- Technical Paper -

EVALUATION ON THE FAILURE MECHANISM OF A SKEW BRIDGE DAMAGED IN WENCHUAN EARTHQUAKE

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ABSTRACT

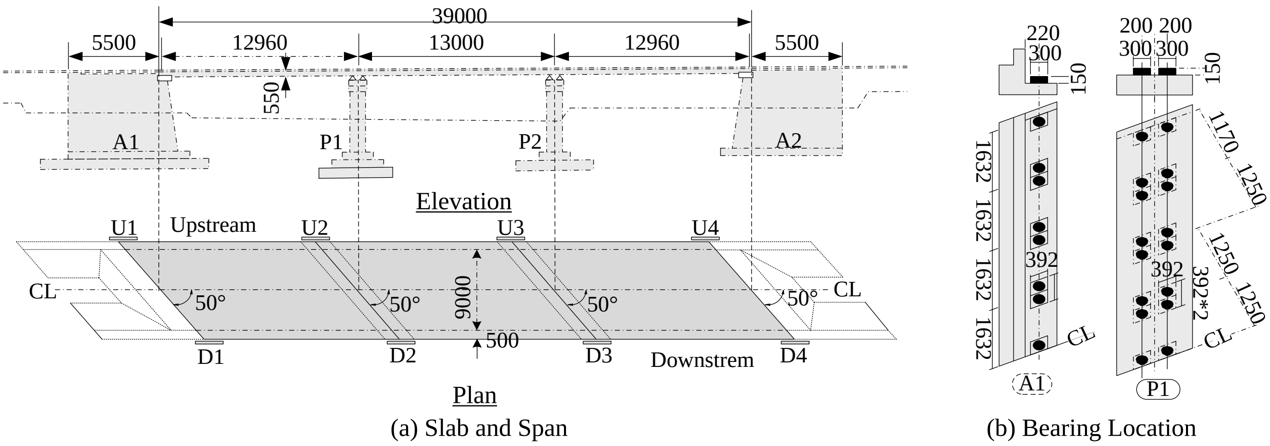
Maweihe Bridge is a skew bridge damaged in Wenchuan earthquake. The superstructure suffered great residual displacement. Abutments and side blocks were damaged due to the pounding. In order to make clear seismic response and failure mechanism of superstructure, dynamic analysis for the superstructure was conducted. The damage of abutment has been evaluated with the pounding stress as the damage degree is strongly related to it. Besides, it is found that velocity before poundings has a positive correlation with the pounding stress.

Keywords: skew bridge, dynamic analysis, failure mechanism, pounding stress

1. INTRODUCTION

Whenchuan 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 14km. Within the scope of 300 kilometers around the epicenter, numbers of structures collapsed. Bridges, as an important part of the transportation system, were extensively damaged to different degrees. Report[1] has been published saying that 1350 bridges were damaged during the earthquake, among which 86 bridges (6.4%) suffered severe damage. Also by incomplete statistics, there were 23 skew bridges being damaged in the Wenchuan Earthquake and about 10 of them suffering severe damage or collapse.

This research presents the evaluation on a skew bridge, Maweihe Bridge, which experienced a relative large residual displacement during the earthquake. Based on the discussion about relationship between main loads (seismic, pounding and bearing loads) in the former research[2], we got that the sliding bearing was relative weak to provide enough resistance. In this paper, authors mainly pay attention to the local damage caused by the pounding stress, which is strongly related to pounding area varying due to the rotation. Structure of Maweihe Bridge can be shown in Fig. 1. It has a length of 39 m and a width of 10 m. The skewed angle reaches 50˚ to the axis. The total bridge consists of three almost equal 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 which there are 16 bearings with Teflon coating located on two abutments separately and the others are the ordinary rubber bearing located on each bents shown as Fig. 1 (b). Nonlinear dynamic analysis is conducted to make clear the seismic response and failure mechanism of the bridge during the earthquake.



