DYNAMIC RESPONSE ANALYSIS OF BRIDGE UNDER SEISMIC LOADING INCLUDING COLLISION

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Abstract

In the Mid Niigata Prefecture Earthquake in 2004, the damage of a bridge pier was found mitigated by the collision between a girder and an abutment. Therefore, in the seismic response analysis, it is important to include the effect of the collisions. A simple and practical method of simulating the collision in the analysis is the introduction of a spring where the collision occurs. However, the constant of such a collision spring is yet to be formulated well. In this study, appropriate collision-spring constants are investigated for simulating the collisions between girders and between a girder and an abutment. The response analysis of a bridge under seismic loading is then conducted to see the influence of the collision.

Introduction

The collision between a bridge girder and an abutment restricts the movement of the girder, which in turn reduces the deformation of a bridge pier, often considerably. This implies that the collision can help mitigate seismic damage of the bridge. In fact, in the aftermath of the Mid Niigata Prefecture Earthquake in 2004 we studied a damaged bridge pier (Photo 1) and concluded that the damage could have been much worse if not for the collision between a bridge girder and an abutment (Kosa et al. 2005). Thus the collision plays an important role in the behavior of a bridge during earthquake, and without including the effect of the collision, the analysis of a bridge behavior during earthquake can be quite misleading.

A simple and practical method of simulating collision in the analysis is the introduction of a spring between two bodies that collide with each other. This spring is called a collision spring and activates only when the two bodies collide with each other; the constant of the collision spring is kept equal to zero when the two bodies are not in contact. The effectiveness of this approach hinges on the behavior of the collision spring. In short, the value of the collision-spring constant is important. Nevertheless, the appropriate value has not been clarified except when the two bodies are identical (Kawashima 1981).

In the present study, the appropriate value of the collision-spring constant between two bodies having different stiffnesses is investigated. The response analysis of a bridge under seismic loading is then conducted to demonstrate the influence of the collision.

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(a) Overview

(b) View around girder end

Photo 1. Bridge damaged during the Mid Niigata Prefecture Earthquake in 2004.

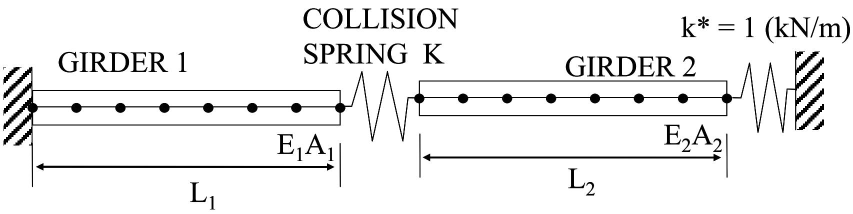


Figure 1. Model A.

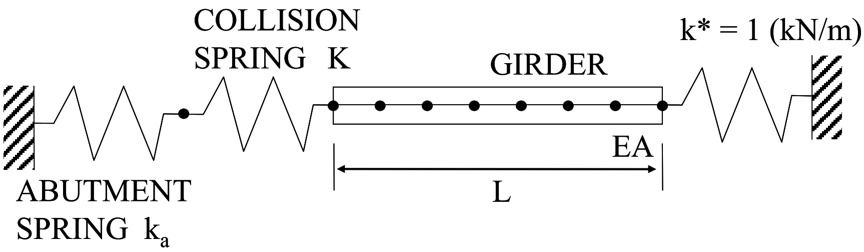


Figure 2. Model B.

<u>Collision-Spring Constant</u>

Analysis Models

The analysis models, Models A and B, are shown in Figures 1 and 2. The two models are to study the collisions between two girders and between an abutment and a girder, respectively. The abutment is modeled by a spring and the girder is by beam elements. The spring with a very small spring constant at the right end of the girder is introduced to prevent the free movement of the girder.

The collision spring is placed between the bodies that would collide. The behavior of the collision spring is shown schematically in Figure 3. The relative displacement is the distance between the two bodies. The origin in Figure 3 represents

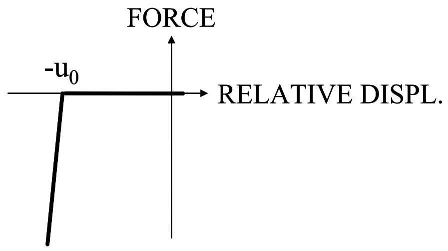


Figure 3. Collision Spring.

