第16回性能に基づく橋梁等の耐震設計に関する
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Seismic Evaluation on Collision-induced Rotation of A Skew Bridge Damaged in Wenchuan Earthquake

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1. INTRODUCTION

Wenchuan Earthquake occurred in Sichuan Province, China, at 2:28pm on May 12th, 2008. It had the magnitude of 8.0. The earthquake epicenter was located at latitude 31.021°N and longitude 103.367°E, with a depth of 14 km. Within the scope of 300 km around the epicenter, numbers of buildings and structures collapsed. Bridges, as an important part of the transportation system, were extensively damaged to different degrees. Reports[1)] have been published said that 1350 bridges were damaged during the earthquake, among which 86 bridges (6.4%) suffered severe damage. Also by incomplete statistics, there are 23 skew bridges damaged in Wenchuan Earthquake and about 10 of them suffered severe damage or collapse.

This paper presents the evaluation on a skew bridge, Maweihe Bridge, which experienced a relative large residual displacement during the earthquake. Nonlinear dynamic analysis is conducted to make clear the seismic response and failure mechanism of the bridge during the earthquake.

Detailed field investigation of Maweihe Bridge was conducted in September, 2009. The objective bridge crosses Mawei River in Wudu Town on the road the Jiulong Town. It is a typical RC skew bridge for highway in China. Due to the earthquake, large residual displacement occurred and several side-blocks were damaged to different degrees. The abutment also appeared obvious damage due to the pounding between girder and abutment during the earthquake.

As for the nonlinear dynamic analysis, authors pay attention to the seismic behavior of the deck of the skew bridge. The characteristic parameters, such as displacement and collision force histories, are plotted. 2-demensional frame model is established and will be explained in Chapter 2. Dynamic analysis is performed for verifying the movement behavior of superstructure. The explanation will be divided into the translational behavior in Chapter 3 and the rotational behavior in Chapter 4. Special attentions will be paid on the movement of deck (in terms of response displacement), the force condition, and the kinetic energy. The study flow of this paper can be shown as **Fig. 1**.

2. OBJECTIVE BRIDGE AND ANALYTICAL CONDITIONS

Maweihe Bridge is a typical skewed bridge, which will be introduced in the followed words. Also the analytical model is established in this chapter.

(1)Bridge Structure

Maweihe Bridge was damaged in the Wenchuan Earthquake. And the drawing of its structure can be

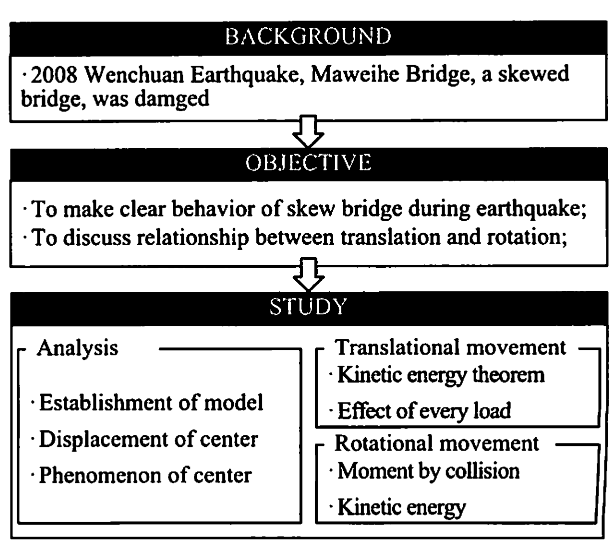
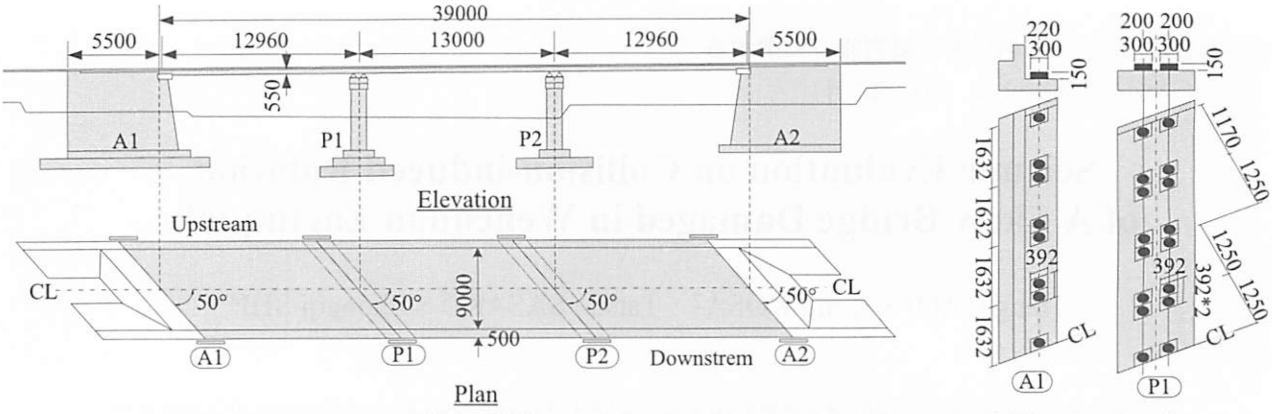


Fig. 1 Study Flow



(a) Slab and Span (b) Bearing Location

Fig. 2 Objective Bridge: Maweihe Bridge

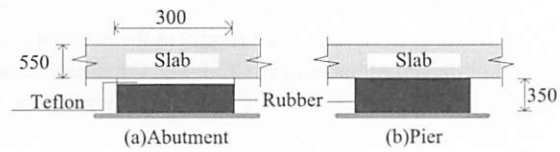
shown as **Fig. 2**. It has a length of 39m and width of 10m. The skewed angle reaches 50°to the axis. The total bridge consists of three almost equaled spans, and the deck of each span consists of 8 hollow reinforced concrete slabs. Each slab is supported by four bearings. So the deck is supported by 96 rubber bearings. Among them, there are 32 bearings with Teflon coating being located on the two abutments (16 for each abutment) shown as **Fig. 3** (a), and another 64 bearings are the ordinary rubber bearings located on bents (32 for each bent) shown as **Fig. 3** (b).

