Experimental and Analytical Study on the Pounding Effect of Bridges with Inclined Decks

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SUMMARY
This paper is aimed to study the pounding effect on bridges with inclined decks experimentally and analytically. A serious of shaking table tests were first conducted by using four sets of bridge models. The good agreement between the experimental and analytical results verifies that the idealizations of the test models are adequate to simulate the dynamic behaviour. Based on the results of the shaking table tests, a six-single-span isolated bridge is then analyzed under extreme earthquakes. The Vector Form Intrinsic Finite Element, a new powerful computational method, is used to predict the failure process of bridges under strong earthquakes. The simulation results reveal that the bridge suffers severer damage as the deck slope increases. Vertical tensile forces may be induced in the isolators of the bridges with large slopes. It is suggested that the pounding effect be taken into account especially for the bridges with inclined decks.

Keywords: Bridge, Pounding effect, Inclined deck, Seismic response, Isolator

1. INTRODUCTION

In the past extreme earthquakes, local cracking or crushing due to pounding between superstructures and even deck unseating, could be observed in the sites. Bridges with inclined decks are generally constructed in areas with complex terrain, route alignment, ramps, interchanges, and so on. This research is aimed to study the pounding effect on isolate bridges with inclined decks through shaking table testing and numerical simulation. Firstly, a series of shaking table tests are conducted to realize the pounding effect on bridges with inclined decks by using four sets of two-single-span-bridge steel models including 0%, 3%, 6% and 10% inclined decks, respectively. The models are intentionally designed to possess nearly identical fundamental structural periods so that the slope can be regarded as the only parameter studied. Harmonic excitations and earthquake ground motions recorded in the past earthquakes are used in the shaking table testing. Analytical models of the test structures are established and calibrated via experimental system identification testing. Numerical simulation results from the experimental tests demonstrate that the analytical models are adequate for describing the pounding effect and dynamic behaviour of the test structures.

Lately, modern bridge seismic design has been developed toward the seismic performance design on entire bridges as well as components thereof. However, it is quite difficult to conduct a shaking table test to study the failure mechanism of full-scale bridges under extreme earthquakes. Based on the results of the shaking table tests for the bridge models, a six-single-span isolated bridge is then analyzed with considering pounding effect of superstructures under extreme ground motions. High-damping-rubber isolators are installed between the decks and the columns. The slope of the decks varies from 0% to 10% at an increment of 2%. The Vector Form Intrinsic Finite Element (VFIFE), a new computational method developed by Ting et al., is adopted in this study to simulate the failure process of isolated bridges with inclined decks. Through the numerical simulation for the ultimate state of the target bridges, it is suggested that the pounding effect be taken into account especially for the bridges with decks of large slopes.

2. SHAKING TABLE TESTING

Four sets of two-single-span-bridge steel models including 0%, 3%, 6% and 10% inclined decks, respectively, are fabricated by using steel plates and rolled shapes as shown in Figures 1 and 2. It is emphasized that the test models do not represent a similitude-scaled reproduction of full-scale bridges. Rather, the test models are designed as small structural systems to simulate the pounding behaviour of two adjacent bridges. The gap between the left bridge and right bridge are 5 mm in all four test models. With the design of bolted connections, the column plates can be replaced after undergoing nonlinear deformation.

The experimental testing was performed on a biaxial shaking table with an area of $3\,\mathrm{m}\times 2\,\mathrm{m}$ and strokes of 700 mm and 400 mm in two directions, respectively, at the Department of Civil Engineering of the National Central University. After assembling each test model, the vibration properties of the structure were identified using a banded white noise with a frequency range of 0-20 Hz as the input to the shaking table prior to the experimental tests. The results indicate that the natural periods of the first dominant vibration modes in the left and right bridges are 0.38 and 0.19 sec., and their corresponding damping ratios are 0.25% and 0.3%, respectively.