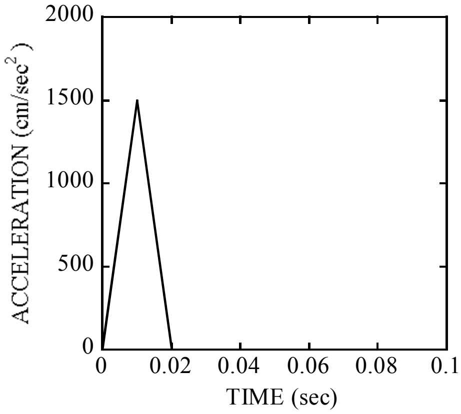


Figure 4. Acceleration.

the initial state. The figure implies that when the relative distance is smaller than $-u_0$, the collision spring is activated: its spring constant becomes non-zero, simulating the physical contact of the two bodies. The value u_0 corresponds to the initial gap between the two bodies.

Going through the dimensions of some existing composite girder bridges in Japan, the following values are employed for the present study:

Model A
$E_1A_1/L_1 = 5.0\times10^5$ kN/m
$E_2A_2/L_2 = 5.0\times10^6$ kN/m

Model B
$EA/L = 5.0\times10^5, 1.0\times10^6, 5.0\times10^6$ kN/m
$k_a = 1.0\times10^5, 3.0\times10^5, 1.0\times10^6, 3.0\times10^6, 1.0\times10^7, 3.0\times10^7, 1.0\times10^8, 3.0\times10^8$ kN/m

where E is Young's modulus, A the cross-sectional area, L the girder length and k_a is the stiffness of the abutment.

The initial gaps u_0 between the two girders and between the girder and the abutment are all set equal to 0.15 m. The acceleration shown in Figure 4 is applied in the longitudinal direction for the sake of simplicity. The damping coefficient of the girder is 0.02. Material nonlinearity is not considered. The increment of time for time integration in the present dynamic analysis is $\Delta t = 1/50000$ sec and 100 beam elements are used for modeling each girder.

Numerical Results and Discussion

Model A

The collision spring has been employed to carry out the dynamic response analysis of a bridge that involves collision. Yet the appropriate spring constant, the slope in the negative region beyond $-u_0$, has not been defined well even though it is likely to influence numerical result. To the best of the authors' knowledge, Kawashima's work (1981) is the only one that deals with this issue squarely. He studied the collision of two identical bars and came up with the following proposal:

$$k = nEA/L \tag{1}$$

where n is the number of elements. To be noted, the usage of the finite element method is presumed and Equation (1) indicates the collision-spring constant may be set equal to the longitudinal stiffness of the element.

This equation can be used right away if the two bodies yield the same k. But oftentimes that is not the case. The present analysis is one of those cases: two different constants of the collision spring are obtained by Equation (1). Therefore, assuming the two collision springs connected in series, the following formula for the collision-spring constant K is proposed:

$$K = \frac{1}{\frac{1}{k_1} + \frac{1}{k_2}} = \frac{k_1 k_2}{k_1 + k_2} \tag{2}$$

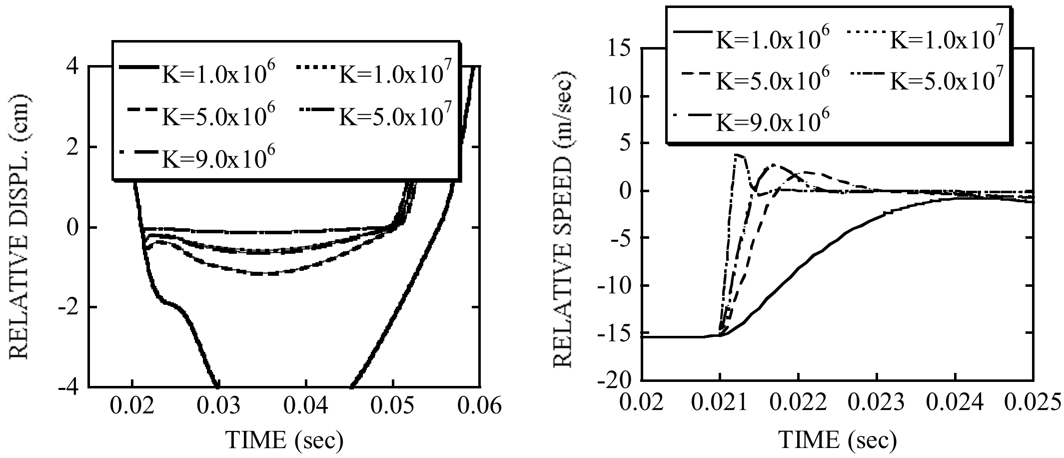
where k_1 and k_2 are the values obtained by Equation (1) for Girders 1 and 2, respectively.

