_G b_W} 
\]

In this equation, \( M \) is mass of the deck, \( a_v \) and \( a_h \) are vertical and horizontal base acceleration, \( h_G \) is height of the centre of gravity of deck from sliding interface level and \( b_W \) is distance between two sliders. Since response acceleration in model and prototype is equal, Equation (1) can be rewritten as follows:

\[
\left( \frac{h_G}{b_W} \right)_{\text{Model}} = \left( \frac{h_G}{b_W} \right)_{\text{Prototype}} 
\]

In real bridge the ratio of \( h_G \) and \( b_W \) is 0.123. Detailed drawing of the model used for the test is shown in Figure 3 in which \( b_W \) and \( h_G \) are 2.25 and 0.28 m, respectively.

2.3. Sliding bearings

Sliding bearings used in isolation system comprised of (i) stainless steel plate bolted to deck and (ii) high pressure shoe (HiPS) fixed to shaking table. Figure 4 depicts components of sliding bearings. HiPS comprises three layers of steel plate, which are bounded by rubber. As

Figure 3. Test set up for shaking table test—1.
shown, one of the steel plates is covered with PTFE to make low friction surface in contact with superstructure. The rubber between steel plates induces flexible support and it helps in getting uniform pressure on sliding surface during earthquake motion.

The diameter of contact surface (PTFE) is taken as 43 mm, which gives an average normal pressure on bearing due to weight of model as 16.9 MPa. In order to evaluate the design parameters of sliding bearings, test model was excited under sinusoidal load with different frequencies and level of accelerations. Recorded values of friction force and displacement of slider are then used to arrive at variation of friction coefficient and velocity for different vertical pressure. Result of this analysis for vertical pressure 16.9 MPa is plotted in Figure 5 for sinusoidal motion with amplitude $3.0\,\text{m/s}^2$ and frequency 5 Hz. From the data points (shown as cross marks), a relation is established between coefficient of friction and velocity.

2.4. Rubber buffers

Buffers used in the study are laminated rubber bearings, fabricated by natural rubber. Design horizontal stiffness ($K_h$) of bearings depends upon the desired period of isolated structure and for rigid body first mode; its value can approximately be obtained by

$$K_h = \frac{W}{g}(2\pi/T_1)^2$$

where $W$ is the weight on the bearing and $T_1$ is the desired time period of isolated structure.

For other stiffness values of bearings, the periods can again be evaluated by the same expression. Dimension of buffer R1 is $250 \times 250 \times 99$ mm with effective stiffness equal to 1.731 kN/mm, which corresponds to the desired period (1.1 s) of scaled model of isolated bridge. In order to investigate the effect of rocking motion for RSI systems with different period, two other buffers with lower stiffness are also used. Period of the prototype with these rubber buffers are 1.75 and 3.0 s that are designated as R2 and R3, respectively.
Shear connectors provide a simple joint connection between rubber buffer and deck to resist seismic shear force. It does not allow any moment or axial force to be transferred to the laminated rubber bearing.

2.5. Earthquake motions considered

The real bridge is located in southern part of Kyoto City. Geological observation shows, that the site is surrounded by three faults namely Hanaore, Momoyama and Uji Gawa. In this regard three acceleration time histories were generated based on tectonic condition and seismicity of the region and named as per the causative faults, respectively. Three other earthquake motions considered are the standard earthquake motions, recommended by Japan Road Association for stiff soil (Group I), moderate soil (Group II) and soft soil (Group III). The response spectrums of these motions for damping ratio 0.05 are presented in Figure 6. In order to get the true input motion for the test model, the response acceleration time history at the top of the pier of the bridge was obtained analytically. For this purpose, the deck is simulated as elastic beam element supported on two isolators and mass of the system is assumed to be distributed along the deck. The piers are assumed to have two degree of freedom. Soil interaction at the bottom of piers is modelled by axial and rotational springs. Seismic isolators are simulated by linear spring with low stiffness in horizontal and very high stiffness in vertical direction. For simulation, time step of input motions at the pier top are compressed by a scale factor of $\sqrt{s_L}$.

2.6. Instrumentation

The test model was well instrumented for recording the response during the experiment. Accelerometers, laser displacement meters, and load cells were placed to measure response quantities at different locations and in different directions. Load cells, which were placed under HiPS, had capability to record force time history in two horizontal and one vertical direction. Accelerometers and displacement sensors were placed on shaking table also to record its response during the test. During all these tests, data acquisition in real time was
performed through a total of 38 channels out of which six channels (three acceleration + three displacement) used for recording the response of shaking table, 20 channels (12 acceleration + 8 displacement) used for recording the response of bridge deck and 12 channels to record response of load cells placed under the isolators.