3. EXPERIMENTAL AND ANALYTICAL RESULTS

Harmonic excitations are first input in the shaking table testing. The excitation frequencies are 1.0 Hz, 2.0 Hz and 2.5 Hz while the corresponding amplifications are 75 mm, 12 mm and 6 mm, respectively. The test models are idealization by using finite element method based on the results of the foregoing system identification testing. To simulate the pounding effect, the pounding force during collision is modelled by impact elements. A linear elastic spring model is first developed by Kawashima and Penzien (1979). This impact model consisting of an elastic spring and a gap is simple and extensively used element.

Figure 3 presents the time histories of both the numerical simulations and experimental test data of the test models with 6% inclined decks subjected to harmonic excitation with a frequency of 2.0 Hz and a amplification of 12 mm. Comparisons between the numerical simulations and experimental test data of the displacements of the left bridge and the right bridge, the relative displacement between two bridges and pounding forces are shown in Figures 3(a)-3(d), respectively. As observed in Figure 3, the time histories of displacement responses and pounding forces computed from the numerical simulations agree reasonably well with the experimental test data. These results verify that the idealizations of the test models are quite satisfactory. Although several types of impact elements have been developed and used, such as a bi-linear spring, a linear spring-damper and a non-linear-spring, the experimental results show that the linear elastic spring model can simulate the pounding behaviour appropriately (Lee et al. 2011).

4. VECTOR FORM INTRINSIC FINITE ELEMENT

The Vector Form Intrinsic Finite Element (VFIFE) is developed based on theory of physics to mainly simulate failure responses of structural systems subjected to extreme loads. To analyze a continuous structural system by using the VFIFE, a lumped-mass idealization is first performed to construct a discrete model. All lumped masses are then connected by deformable elements without mass which exhibit resisting forces during deformation. Applying Newton's Second Law of Motion, the equations of motion are assembled at each mass for all degrees of freedoms. Assume that a structural system consists of a finite number of particles. The equations of motion for a particle α are written as