To investigate the validity of Equation (2), the dynamic analysis of Model A is conducted with various collision-spring constants K in the range of 1.0×10^6 - 5.0×10^7 kN/m.

The results are presented in Figure 5. A small collision-spring constant leads to large relative displacement in the negative region: large overlapping of the two bodies occurs, which is a fictitious phenomenon arising from the approximation of the collision behavior in the numerical simulation. The overlapping can be suppressed by using a larger collision-spring constant. But the large collision-spring constant results in a peculiar phenomenon, vibration in the relative speed. Moderate magnitude of the collision-spring constant, not too small and not too large, needs be employed. Judging from the results in Figure 5, it may be realized that the collision-spring constant K in the range of 5.0×10^6 - 5.0×10^7 kN/m is acceptable. Since Equation (2) gives 9.0×10^6, this formula can be considered valid for the collision-spring constant between two girders having different stiffnesses.

Model B

In general, the stiffnesses of the girder and the abutment are not the same and the dynamic behavior of the abutment during earthquake is very different from that of the girder. No good guidelines are available for the collision-spring constant K between the girder and the abutment.



(a) Relative displacement. (b) Relative speed.

Figure 5. Results of Model A.

Since the dynamic movement of the girder is much bigger, the collision-spring constant may be determined by Equation (1) solely with the girder stiffness The influence of the abutment on the collision-spring constant is ignored. The collision-spring constant thus obtained is denoted by k. Referring to the result of Model A, Equation (2) may be used with k_1 computed by Equation (1) with the girder stiffness and $k_2 = k_a$. This collision-spring constant is K_0.

With various values of collision-spring constants, the dynamic response analysis of Model B is conducted. The range of the acceptable collision-spring constants are found through this analysis and shown in Figure 6 as line segments. In this figure, k and K_0 mentioned in the previous paragraph are also plotted and both are found unacceptable.

It is also noticed in the numerical results that the maximum collision-spring constant K_{max} in each acceptable range varies almost linearly with k_a in this double-logarithmic graph of Figure 6. Figure 7 further presents the maximum acceptable collision-spring constants for all the cases, showing that the lines connecting the maximum acceptable collision-spring constants associated with the same values of k_1 are parallel to each other.

Based on these observations, the following formula is constructed:

$$log\ K_{max} = log\ k_a + \alpha \tag{3}$$

where α is dependent on k_1 and the regression analysis yields

$$\alpha = -0.945 \times \log \mathrm{k}_1 + 11.2 \tag{4}$$

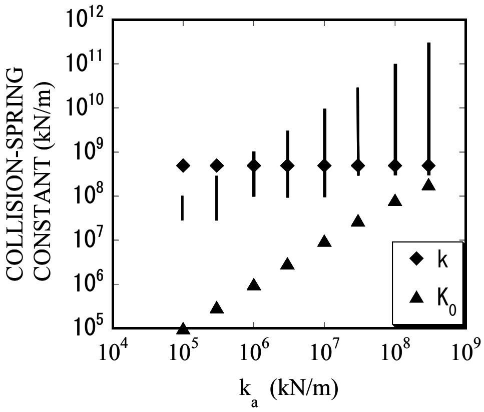


Figure 6. Results of Model B.

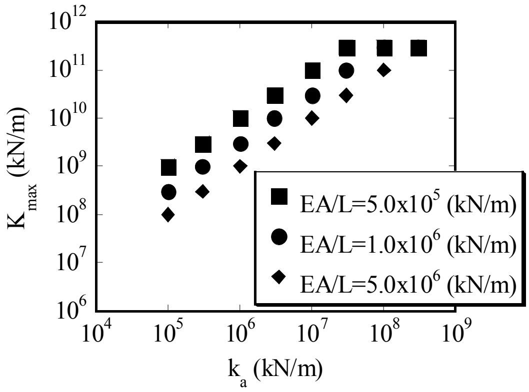


Figure 7. Maximum acceptable collision-Spring constants.