3. RESULTS OF THE SHAKING TABLE TEST—1

Since this test focuses on effect of rocking motion on behaviour of RSI system, only relevant data is processed. First the time history of normal force on sliders due to rocking is extracted from recorded data and is analysed for this purpose. Then the effect of rocking motion on normal forces and hysteretic behaviour of sliding bearings are studied for different earthquake motions.

3.1. Time history of normal force

One of the main reasons of difference between variation in normal force occurs on sliding bearing due to effect of (i) vertical acceleration and (ii) rocking motion, is the difference in modes by which the bearings resist the two cases. In fact, vertical inertia force is supported by all bearings equally whereas overturning moment due to rocking motion is resisted by forces on bearings that are opposite in nature. More simply, due to rocking motion, normal force on some sliding bearing is increased while on others it gets reduced. Figure 7 shows part of the time history of sum of normal force on sliding bearings A plus C (see Figure 3) and bearings B plus D. Variation of normal force on these two bearing pairs for HanaOre earthquake motion shows that due to rocking effect, increase in total vertical force on bearing A and C is almost same as the reduction in vertical force on bearing B and D. Time history of normal force on slider A due to effect of rocking for T2-I-1 motion is shown in Figure 8. Variation of normal force because of rocking motion was obtained by subtraction of the recorded normal force and normal load due to vertical acceleration alone. In this figure, normal force is compared for RSI systems with period 1.10, 1.75 and 3.0 s. It can be observed that difference between maximum and minimum value of normal force for system with period 1.10 and 1.75 s is about 15 kN whereas it reduces to less than 12 kN for isolation system with period 3 s. Likewise, variation of normal force in system with period 3.0 s, for other earthquakes also, is considerably less than systems with period 1.10 and 1.75 s. Reduction of the effect of rocking motion in systems with higher period may be due to result of decrease in maximum shear force in long period range.
3.2. Effect of the rocking motion on hysteresis behaviour

In order to study rocking effect on hysteretic behaviour of isolation system, hysteresis loops for pairs of sliders (A + C) and (B + D) are compared with combined hysteresis loop for all the four sliders. Because normal force on sliding bearing A and C counteracts to normal force on bearing B and D, this comparison can be helpful to recognize rocking effect. In Figure 9, variation of horizontal force recorded by load cells versus relative displacement of
deck is plotted for system with rubber buffer R1 under Momoyama motion. It is observed that hysteresis loop in each pairs of the sliders has trapezoidal shape but in sliders A and C is nearly symmetrical to that for sliders B and D. Meanwhile in isolation system with rubber buffer R3, due to reduction of rocking effect, hysteresis curve for each pairs of slider is similar and has rectangular shape.

For isolation systems with three different periods, it is observed that the resultant hysteresis loop of all sliders has rectangular shape. This indicates that the effect of rocking motion is there in response of individual isolator whereas it gets cancelled in the response of total system. Therefore, the rocking motion has small influence on seismic behaviour of deck isolated by RSI system in horizontal direction.

4. SHAKING TABLE TEST—2: COMPARATIVE PERFORMANCE AND VERTICAL ACCELERATION EFFECT

4.1. The structure

A five span steel highway bridge, supported on reinforced concrete piers is considered for this test. Total length of the bridge is 271.2 m. Each of the middle three spans of the bridge is 57 m. Details of the structure are shown in Figure 10. The non-isolated bridge structure is analysed for its dynamic characteristics. Natural period of the bridge is 0.58 s and dynamic analysis of the system shows, due to flexibility of the girders, all five dynamic mode shapes happen in the deck. The piers participate in free vibration of system from the sixth mode.

4.2. Design of the model

In order to design the scaled model of real bridge, the deck is analysed continuous beam subjected to gravity loads. As shown in bending moment diagram for the bridge deck (Figure 11), A and B are points of contra flexure. In fact the portion of the bridge between these two points was taken as test model to simulate the behaviour of prototype bridge structure. The geometrical scale for the model is selected considering the limitations of the shaking table and its value for this test is taken as 1:15.45. The bridge deck is simulated by steel plate, the thickness of which is taken such that the resulted mass of the deck gives
scaled frequency of the un-isolated structure. To simulate the shear force acting at the points of contra flexure, additional weights in the form of steel plates are put at the both ends (Figure 12).
4.3. The isolation systems

Three types of isolation systems are used in this test. The bearings designed for the test model are based on scale versions of those designed for prototype structure.