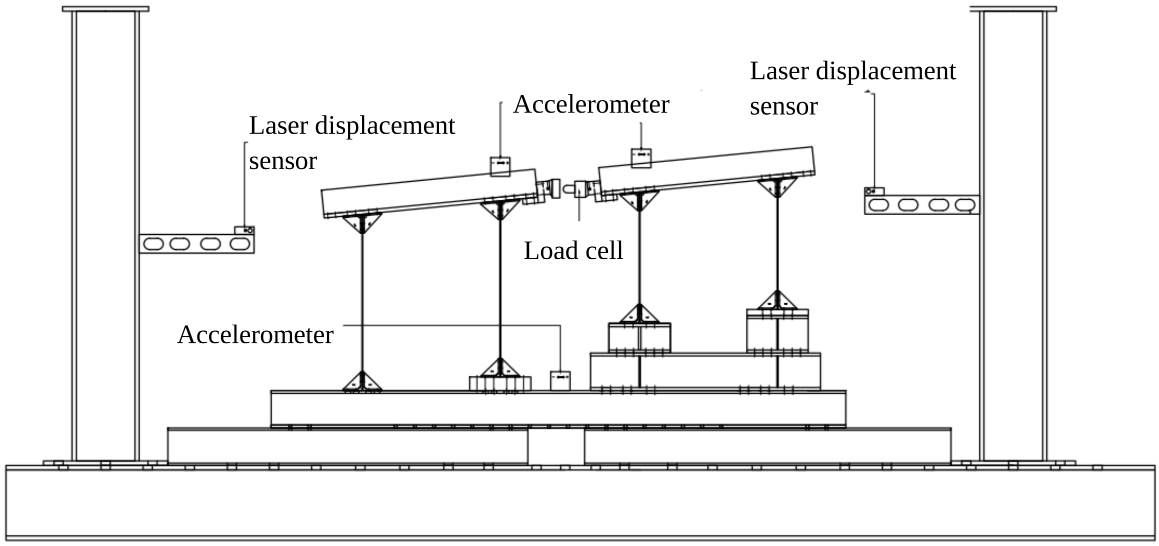

Figure 1. Test models with inclined decks and sensors

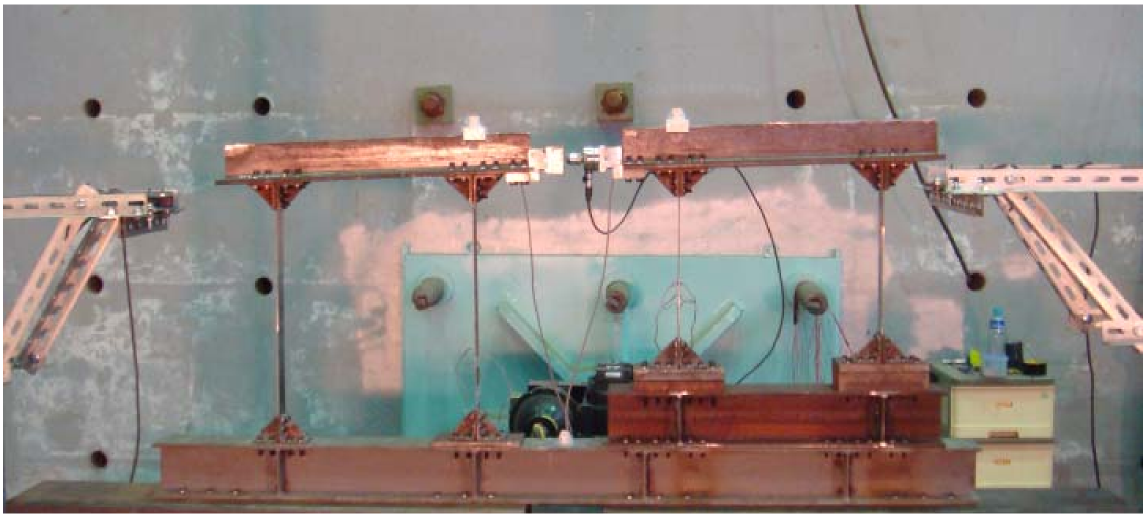

Figure 2. Photo of the test models and sensors installed on a shaking table

$$\mathbf{M}^{\alpha}\ddot{\mathbf{d}}^{\alpha}(t) = \mathbf{P}^{\alpha}(t) - \mathbf{f}^{\alpha}(t) \tag{2.1}$$

where $\mathbf{M}^{\alpha}$ is the diagonal mass matrix of the particle α and $\mathbf{d}^{\alpha}(t)$ is the displacement vector when the particle α is at time t; $\mathbf{P}^{\alpha}$ is the vector of applied forces or equivalent forces acting on the particle; $\mathbf{f}^{\alpha}$ is the vector of the total resistance forces or internal resultant forces exerted by all the elements connecting with this particle.

It is noted that each element without mass is assumed to be in static equilibrium. Observed from Eq. (2.1), the VFIFE analysis is exempted from the assemblage of the global stiffness matrix for structures consisting of elements with multiple degrees of freedom. Therefore, a matrix algebraic operation for the entire system is not required. In stead, each equation of motion for each particle, Eq. (2.1), can be individually solved. Since the failure of structures involves changes in material properties and structural configuration, it is necessary to use discrete time domain analysis to solve the equations of motion. The central difference method, an explicit time integration method, is thus selected in the VFIFE to solve the equations of motion, Eq. (2.1).