(2)Analytical Modeling and Conditions

Aiming at verifying behavior of superstructure of this bridge, model is made for slab only, since no obvious damage was observed for piers. Model is established by mass point system with beams and springs. Wave input uses the data measured by Bajiao Station, which is the nearest station to objective bridge.

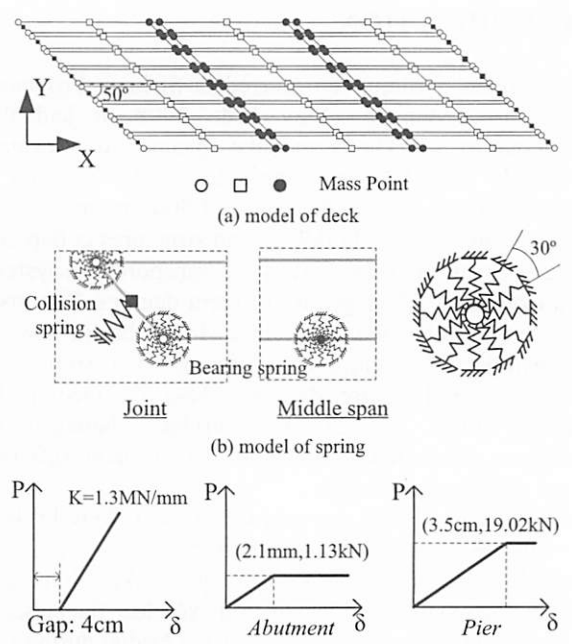
The deck of the objective bridge is modeled as a mass point system with rigid beams connecting, shown as **Fig. 4** (a). As for the mass point system, the total number of mass points is 144 and the weight of deck is 5,184,000 kg, which means each mass point is attached weight of 36,000 kg. All beams are set as rigid. Springs are attached to certain mass point shown as **Fig. 4** (b).

As for the springs, this model contains two types of spring, collision spring and bearing spring. Collision spring is used to model the joint of bridge, which is attached to the end of the deck. 8 springs is set at each side as each span consists of 8 reinforced concrete slabs. So in other words each slab attached 1 spring in the middle. Also according to the specification in Japan[2)], it is shown that the force acting on the deck by parapet is perpendicular to the parapet. So the direction of collision spring is set as perpendicular to the parapet, which can be shown as **Fig. 4** (b). As for the stiffness, based on the result of experiment[3)] on concrete subjected to concentrated shear load, the stiffness of collision spring is set as 1.3 MN/mm. Also the gap in the joint is 40mm, so the model of collision spring can be briefly shown as **Fig. 4** (c). Bearing spring is used to model the rubber bearing, which is attached to the particles corresponded to the abutments and bents. There are two types of bearing, Teflon-rubber bearing and ordinary rubber



(a)Abutment (b)Pier

Fig. 3 Bearing System



(a) model of deck

(b) model of spring

(c) stiffness of spring

Fig. 4 Analytical Modeling

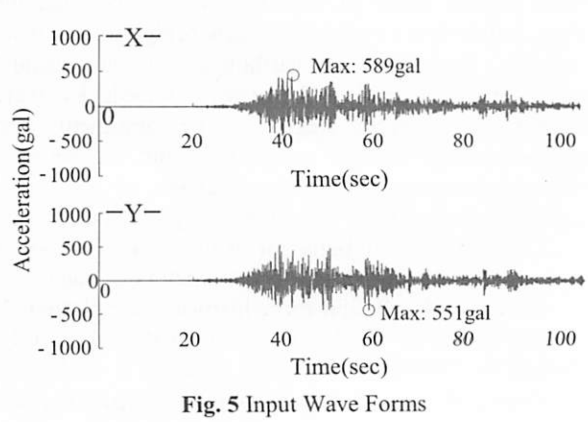


Fig. 5 Input Wave Forms

bearing, acting in the objective bridge. Teflon-rubber bearing (friction coefficient μ=0.03) shown in the **Fig. 3** (a) is located on the abutments and ordinary rubber bearing (friction coefficient μ=0.5) shown in the **Fig. 3** (b) is located on the bents. And the model image of the two types of bearing is shown as **Fig. 4** (b) that each of the bearing spring is consist of 6 springs with same stiffness in different direction. As for stiffness of bearing spring, it is calculated by horizontal experiment of rubber[4], and it is finally defined as **Fig. 4** (c) shows.

Wave input was measured by the Bajiao Station. The wave used in analysis was modified from this group of data, which can be shown as **Fig. 5**, because the direction of bridge axis angles to the North with 65.5°. During the analysis, the wave is input in both X and Y direction (As **Fig. 5** illustrates) in the same time. The wave was measured from 0s to 160s as **Fig. 5** illustrate. Since the wave was weak at the beginning, 30s is set as the start of analysis. This area of wave takes the most of the effect on the deck, and the max-value of input acceleration reaches 589 gal and 551 gal in X and Y-direction.