Then the following formula may be proposed to estimate the collision-spring constant K:

$$\log K = \log k_a + 0.9\alpha \tag{5}$$

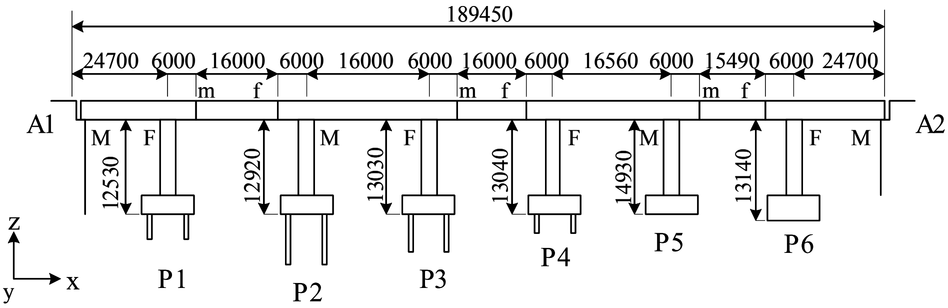
Response Analysis of Girder Bridge

Referring to an existing bridge, a bridge model is constructed and analyzed. Figure 8 shows the schematic of the bridge: the bridge is a 7-span cantilever girder and the length is 189.45 m. In the figure, M, F, m and f stand for a movable bearing support, a fixed bearing support, a movable hinge and a fixed hinge, respectively. An abutment is assumed at each end of the bridge.

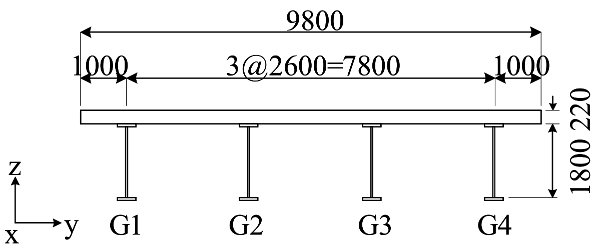
The superstructure is a composite girder with four steel I-shaped girders and a concrete deck. The web plate is constant while the upper-flange width varies from 290 to 490 mm and the upper-flange thickness is from 12 mm to 25 mm; the lower-flange width varies from 200 to 540 mm and the upper-flange thickness from 12 mm to 25 mm. The bridge piers are of a rectangular cross section with 2.2 m × 10.6 m at the top and 3.6 m × 13.6 m at the bottom. The nonlinear material behaviors of steel and concrete shown in Figure 9 are assumed with the yield stress of steel σ_y and the compressive strength of concrete σ_{ck} equal to 360N/mm^2 and 21N/mm^2, respectively. The behavior of the foundation is modeled by springs whose constants are determined by Design Specifications of Highway Bridges (Japan Road Association 2002). The collision-spring constants are determined by the formulas given above.

The seismic wave in the form of acceleration recorded during the Mid Niigata Prefecture Earthquake in 2004 is used in the analysis (Figure 10). The initial gaps are assumed 0.25 m. Two analyses are conducted: one ignores the collision effect and the other includes it.

Figures 11 and 12 summarize the results of the movements of the girders and

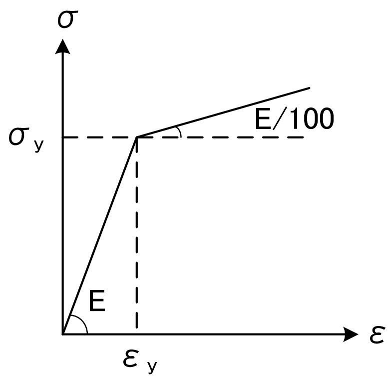


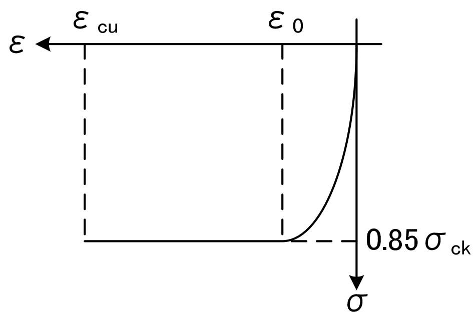
(a) Side view.