The target period for prototype structure was 1.3 s, which for test model is scaled to 0.33 s. Stiffness of the isolation systems is adopted such that it can result in desired time period at design displacement. The sliding bearings used in RSI systems (HiPS) are combination of PTFE-stainless steel with same property as the sliders in shaking table test 1. Following is the brief description of isolation systems used in this test.

**Isolation system I:** This system comprises of sliding bearings and low damping laminated rubber buffer. As shown in Figure 12, two sliding bearings and a buffer (type I) is provided on each support. The buffers in isolation system I are made from natural rubber (NR) of shear modulus 1.20 N/mm².

**Isolation system II:** This system also comprises of two sliding bearings and a buffer (type II) at each support. Here again the rubber used in buffer is natural rubber (NR), which has design shear modulus of 1.20 N/mm². Stiffness of this buffer was kept low as compared to buffer type I, expecting that the realized effective stiffness for combined system (slider + buffer) at design displacement of 10.71 mm, will be same as that of buffer type I.

**Isolation system III:** This system comprises of two laminated rubber bearings at each support. The rubber bearings are made from natural rubber that has design shear modulus of 1.20 N/mm². The placement of bearings used in this system is shown in Figure 12.

4.4. Earthquake motion

In order to investigate the performance of the isolation systems for different input characteristics numbers of real and standard earthquake motions are used. The real motions
considered for this test are those, which were recorded during Hokkaido earthquake of 2003 (HKD 100 station) Hiroshima earthquake of year 2001 (Geiyo HRS017 station) and Kobe earthquake of 1995 (JMA and Takatori station). These motions cover a wide range of characteristics viz. frequency content, duration and peak ground accelerations. Acceleration response spectra of the earthquakes for damping values of 5% are shown in Figure 13. The response spectra of Hokkaido and Geiyo earthquakes show very clear peak around 0.28 and 0.13 s, respectively. A response spectrum for Kobe (Takatori) shows peaks near 0.40 and 1.25 s while Kobe (JMA) has two peaks near 0.35 and 0.70 s. The standard earthquakes are typical of stiff soil (T2-I-1), medium soil (T1-II-3) and soft soil (T1-III-3).

In order to get the true response from test model of the bridge supported by piers, first the response acceleration time history at top of the pier of seismically isolated bridge is obtained analytically for the above earthquake base motions. The analysis is carried out for unidirectional and bi-directional base motions in longitudinal and vertical direction for all earthquake motions. The acceleration time history of input motion and response at pier top is found to be very similar. This indicates that the piers are very stiff and behave like a rigid block.

Figure 13. Response spectrum of the earthquake motions.
4.5. Instrumentation of the test model

Again, the test model was well instrumented for recording the response during the test. Accelerometers, Laser displacement meters, load cells and strain gauges were placed to measure response quantities at different locations and in different directions. Load cells were placed under HiPS for isolation systems I and II and under laminated rubber bearings for the third isolation systems. In addition, 5 strain gauges were used to enable the recording of strain values at deck surface at mid span and at supports. Displacement meters were also provided below the deck plate, near the four supports to get rotation of the bridge deck. During all the tests, data acquisition in real time was performed through a total of 61 channels out of which six channels (three acceleration + three displacement) used for recording the response of shaking table, 43 channels (15 acceleration + 22 displacement + six strain gauges) used for recording the response of bridge deck and 12 channels to record response of load cells under the isolators.

5. RESULTS OF THE SHAKING TABLE TEST—2

5.1. Amplification of the acceleration

First of all, average values of accelerations along the longitudinal direction, recorded on deck top are computed. Then ratio of this average peak acceleration to peak shaking table acceleration (amplification ratio) is obtained for different isolation systems and earthquake motions. In order to study the comparative performance, these amplification ratios are plotted in Figure 14(a). Amplification ratio for isolation system I and II (NR buffers + friction bearings) has low average value of 0.33 in high frequency earthquake like Geiyo whereas increase to high value of 1.37 for Kobe Takatori motion. In standard earthquakes motions (T2-I-1, T1-II-3, T1-III-3), maximum response acceleration of isolation system I and II is close to each other.

Isolation system III (natural rubber bearing alone) shows very good performance to input motions of Geiyo and Hokkaido. However for Kobe Takatori and Kobe JMA earthquake, amplification factor is more than other systems. This may be because of resonance effect.