3. TRANSLATIONAL MOVEMENT

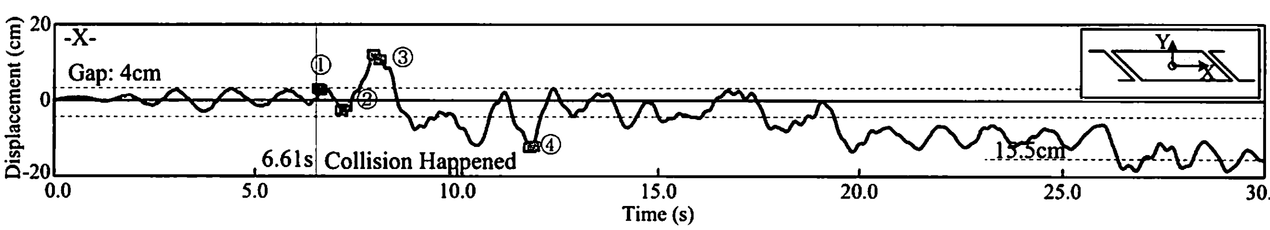
With the model established in Chapter 2 and the wave data input shown as **Fig. 5**, some analytic result about collision between slab and abutment and displacement of deck center, also the description of behaviors are shown and discussed in this Chapter.

(1)Movement Behavior and Collisions

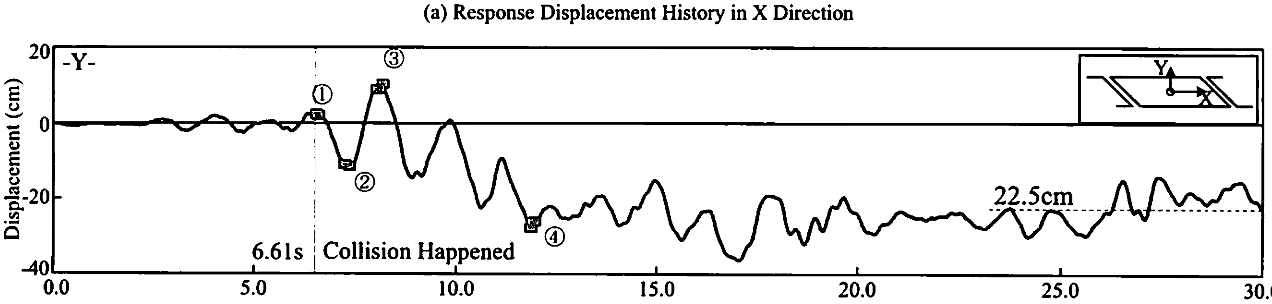
Nonlinear dynamic analysis was conduct to make clear the seismic behavior of objective bridge. The motion of deck is represented by displacement of deck center as it has not been affected by rotation so seriously. **Fig. 6** illustrated the displacement history of deck center, during which the collision happened and collision force history can be shown as **Fig. 7**.

The motion of deck can be roughly divided into two parts: The first part is the deck moved under no collision before 6.61s. As the **Fig. 6** illustrated, before 6.61s the displacement of center is almost limited within 4.0 cm, so there is no collision happening during this part. The second part is after 6.61s when the first of the four collisions happens. During all the procedure of motion, 4 times collision happen which can be inferred from **Fig. 7**. The first collision, which also gets the max-value of 34.7 MN in 6.64s, occurred as plane collision at A2.Then the followed three collisions, shown in **Fig. 7**, reached about 10MN and occurred at the A1 and A2 in order. Finally, taking the end of analysis as the residual displacement, general damage by analysis is illustrated in **Fig. 6**. Displacement of center in analysis reaches 155 mm in X-direction and 225 mm in the Y-direction.

During the four collisions, the slab occurred movement, shown as **Fig. 8** which paid attention to the deck center. According to the figure, at the first collision, the superstructure collided to A2 and then the deck