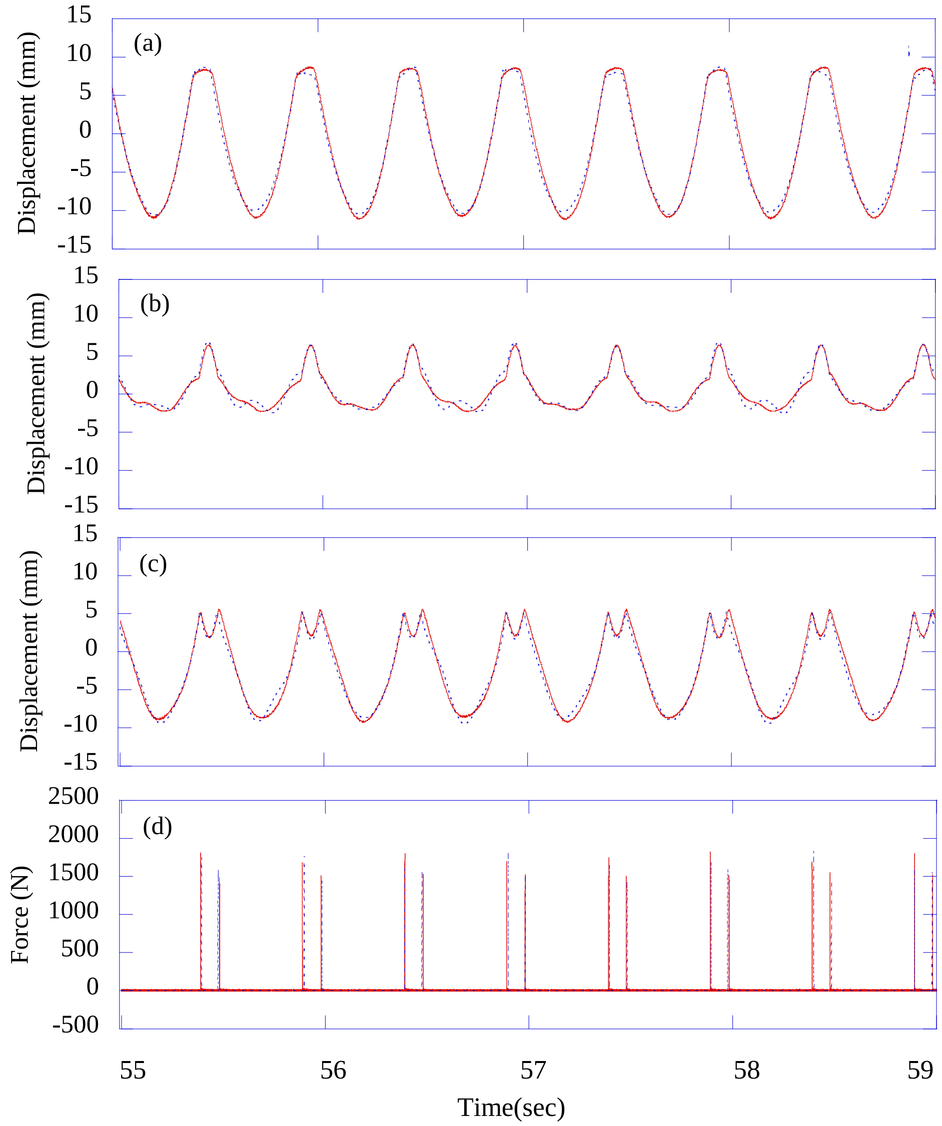

Figure 3. Comparison of numerical simulation (dashed curve) and experimental data (solid curve) : (a) displacement of the left bridge (b) displacement of the right bridge (c) relative displacement between two bridges (d) pounding force

Compared to the traditional finite element method, the unique of the VFIFE is that element internal forces are calculated by using the element deformations obtained through subtracting rigid body displacements from total displacements. A set of deformation coordinates is defined for each element in each time increment to calculate the element deformations. Therefore, the VFIFE is capable of dealing with structural dynamic problems with large displacements, deformations and rigid body motion simultaneously.

When subjected to extreme earthquakes, bridges may undergo highly nonlinear behaviour even structural failure. In the past large earthquakes, some bridges suffered deck unseating. Generally, deck unseating follows high material nonlinearity, geometric nonlinearity as well as rigid body motion. To simulate the ultimate states of bridges, the failure mechanism of major bridge components should be taken into account.