5.2. Relative displacement of the deck

In resilience sliding isolation system, restoring spring like buffer reduces residual displacement of system after earthquake. It was observed during these experiments that in all cases residual displacement was negligible. However, maximum relative displacement of deck governs the width of expansion joint between deck and abutment. To study the relative effectiveness of the isolation systems in controlling the displacement at the isolation level, the maximum relative displacement of the deck top and shaking table is plotted in Figure 14(b). It can be observed in this figure that isolation system I and II have less relative displacement than isolation system III for different earthquake motions. This may be because of energy dissipation in sliders. The difference increases for earthquakes with lower frequency content and higher maximum acceleration.

5.3. Rotation of supports

It was expected that rotation of supports during earthquake for a long span bridge may be important in controlling the behaviour of isolation system, especially the sliders. In this
regard rotation of bearings was recorded near the supports of deck for different conditions. Figure 14(c) shows average of maximum rotation of bearings for the three isolation systems. However, no clear relation between characteristics of earthquake motion or isolation system with rotation of support could be identified.

5.4. Maximum transmitted energy

The magnitude of dissipated energy alone cannot show efficiency of isolation system. The difference at any time, $t$, between input energy and the total dissipated energy is stored temporarily in the structure in the form of kinetic and strain energy. In seismic isolation systems, this stored energy in structure, i.e. energy transmitted through isolators to the structure gives more realistic index to show efficiency or capacity of different isolation system to control structural damage. The peak value of this parameter for seven earthquake motions is shown in Figure 14(d). It can be observed that maximum transmitted energy for different isolation systems under excitation of Geiyo and Hokkaido earthquakes, is negligible. However for long period motion of Kobe (Takatori) earthquake, it has considerably high values.

Among three isolation systems, maximum transmitted energy for isolation system III is more than that for other systems. Isolation system I and II performs exceptionally well under Kobe (JMA) and Kobe (Takatori). This shows efficiency of RSI system for low frequency earthquakes motions.
5.5. Effect of vertical acceleration

With the objective of studying effect of vertical acceleration in detail, the bridge model is excited with vertical and horizontal acceleration simultaneously. Figure 15 shows hysteretic behaviour of four sliders used in isolation system I under Kobe Takatori earthquake motion with and without vertical component. As shown, no significant effect of vertical component is observed.

Effect of vertical component of excitation on maximum response of system is also investigated by comparing the maximum displacement and acceleration values for motion without and with vertical component. It can be observed from Figure 16(a) and (b) that there is no considerable effect of vertical component on relative displacement and
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acceleration amplification ratio for four earthquakes excitation. Moreover, same results were obtained for isolation system II.

6. ANALYTICAL STUDY ON THE TEST MODELS

The dynamic non-linear analysis is carried out by using computer program SAP2000 [15]. The sliding bearing is modelled with a bilinear element. Its behaviour is based on the model proposed by Wen et al. [16] and friction coefficient (μ) is calculated by expression proposed by Constantinou et al. [17].

\[ \mu = \mu_{\text{max}} - (\mu_{\text{max}} - \mu_{\text{min}}) \exp(-\alpha v) \]

Here, \( v \) is sliding velocity, \( \alpha \) is a constant for given pressure and condition of interface. Response of the models recorded during two shaking table tests is compared with results of numerical analysis. Furthermore, the results obtained from the shaking table test—2 are compared with scaled values of the responses of numerical analysis of the real bridge.

6.1. Analytical model for shaking table test—1

The results of shaking table test are compared with numerical analysis for validation of the algorithm used in the analysis. The numerical model of shaking table test—1 is shown in Figure 17(a). Variation of friction coefficient with velocity is considered to follow the

Figure 17. Analytical model for shaking table test—1 and comparison of its responses with experimental results: (a) numerical model; and (b) comparison of hysteresis loop under excitation of T2-II-1.
expression shown in Figure 5. In other words, the parameters \( \mu_{\text{max}} \), \( \mu_{\text{min}} \) and \( z \) are taken as 0.20, 0.10 and 24 cm/s, respectively.

Laminated rubber bearings are assumed as a linear spring with total effective stiffness \( K_e \). Effective stiffness values for buffers are calculated from their recorded force and displacement values.

The mass of the structure is assumed to be lumped mass element with three degrees of freedom (two displacements and one rotation). Total mass of system and moment of inertia is taken as 10 ton and 15.94 ton m\(^2\), respectively. The recorded acceleration on shaking table for each earthquake is considered as time history for input base motion in numerical analysis.