(a) Response Displacement History in X Direction



(b) Response Displacement History in Y Direction

Fig. 6 Response Displacement Histories of Deck Center

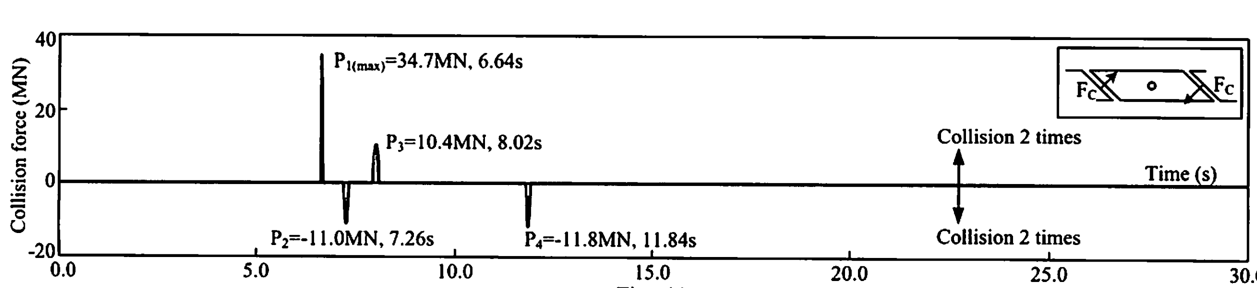


Fig. 7 Response Displacement Histories of Deck Center

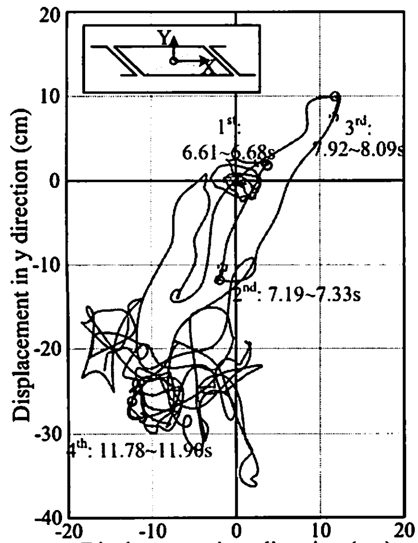


Fig. 8 Orbit of Deck Center

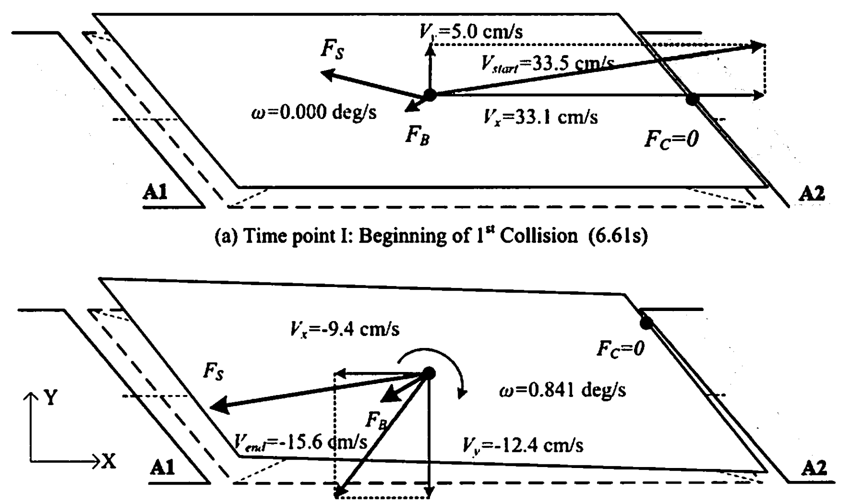


Fig. 9 Velocity Vector during 1st Collision

moved towards left-down colliding to the A1 which is the second collision. After the first two collisions, the system also occurred another two collision at A2 and A1 separately. As the **Fig. 8** illustrated, the displacement of deck get larger and larger related to the initial center.

In order to make clear the movement of superstructure more deeply, here taking the first collision for discussion firstly. During the first collision, the behavior of deck and force condition can be briefly shown as **Fig. 9** ((a) for time point I when collision begins, (b) for time point II when the deck starts to leave from A2. Till time point I (**Fig. 9** (a)) just bearing and seismic force are taking effect on the deck and they all direct to backwards of deck move. So both the seismic and bearing forces take a negative effect on the deck-move. The initial velocity comes to 33.1 cm/s in the X-direction and 5.0 cm/s in the Y-direction. And at this moment, the slab still have not occurred any rotation, thus the deck ran into the abutment. Then collision happened, seismic, bearing and collision forces affect the deck at the same time. The collision comes to an end at time point II (**Fig. 9** (b)) and then the collision decreases back to 0. At the end of collision, the seismic and bearing force still take a negative effect on deck move, also the deck occurred rotation which angular velocity reaches 0.841 deg/s. Also according to the **Fig. 9**, under the effect of collision and negative effect of seismic and bearing force, the direction and value of the velocity of deck all get a change, the final velocity comes to -9.4 cm/s in X-direction and -12.4 cm/s in Y-direction.

During the first collision, the direction of velocity also made a change because of the skewed interface. As the **Fig. 10** shows, the deck collided to the abutment with an initial velocity of 33.5 cm/s. The direction of initial velocity angled to the normal direction with 31°. However, after the first collision, the superstructure leaves A2 with a velocity of 15.6 cm/s. And the direction of this reflection velocity angled to the perpendicular direction with 13°. According to the **Fig. 10**, the reflected velocity decreases for 53.4 % compared with initial velocity, while the reflected angle drops 58.1 % of the initial angle.

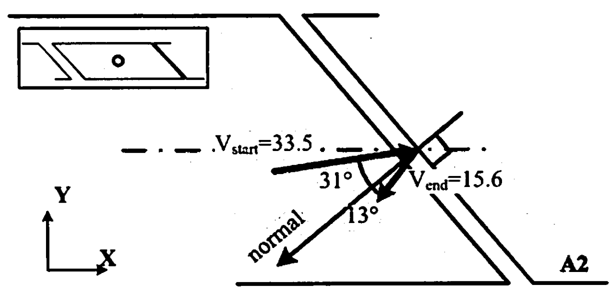


Fig. 10 Reflection Behavior of Deck and Velocity Change in the 1st Collision

Consequently, it became obvious to us that the deck collided with abutment and was rebounded back. However, the reflection velocity and the reflection angle might decrease by about 50 % (53.4 % for the velocity and 58.1 % for the angle), compared with the initial velocity and angle.

(2)Work by External Forces VS Kinetic Energy

In order to simplify the movement, the discussion is based on the center, during the first collision all three main force taking effect on the deck, which can be briefly shown as **Fig. 11**. Also according to the analytical result for displacement of deck center, the trail and velocity histories of center during 1st collision can be shown as **Fig. 12**. Under the effect of the three different forces, the deck behaved as the **Fig. 12** shows. At the beginning of the 1st collision, the angel between direction of loads and initial velocity beyond 90°, the loads acted on the deck make a negative work. And after reaching the max-value, the angel between force and velocity is smaller than 90°, so the all of the loads provide a positive work. This relationship between work and energy can be also inferred from **Fig. 13**. Here pay attention to discuss the different effect of three forces on the movement of deck.