The studied failure components are isolators, unseating prevention devices and plastic hinges of decks and columns. Firstly, isolators are idealized as a bilinear model. Once the resistance force of an isolator reaches the designated rupture strength, the isolator fractures and then no longer exerts resistance shear force. Assume that the isolator becomes a sliding-like bearing and friction force exists on the fractured surface. When the relative displacement between superstructure and column exceeds the unseating prevention length, the superstructure will lose the supporting force provided by the column and then fall down from the cap beam due to the gravity force. The failure of isolators represents a typical failure mechanism completing material linear and nonlinear behaviour, fracture, and sliding of structures. Such elements in the VFIFE have been developed in the previous studies (Lee et al. 2009, 2010).

After an isolator ruptures, the interface between the superstructure and the column turns to a sliding surface if the relative displacement between the superstructure and the column is still within the unseating prevention length. The motion on the sliding surface can be separated into stick and slip phases. When the friction force is smaller than the maximum static friction force, there is no relative motion in the interface, namely in stick phase. Once the friction force overcomes the maximum static friction force, relative movement starts in the interface and the friction force converts to dynamic friction force, namely in slip phase. In this study, assume that the maximum static friction force is equal to the dynamic friction force, and the dynamic friction coefficient remains constant during sliding.

In the calculation process of the VFIFE, the material properties and structural configuration are assumed to be unchangeable in each time increment. Therefore, the interface should be in either stick phase or slip phase during each incremental time. Before solving the response at the next time step $i+1$, the condition at the interface must be determined. In this study shear-balance procedure, which was proposed by Wang et al. (2001) for analyzing sliding structures by state-space approach, is used to determine the phase of the interface.

The bilinear model is also used to idealize reinforced concrete columns and steel columns. No matter how the elements may change properties and configuration, even fracture in each time step, they are assumed to be unchangeable in each time interval $t_i \le t \le t_{i+1}$ in the VFIFE. Thus, the internal forces are calculated based on the element properties and configuration at the initial time t_i. The deformation coordinates of elements are redefined at the beginning of each time step. In other words, once an element undergoes nonlinear or discontinuous behaviour, all changes are reflected only at the beginning of next time step.

5. TARGET BRIDGES AND ULTIMATE STATES

An isolated bridge based on Japan highway design codes is analyzed under extreme near-field ground motions to predict the collapse mechanism while considering pounding effect of superstructures. High-damping-rubber isolators are installed between the superstructures and the columns or the abutments. This bridge consists of a six-span deck with a total length of 6@40 m = 240 m and a width of 12 m, which is supported by five reinforced concrete columns with a height of 12 m in each and two abutments, The slope of the decks varies from 0% to 10% at an increment of 2% as shown in Figure 4. The columns are idealized as a perfect elastoplastic model with a fracture ductility of 21.5 shown in Figure 5(a). The isolators are idealized as a bilinear elastoplastic model shown in Figure 5(b). After isolators rupture, the dynamic friction coefficient on the fracture interface is assumed to be 0.15.

The pounding effect of two adjacent decks is considered by using an element with a gap of 28 cm. The unseating prevention length at each column and abutment is 96 cm. In simulation, the bridges are subjected to near-field ground motions recorded at JR Takatori station, in the 1995 Kobe, Japan earthquake, as shown in Figure 6. The ground acceleration is amplified from 100% to 230% at an increment of 10%.