(a) Slab and Span (b) Bearing Location

Fig. 1 Objective Bridge: Maweihe Bridge

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Detailed field investigation of Maweihe Bridge was conducted in September, 2009. The objective bridge crosses Mawei River in Wudu Town on the road to Jiulong Town. In order to make clear the damage condition, brief figure based on filed investigation will be roughly plotted in Chapter 2. Based on the bridge structure, analytical model is established in Chapter 3. Then the dynamic analysis with the analytical model, which pays attention to pounding behavior of skew bridge, is conducted and the evaluation is shown in Chapter 4. With the discussion on pounding condition, we can get a certain relationship between pounding stress and damage degree and reappear the actual damage of different members. As well, the relationship between deck motion and pounding will be discussed further in this paper.

2. ACTUAL DAMAGE

According to the field investigation for Maweihe Bridge, little damage was observed on the bents. However, relatively large residual displacements and in-plane rotation of the deck were the main damage caused by the earthquake. Poundings happened between deck and abutment, which also was an important factor leading to the rotation of deck. Besides, side blocks and both sides of abutment had been damaged to different degree during the earthquake because of the poundings.

As Fig. 2 illustrates, the end of the slab on abutment A2 was raised from the roadbed in the actual damage. The obtuse corner suffered serious damage. At the other side of abutment (A1), there was a great crack occurring between parapet and substructure at the obtuse corner. There was also some concrete crushing along the cracks. Side blocks also suffered serious damage as shown in Fig. 2. As for the displacement, the deformation of deck center reached 315mm and 75mm in axial and transverse. Also the rotational angle of actual damage reached 1.32°.

3. Analytical Conditions

Model in analysis was established by the bridge structure and damage condition shown in Fig. 3. A frame model is established for deck and the pounding spring is set for the joint. Since no obvious damage was observed for piers, model hadn't been established for them. Also the side block (U1~ U4, D1~D4 in Fig. 2) hasn't been modeled due to its small division shown as Fig. 2. It can't provide great resistance based on trial calculation. The deck of the objective bridge is modeled as a frame model with rigid beams connecting, shown as Fig. 3 (a). As for the mass point system, the total number of mass points is 144 and the weight of deck is 586,000 kg. Springs are attached to certain mass point shown as Fig. 3 (b). This model contains two types of spring, pounding spring and bearing spring.

Pounding spring is used to model the joint of bridge, which is attached to the end of deck shown in Fig. 4. 8 springs are set at each end as each span consists of 8 reinforced concrete slabs. In other word, each slab is attached 1 spring. Also according to the specification in Japan[3], it is shown that the force acting on the deck by parapet is perpendicular to the parapet. The direction of pounding spring is set as perpendicular to the parapet shown as Fig. 4 (a). As for the stiffness, based on the result of experiment[4] on concrete subjected to concentrated shear load, the stiffness of pounding spring is set as 1.3 MN/mm, which can be shown as Fig. 4 (b). Also the gap in the joint is 40mm. Damping is currently ignored for simple.

Bearing spring is used to model the rubber bearing, which is attached to the particles corresponding to the abutments and bents. There are two types of bearing, Teflon-rubber bearing and ordinary rubber bearing, installed on the bridge. Teflon-rubber bearing (friction coefficient μ=0.03) located on the abutments as Fig. 5 (a) shows and