For discussing different loads, as the **Fig. 11** briefly illustrated, the three loads (collision force, bearing resistance and seismic force) take effect on the movement of deck during the collision. Both the bearing force and collision force can be referenced from the analytical, and the seismic force was calculated by the wave acceleration input. Here the kinetic energy theorem is used to evaluate the different contribution of forces. Theoretically, shown as the Eq. (1), the work applied by loads should be equal to the kinetic energy change. Also the error between work applied by loads and the kinetic energy change can be used to prove the reasonableness of the discussion. The definition of change of kinetic energy can be shown as Eq. (2) followed (detailed explanation of kinetic energy will be introduced in Section 4.2), and the work by all the three different loads can be explained as Eq.(3), among which the C, B and S stand for the value of collision, bearing and seismic force separately. Moreover, the integral interval used in the Eq. (3) used 0.01s to conduct the calculation.

$$\Delta E_K = W_i \quad (1)$$

$$\Delta E_K = E_{Kt} - E_{Kt0} \quad (2)$$

$$W_i = \int_{t_0}^{t} F(t)_i \, ds \quad (i = C, B, S) \quad (3)$$

where,

ΔE_K : change of kinetic energy;
E_K : kinetic energy (details in Section 4.2);
W : work by external forces;
C, B, S : collision, bearing, seismic;
t_0, t : t_0=6.61s, t≤6.68s;
M : weight of deck;

To simplify the discussion, the behavior of superstructure was divided into X-direction and Y-direction. In this paper, it mainly paid attention to the first collision. Based on the calculation method stated above, energy relationship of each time point in X-direction during the 1st collision was calculated. Finally, the result of different contribution of work by the three loads can be illustrated as **Fig. 13**. Firstly, according to the calculation, the work provided by the three main loads generally accords with the change of kinetic energy which can be also inferred from **Fig. 14**. We can see that from 6.61s to 6.65s, the kinetic energy drops due to negative work by external force. Then, since the absolute value of work becomes smaller, the kinetic energy grows slowly. As a result, the algebraic sum of kinetic energy and work by external forces (in terms of E_K - W, solid line with cubes in **Fig. 14**) does not change obviously. According to the **Fig. 13**, collision force takes effect of about 33.9%, which verify that the collision is already very large and serious damage may be caused. However, the bearing just takes about 9.8% which is relative low compared with the other loads and it is 1/3 of the collision force. According to the bearing types stated above, the bearing at abutment used Teflon plated bearing which can decrease the criticality of sliding and reduce the friction between super and substructure. So the bearing provides a relatively low effect on the total work. Besides, the seismic force takes about half of the effect on the deck move, and this effect is in the same direction as collision force and bearing force. Also according to the **Fig. 13** and **Fig. 14**, when the accumulated work by the loads increases, the change of

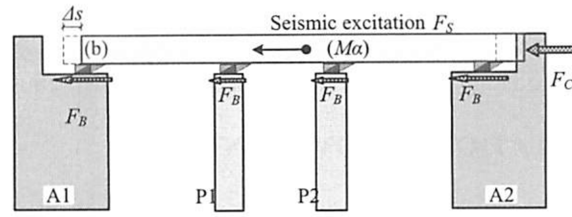


Fig. 11 Mechanism of Work by External Force

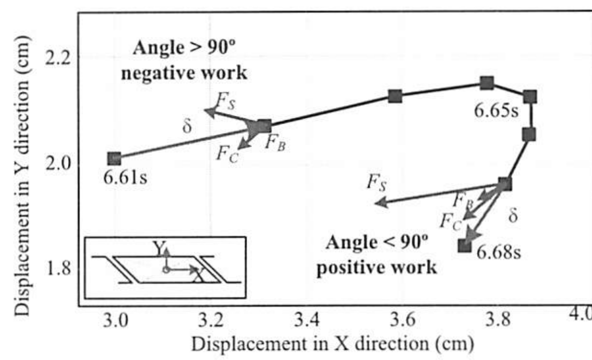


Fig. 12 Calculation Example during the 1st Collision

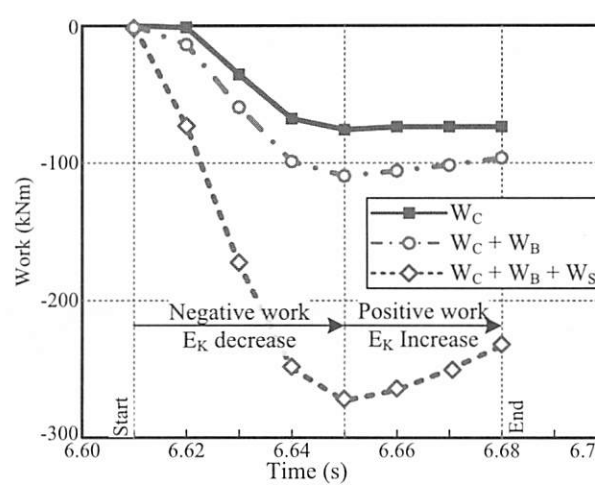


Fig. 13 Work by External Force during the 1st Collision

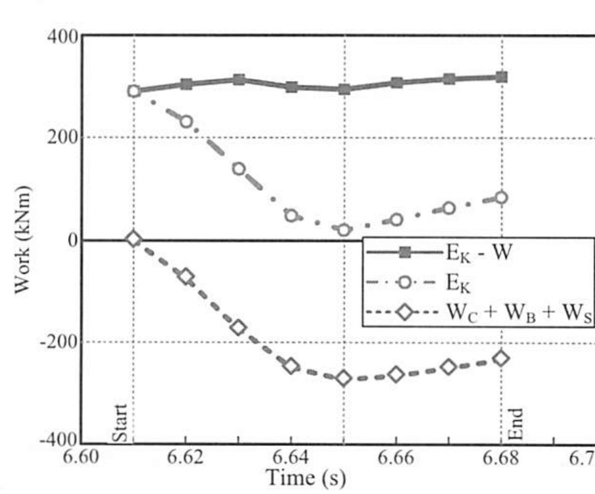


Fig. 14 Change of Energy due to Work by External Forces

kinetic by analysis increases. And otherwise, if the load make a positive work which the work by the loads decreases, the change of kinetic by analysis increase, which generally accord with the basic physical theorem.