(b) Cross section.

Figure 8. Bridge model (Units: mm).





(a) Steel.

(b) Concrete.

Figure 9. Material behavior.

piers. Figure 11 shows the maximum horizontal displacement at four points in the superstructure: the closest point to A1, the mid-span, the closest point to A2 and the point right above P3. Figure 12 presents the maximum horizontal displacements of P1, P3, P4 and P6. It is clearly observed from these figures that the collisions suppress the movement of the bridge, possibly reducing the damages of the piers.

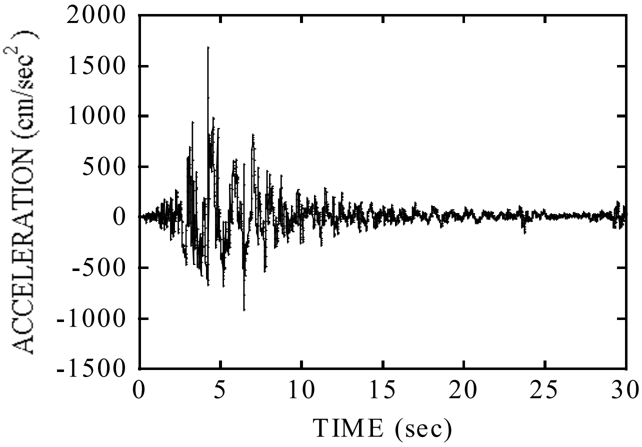


Figure 10. Acceleration recorded during the Mid Niigata Prefecture Earthquake in 2004.

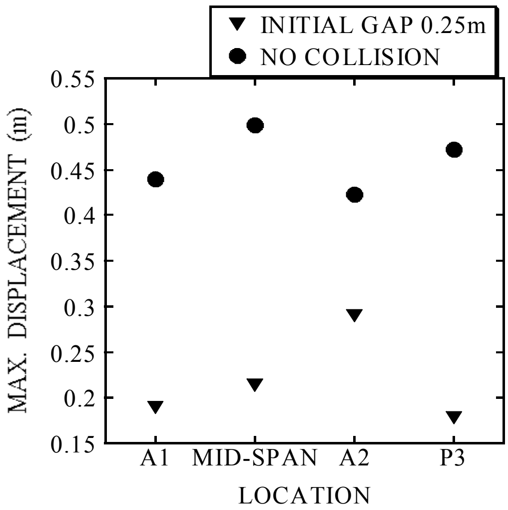


Figure 11. Maximum horizontal displacement of superstructure.

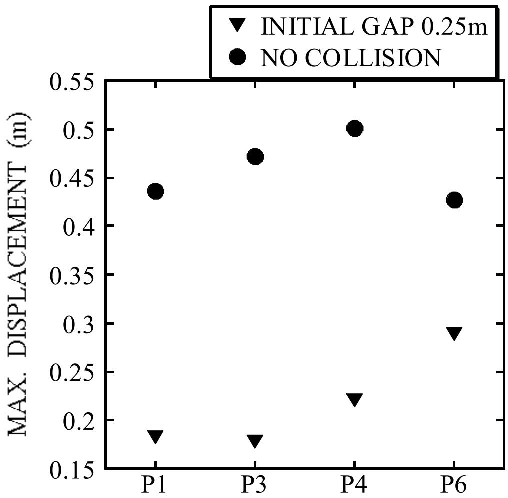


Figure 12. Maximum horizontal displacement of piers.

Concluding Remarks

To include the effect of the collisions, the so-called collision springs are often used. Yet the appropriate constant of the collision spring is not available in the literature except when the two bodies are identical. The present study tackled this issue and, through numerical study, it proposed the formulas for acceptable collision-spring constants between girders and between a girder and an abutment. The dynamic response analysis of a girder bridge was then conducted and the significant influence of the collisions was indeed observed. Therefore, it is crucial to simulate collisions when the dynamic response analysis of a bridge is conducted. To that end, the formulas for acceptable collision-spring constants should be useful.

References

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