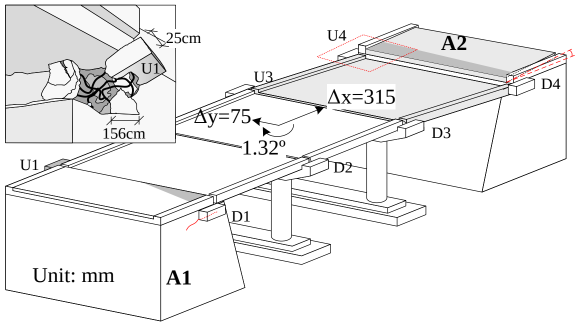
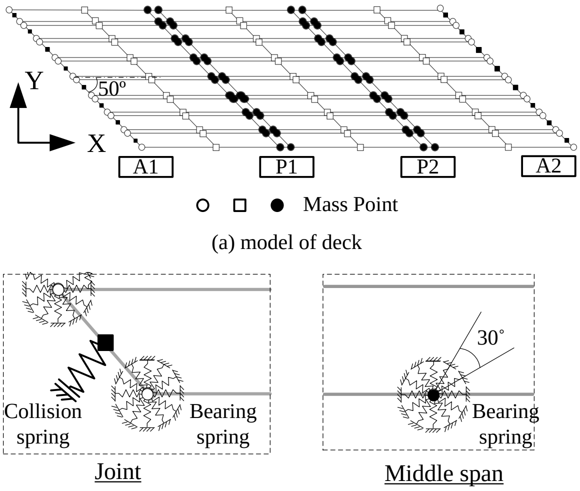


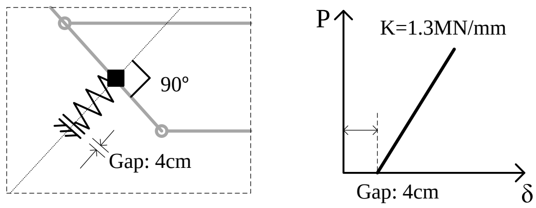
Fig. 2 Objective Bridge: Maweihe Bridge



(a) model of deck

(b) model of spring

Fig. 3 Analytical Modeling



(a) Arrangement of spring (b) Characteristics

Fig. 4 Modeling of Pounding Spring

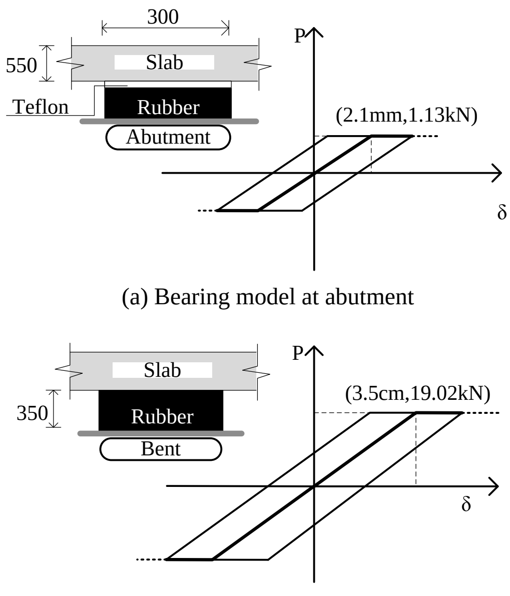
ordinary rubber bearing (friction coefficient μ=0.5) located on the bents as Fig. 5 (b) shows. The model image of two types of bearing is shown in Fig. 5 (a) and (b) separately. Each bearing spring consists of 6 springs with same stiffness in different direction. As for the characteristics of the bearing spring, the author launched the loop of the bearing spring just show as Fig. 5. The initial stiffness of bearing spring is calculated by horizontal experiment of rubber[5]. Before the load reaches the critical value, the bearing works as an elastic member. However, when the load exceeds the critical value, the resistance provided by the bearing will stay steady and the superstructure will slide. When the load on the bearing gets smaller than the sliding condition, bearing will go back to the elastic state until loads reach critical value again.

Wave data were measured by the Bajiao Station (nearest station to the objective bridge with distance of 97km), and the wave input in analysis is modified from this group of data as the bridge angles to North with 65.5˚. The modified wave input can be shown in Fig. 6. During the analysis, the wave is input in both X and Y direction in the same time. Since the wave was weak at the beginning, 30s~60s (0~30s shown in Fig. 6) is used for the 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. For integration, Newmark-β (β=1/4) method is applied with time step being 1/5000s.