4. ROTATIONAL MOVEMENT

In Chapter 3, the behavior of translational movement and the work by external forces were explained. However, during the collisions, there is the rotational movement of deck as well. This behavior will be explained in details. The mechanisms of occurrence of rotational will be explained in Section 4.1, followed by the comparison of kinetic energy between translational components and rotational components.

(1)Rotational Movement Behavior

Details of collision force history (6.0s ~ 9.0s) is shown in **Fig. 15**. As mentioned formerly, the 1st, the 2nd, and the 3rd collision occurs at 6.61s ~ 6.68s, 7.19s ~ 7.33s and 7.92s ~ 8.09s. Correspondingly, the histories in this time period (6.0s ~ 9.0s) of rotational velocity and rotational angle is plotted in **Fig. 16** and **Fig. 17** respectively.

As the rotational velocity history illustrated in **Fig. 16**, we can find the rotational velocity of deck increases dramatically during every time of collisions, while it drops gradually without occurrence of collision. As a result, as shown in **Fig. 17**, the rotational angle begins to increase from the start time point of the 1st collision at 6.61s. Then it keeps increasing clockwise with the positive rotational velocity.

The rotational moments induced by collision force and by unbalance force couple from bearing system are considered to be the main reason of occurrence of rotation. Mechanism is illustrated in **Fig. 18**. As shown in **Fig. 18** (a), when deck begins to collide with abutment, resistance by abutment (collision force F_C) acts on deck, vertically to abutment. The eccentric length (d) of this collision force can be expressed by two parts: d_1 for the vertical distance from the deck center to the acute angle as a constant value decided by deck dimensions, and d_2 for the distance between the acute angle and the center of collision force as a variable decided by distribution of collision force along the abutment. Thus, the moment by collision force can be written as:

$$M_C = F_C \times d \quad (4)$$

$$d = d_1 + d_2 \quad (5)$$

where,

M_C : rotational moment by collision force;

d : arm length of eccentric collision force;

This moment by collision force starts to induce the rotation of deck. Therefore, different displacement of every point on deck will occur, which suggests that the displacements of every bearing are distinguished. It can

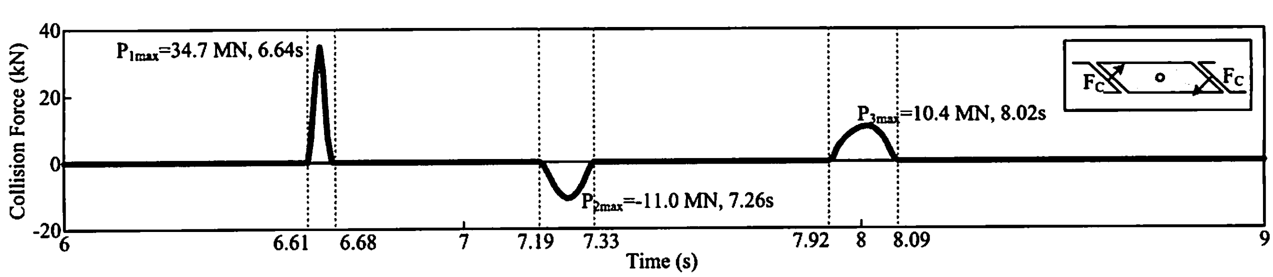


Fig. 15 Details of Collision Force History (6.0s ~ 9.0s)

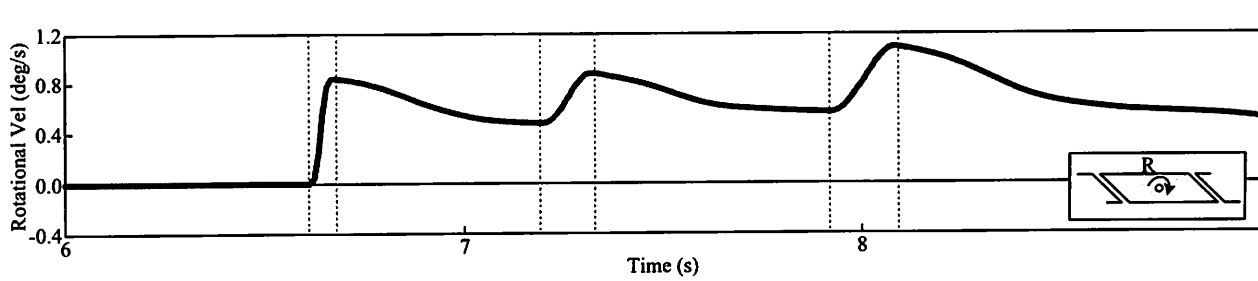


Fig. 16 Rotational Velocity History of Deck (6.0s ~ 9.0s)