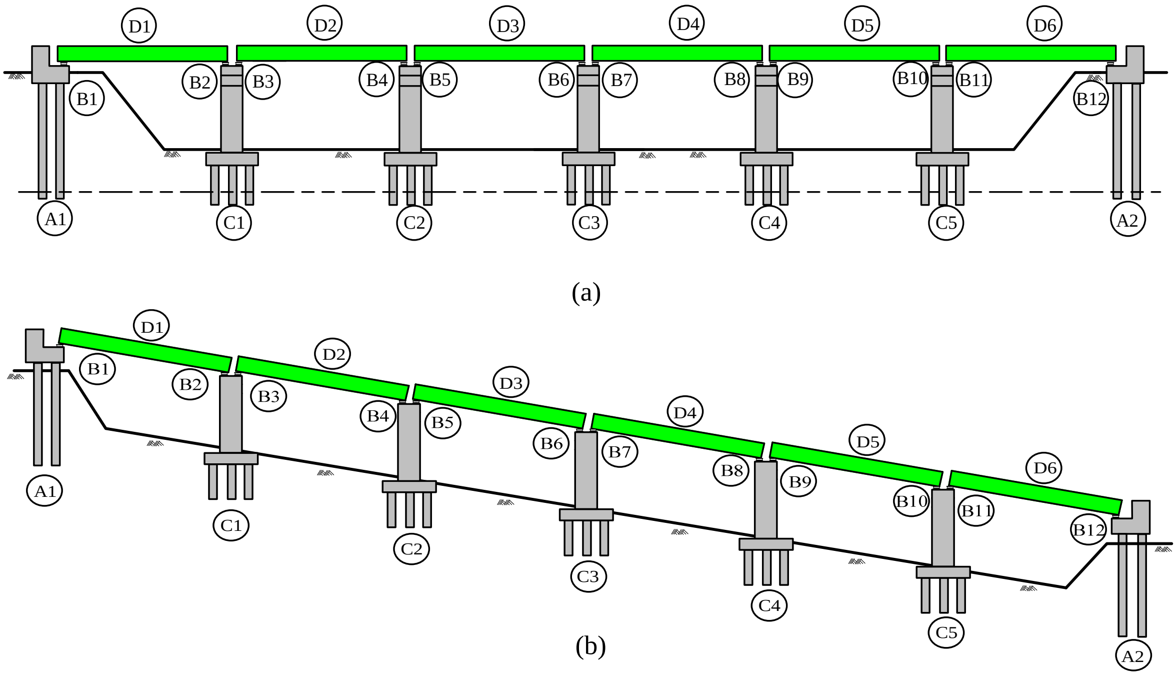

Figure 4. Target bridges with (a) level decks (b) inclined decks

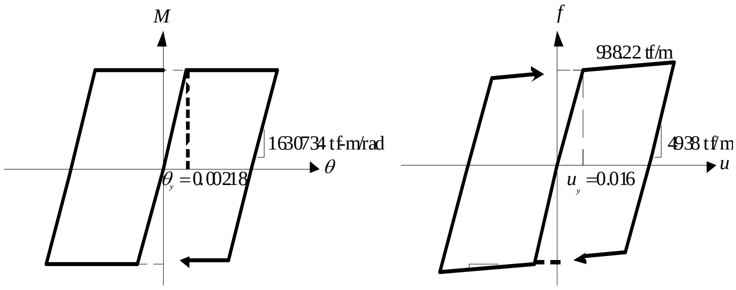

Figure 5. Material property (a) column (b) isolator

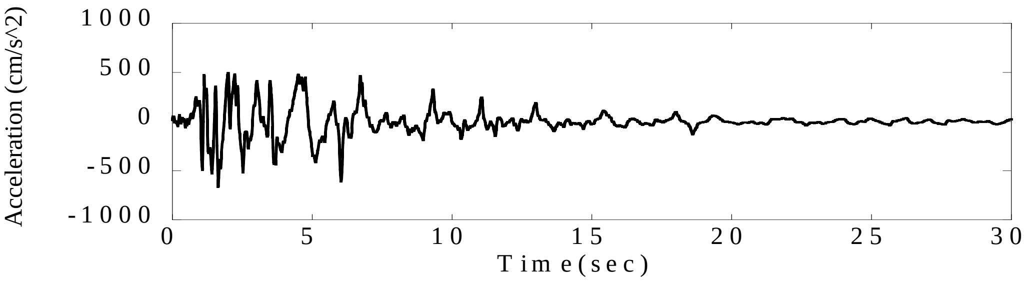

Figure 6. Ground motion recorded at JR-Takatori station in the 1995 Kobe earthquake

Through numerical simulations, the ultimate states of the bridges with decks of various slopes are demonstrated and compared. Figures 7 and 8 depict the failure procedure of the bridges with level decks and 8% inclined decks, respectively, under 200% of the JR Takatori record. The first characters B, C, D of the notions in the figures denote the isolator, column and deck, respectively. Obviously, the bridge with 8% inclined decks suffers severer damage than the bridge with level decks. In the bridge with level decks, only one deck unseats due to the failure of isolator B2 and column C1. However, four decks unseat in the bridge with 8% inclined decks. Decks D1 and D2 unseat due to the failure of column C1 while decks D3, D4 and D5 unseat due to excessive displacement larger than unseating prevention length.