4. EVALUATION ON DIFFERENT POUNDING CONDITION

4.1 General Result

Poundings happened between deck and abutment during the procedure of analysis. The pounding force history is shown in Fig. 7. According to the pounding force history, three poundings happened in analysis, in which twice at abutment A2 and once at



(a) Bearing model at abutment

(b) Bearing model at bent

Fig. 5 Modeling of Bearing

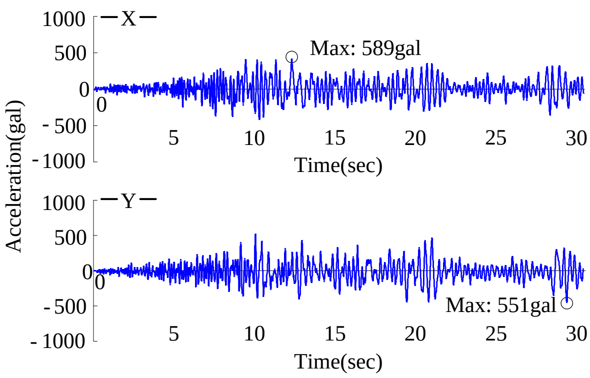


Fig. 6 Input Wave Forms

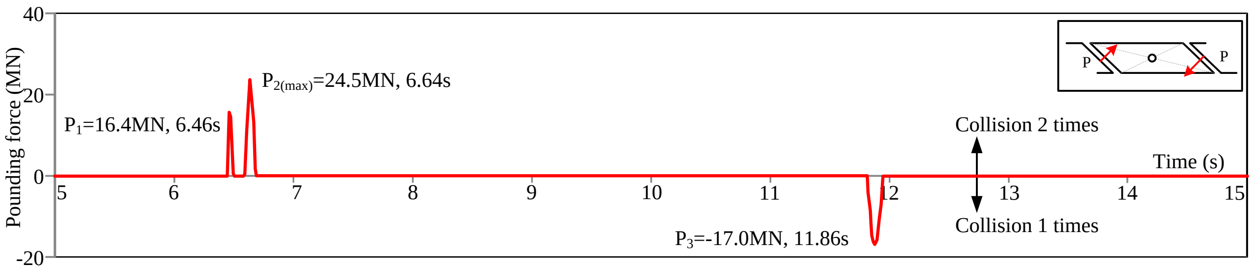


Fig. 7 Pounding Force Histories

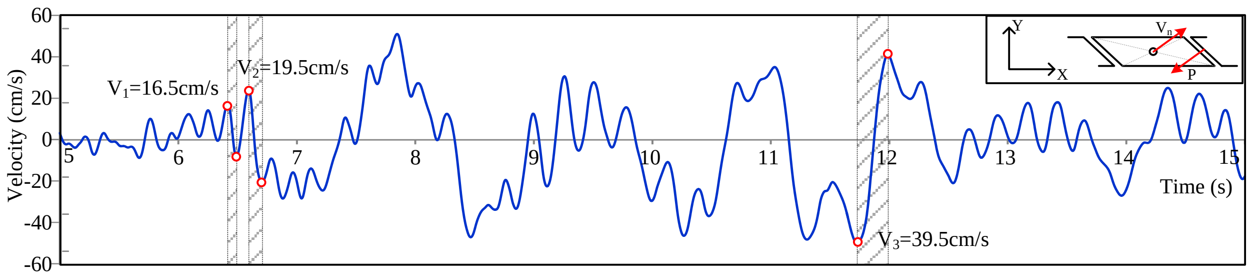


Fig. 8 Velocity Histories

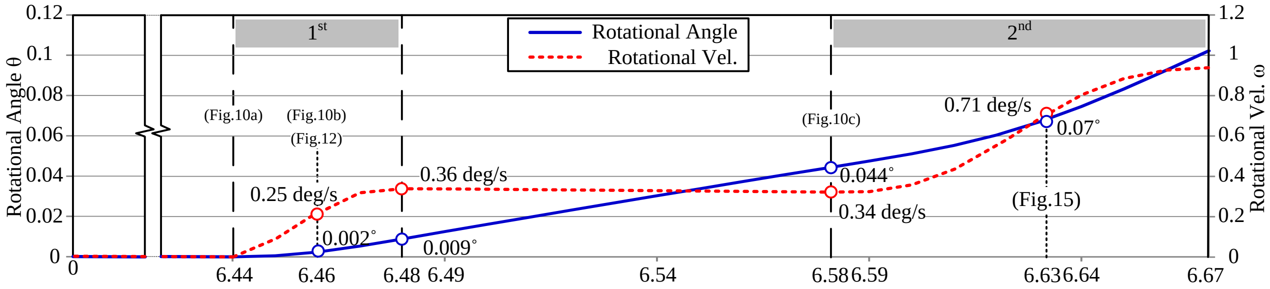


Fig. 9 Rotational Behavior during the Poundings

abutment A1. The 1st and the 2nd pounding happened closely at A2 abutment shown in Fig. 7 so that they caused the damage of A2. As well, the 3rd pounding happened at A1 side and caused the damage of A1 abutment. The max value of pounding force was 24.5MN at the 2nd pounding. The velocity, which was in normal direction, is plotted to show the deck motion during the earthquake in Fig. 8. It can be inferred that deck motion become more violent after the 1st pounding. The pounding velocity (velocity before poundings) reached 16.5cm/s, 19.5cm/s and 39.5cm/s for each pounding in order shown in Fig. 8. Based on the former research, pounding velocity had a positive correlation with pounding force for straight bridge. As for skew bridge, this relationship will be discussed further in next part of this paper.