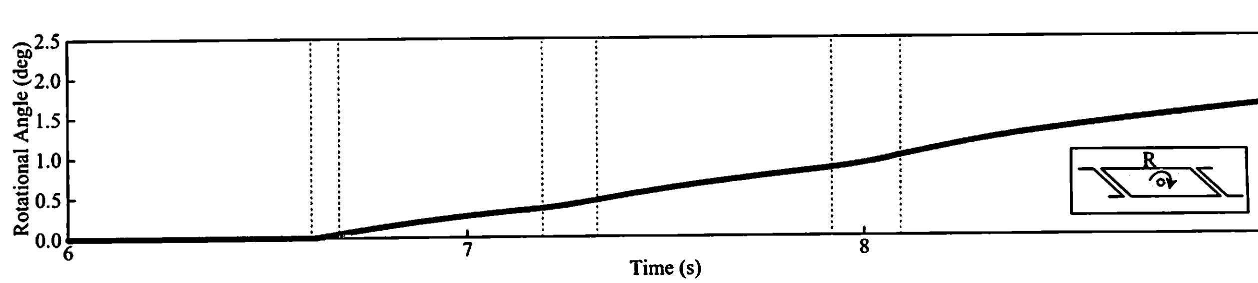


Fig. 17 Rotational Angle History of Deck (6.0s ~ 9.0s)

be inferred that unbalance of resistance from bearing system will happen. Consequently, moment due to unbalance of bearing resistance, namely M_B, is induced as well acting on deck. As a result, the deck rotates under the effect by the moments due to the collision force (M_C) and due to the bearing resistance (M_B). The rotational acceleration (α) of deck can be expressed:

$$\alpha = (M_C + M_B) / I \quad (6)$$

where,

α : rotational acceleration;
M_B : rotational movement by unbalance bearing resistance;
I : inertial moment of deck to its center;

Furthermore, the rotational velocity (ω) and angle (θ) can be easily computed by integration. The comparisons between analytical result and calculated result are shown in **Fig. 19** for the rotational acceleration (α) and in **Fig. 20** for the rotational angle (θ). We can see for the acceleration, calculation (30.32 deg/s^2) based on Eq. (6) provides error 2.12% to analytical result (29.69 deg/s^2) at the peak of the 1st collision at 6.65s. For the rotational angle, at the end of the 1st collision (6.68s), calculation (0.03351 deg) is only 1.48% greater than the analytical result (0.03302 deg).

After the 1st collision, only the moment by unbalance of bearing resistance acts on deck, and causes negative rotational acceleration. However, till the next time of collision, the rotational velocity keeps in the direction of clockwise. Thus the rotation of deck becomes greater and greater. Besides, calculation of rotation for other time of collision also shows acceptable accuracy with error no greater than 3.0%.

(2)Kinetic Energy: Translational and Rotational Components

To evaluate the relationship between translational movement and rotational movement, two components of kinetic energy of deck is calculated based on following equations:

$$E_T = 1/2 \times m \times (v_x^2 + v_y^2) \quad (7)$$
$$E_R = 1/2 \times I \times \omega^2 \quad (8)$$

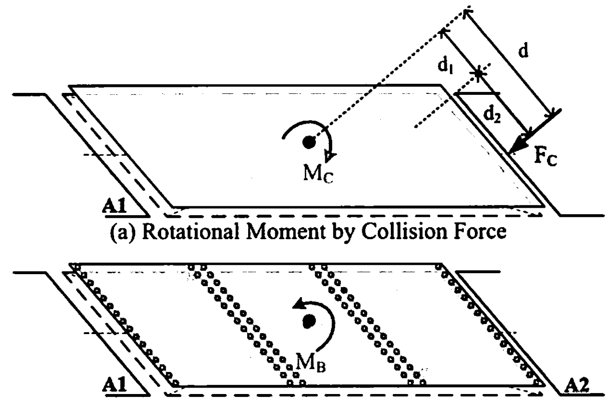
where,

E_T : translational kinetic energy;
E_R : rotational kinetic energy;
ω : rotational velocity of deck;

Thus the total kinetic energy (E_K) can be expressed as:

$$E_K = E_T + E_R \quad (9)$$

Velocity histories during the 1st collision of deck center are shown in **Fig. 21** and **Fig. 22** for the translational direction and the rotational direction respectively. We can see that in x direction (axial direction of bridge), the velocity of deck center decreases from +0.33 m/s, becoming negative at about 6.65s, and finally to -0.09 m/s during the 1st collision. In y direction (right-angle direction), it decreases as well from +0.05 m/s to -0.12 m/s, while it firstly becomes negative at about 6.64s. Therefore, the translational kinetic energy is 290.1 kN·m at the start of the 1st collision (shown in **Fig. 23**), and keeps decreasing until about 6.65s. Then, with



(a) Rotational Moment by Collision Force
(b) Rotational Moment by Unbalance of Bearing Resistance