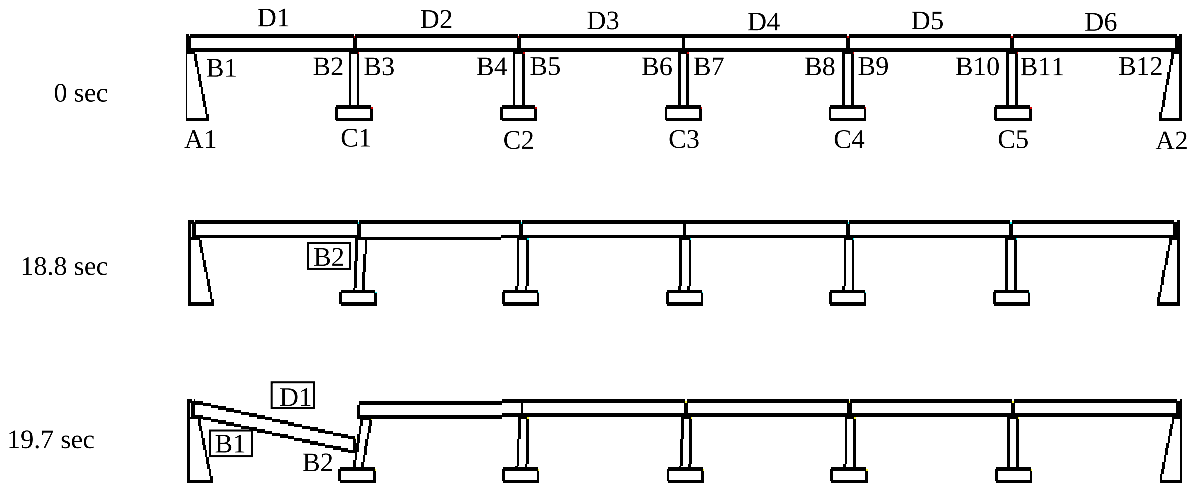

Figure 7. Failure process of the bridge with level decks under 200% of the JR Takatori record.