### 6.2. Comparison of the results

Hysteretic behaviour and shear force response recorded during experimental test are compared with numerical results obtained from dynamic analysis. Figure 17(b) shows hysteresis loop of system with buffers R2 and R3 under base motion T2-II-1. The figure shows that there is good agreement between results obtained from experimental and analytical study. The experimental response corresponds to base motion having horizontal and vertical component both, whereas the analytical response shown here is obtained for base motion having horizontal component only. The proximity of results again shows that vertical acceleration has insignificant effect on response of isolation system.

### 6.3. Analytical model for shaking table test—2

Figure 18(a) shows the analytical model of structure used in shaking table test—2. As shown in this figure, deck is modelled as beam element with lumped masses. Additional weights, put to simulate the shear force, are modelled by lumped mass at the two ends. Non-linear friction

![Analytical model](image)

Figure 18. Analytical model of: (a) test model; and (b) real bridge, in shaking table test—2.
element is considered for modelling the behaviour of sliders and a linear spring is considered for modelling the behaviour of buffers. Viscous damping ratio for rubber buffer is considered to be 10 percent. Effective stiffness of non-linear spring is calculated for maximum recorded displacement of buffer and corresponding force during the shaking table test. Moreover, the tangent of initial part in hysteresis curve of friction sliders of each test is taken as initial stiffness of friction. Maximum and minimum values of friction coefficient and value of $\mu$ are again taken as 0.10 and 0.20 and 24 s/m.

6.4. Analytical model of the real bridge

Analytical model of real bridge is shown in Figure 18(b). The mass of the system is considered to be distributed along the deck and piers. Elements of bridge are assumed as elastic frame elements. The number of elements in each span of deck and the pier are four and three, respectively, with six degrees of freedom of each node. Variation in cross sectional dimension of pier is also considered in modelling of this element. The damping in the deck and piers is taken as five percent of the critical in all the modes of vibration. Isolation system at top of the piers is modelled as combination of linear spring and non-linear friction element. Stiffness of buffers are calculated by scaling the value obtained from its force–displacement behaviour recorded during the test and the coefficient of friction follow the expression shown in Figure 5.

6.5. Comparison of the results

Response quantities of interest are deck acceleration and the relative displacement at the isolation level. Deck acceleration under Kobe (Takatori) earthquake motion are shown in Figure 19. In this figure, experimental results are compared with (i) analytical response of the test model and (ii) scaled value of analytical response of the real bridge. It can be observed that the results are in close agreement.

Figure 19. Acceleration time-history of shaking table test—2 and Analysis.
Analytical response is obtained for horizontal excitation only whereas experiment results are recorded for simultaneous horizontal and vertical excitation. Thus, it can be concluded that presence of vertical acceleration has insignificant effect on total response of seismically isolated highway bridge with RSI system.

It can also be concluded that simple analytical models can be used to obtain structural response of full-scale bridge with sufficient accuracy. This may be due to the fact that seismic isolation system changes first mode of vibration of structure system to a rigid body mode and therefore structural characteristic has minimum effect on dynamic response. Thus response of a full-scale complex seismically isolated structure can be predicted with acceptable accuracy by experiments using a simple scaled model of the structure.

7. CONCLUSIONS

In this paper, a series of shaking table tests are carried out on two seismically isolated bridge models to study the performance of RSI isolation systems. In addition, the effects of rocking motion and vertical acceleration, on seismic performance of RSI system are investigated. Moreover, performance of RSI system is compared with system having solely natural rubber bearings. Also, the response of model recorded in shaking table test is compared with analytical response of the prototype and model. The results of the study can be summarized as below:

1. In seismically isolated highway bridge, variation of normal force on sliding bearing due to rocking effect is considerable when compared with that due to effect of vertical acceleration.
2. Effect of rocking motion on variation of the normal force gets reduced with reduction in stiffness of buffers.
3. Due to rocking effect, hysteresis loop of individual sliding bearing changes to a trapezoidal shape, whereas hysteresis loop of total sliders in the system remains as rectangular.
4. Seismic response of bridges isolated by RSI system is almost the same for earthquake excitation with and without vertical components. (i.e. vertical acceleration has insignificant effect).
5. RSI shows better performance than natural rubber bearing system in controlling response acceleration and relative displacement of deck.
6. For seismically isolated bridges, dynamic response of full-scale complex structures can be predicted with acceptable accuracy by experiments on its simple scaled model.

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