Fig. 18 Mechanism of Rotational Moments

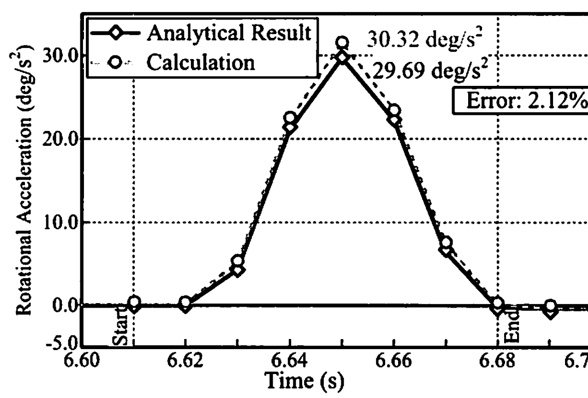


Fig. 19 Calculated Rotational Acceleration during the 1st Collision

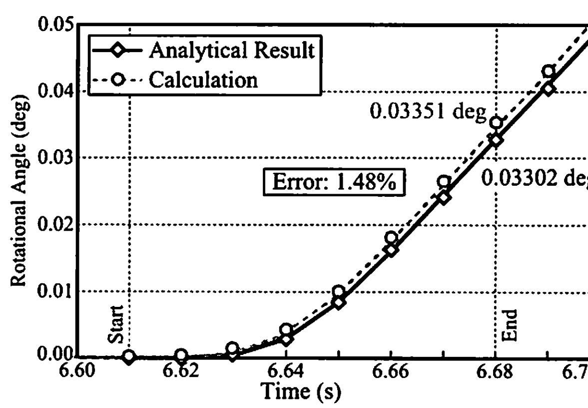


Fig. 20 Calculated Rotational Angle during the 1st Collision

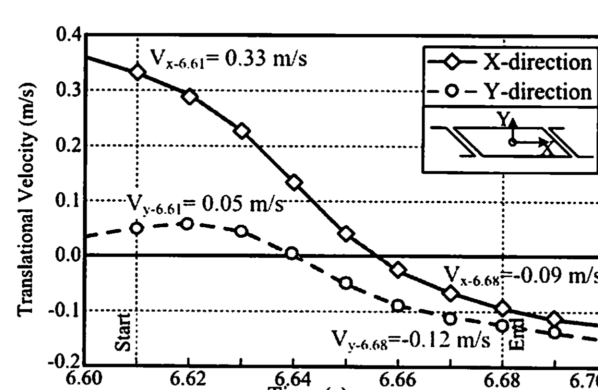


Fig. 21 Translational Velocities during the 1st Collision

the turn-back of deck from A2, its translational kinetic energy begins to increase, and reaches 98.1 kN·m at the end (6.68s). On the other hand, with the rotational movement becomes more and more obvious, the rotational velocity rises from 0.00 deg/s at 6.61s,to 0.84 deg/s at 6.68s. Thus, the rotational kinetic energy increases from 0.0 kN·m to 21.9 kN·m during the 1st collision (plotted in **Fig. 23**).

By summing them up, the total kinetic energy of deck (E_K) is got as 290.1 kN·m at the start and as 120.0 kN·m at the end of the 1st collision. This drop of kinetic energy is caused by the work due to external forces (collision force, bearing resistance and seismic force) as being explained in Section 3.2. In details, before 6.65s, the total kinetic energy drops with the drop of the translational kinetic energy, since the rotational kinetic energy is still not notable. Then, with the increase of both translational and rotational kinetic energies, the total increases as a result. Finally, at the end of the 1st collision (6.68s), the rotational kinetic energy reaches 21.9 kN·m, occupying about 26.2% in the total kinetic energy.

In a word, the rotation started with the collision between abutment and deck. During the collision, the translational kinetic energy decreased when deck collided into abutment, while increased when deck was reflected back. During this procedure, rotational movement occurred and the rotational kinetic energy occupied as great as about 26% of the total kinetic energy. Besides, as mentioned in Chapter 3, the total kinetic energy dropt due to the negative work of external forces (collision force, bearing resistance and seismic force). Both these two phenomena resulted the deck being reflected with smaller velocities, although the general movement was similar to specular reflection.

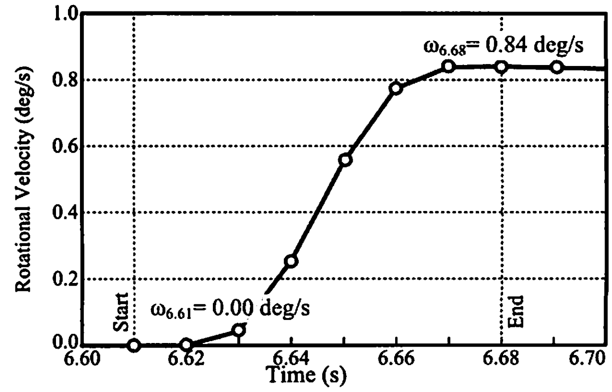


Fig. 22 Rotational Velocity during the 1st Collision

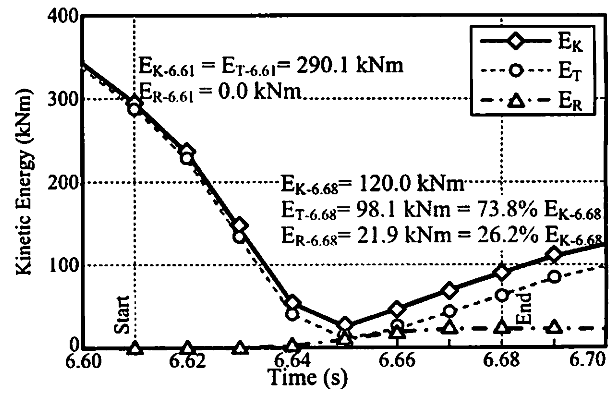


Fig. 23 Change of Kinetic Energy during the 1st Collision: Translational Component VS Rotational Component

5. CONCULSIONS

Based on the dynamic analysis for Maweihe Bridge, and the evaluations mainly on the translational movement behavior and the rotational movement behavior, following conclusions have been drawn:

(1) Based on the discussion of translational movement for the 1st collision, the deck collided with abutment and the deck rebounded. However, the reflection velocity and the reflection angle might decrease by about 50 % (53.4 % for the velocity and 58.1 % for the angle), compared with the initial velocity and angle.

(2) According to the calculation of work by external forces(collision force, bearing resistance and seismic force), the negative work resulted the drop of the kinetic energy of deck. Among all, the collision force contributed over 30% in the work during the 1st collision.

(3) For the rotation behavior, deck began to rotate at the start of the 1st collision. The rotational moment by the eccentric collision force caused the rapid increase of rotational velocity when collisions happened. Then, the negative rotational moment by the unbalance of bearing resistance made the rotational velocity decreased between each two times of collisions (when collisions did not happen). Considering both these two moments, the rotational acceleration, velocity and angle were calculated with good accuracy (error smaller than 3%) compared with analytical result.

(4) Except the negative work by external forces, the increase of rotational kinetic energy caused the drop of translational velocities as well. At the end of the 1st collision, the rotational kinetic energy occupied about 26% in the total kinetic energy.

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