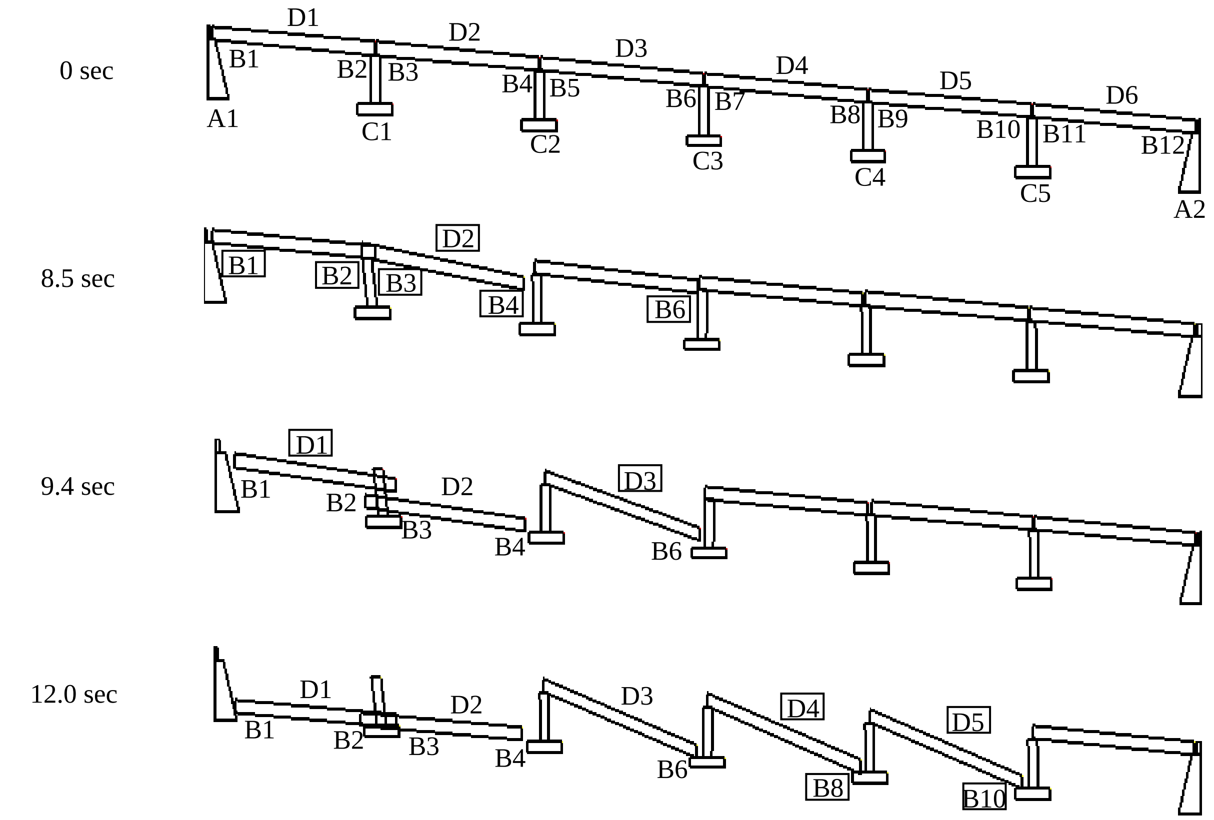

Figure 8. Failure process of the bridge with 8% inclined decks under 200% of the JR Takatori record.

The numerical simulation results reveal that the bridge suffers severer damage as the slope of the decks increases if the structural properties of bridges are identical except for the slope of decks. The analytical results also show that as the slope increases, the vertical bearing force increases for the isolators located on which the pounding occurs. The vertical bearing force even becomes tensile in the cases with large slopes which is beyond the expectation in design and may impair the safety of bridges. It is suggested that the pounding effect be taken into account especially for the bridges with decks of large slopes.

6. CONCLUSIONS

This paper is aimed to study the pounding effect on bridges with inclined decks experimentally and analytically. First of all, a serious of shaking table tests were conducted by using four sets of steel bridge models. Numerical models of the test models were established based on the system identification testing. The good agreement between the experimental data and analytical results verifies that the idealizations of the test models are adequate to describe the dynamic behaviour of the test models. In addition, the linear elastic spring model can simulate the pounding behaviour appropriately

Since it is quite difficult to conduct a shaking table test to study the failure mechanism of full-scale bridges under extreme earthquakes, numerical analysis is adopted to simulate the ultimate states of bridges with inclined decks. Based on the results of the shaking table tests for the bridge models, a six-single-span isolated bridge is then analyzed with considering pounding effect of superstructures under extreme ground motions. Since the VFIFE is superior in managing the engineering problems with highly nonlinearity, fracture and even collapse, it is used in this study to predict the failure process of the bridges with inclined decks under strong earthquakes. The JR Takatori ground motion recorded in the 1995 Kobe earthquake is selected and amplified from 100% to 230% to be the seismic excitations. The numerical simulation results reveal that the bridge suffers severer damage as the slope of the decks increases. Vertical tensile forces may be induced in the isolators of the bridges with large slopes. Generally, the tensile capacity of bearings is much smaller than the compression capacity. Once the tensile force is beyond the expectation in design, it may impair the safety of bridges. It is suggested that the pounding effect be taken into account especially for the bridges with decks of large slopes.

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