As for skew bridge, rotation will happen to the deck during the earthquake. Rotational angle and velocity histories are plotted shown in Fig. 9. Before the 1st pounding, the deck just moves in plane and without rotation. Deck behavior during this period can be represented by time at 6.64s shown in Fig. 10 (a), when the deck translates under balance loads. Then the 1st pounding happens, the deck begins to rotate due to the pounding. When the pounding force gets the max-value at 6.46s, the deck already has a small rotational angle of 0.002° so that the loads on the deck become unbalance but not so great shown in Fig. 10 (b). Also condition of pounding at this moment will be detailed discussed in the next section. The rotational angle keeps increasing as the rotational velocity increases until end of the 1st pounding. At the end of 1st pounding, the rotational velocity gets 0.36deg/s and the angel gets 0.009°. The rotational velocity decreases slowly due to the unbalance of bearing resistance before the 2nd pounding, and rotational angel still keep increase as the velocity hasn't decreased to zero. Deck behavior during this period before the 2nd pounding can be described in Fig. 10 (b), the deck already has a rotational angle of 0.044° before the 2nd pounding. During the 2nd pounding, the pounding force gets max value at 6.63s and the rotational angel reaches 0.07°, and it will be discussed further in Fig. 15 next section.

4.2 Detailed Pounding Condition and Damage

Poundings of skew bridge are different from that of straight bridge, authors think that not only the magnitude of pounding force should be discussed but the pounding area is necessary to be considered as it

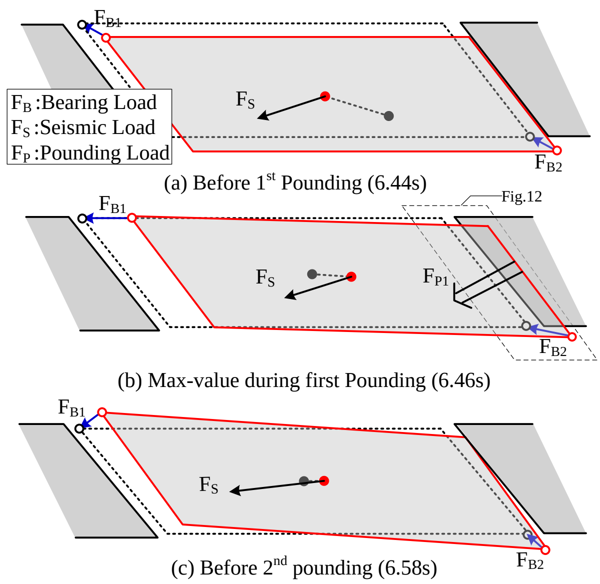


Fig. 10 Pounding Condition of 1st Pounding

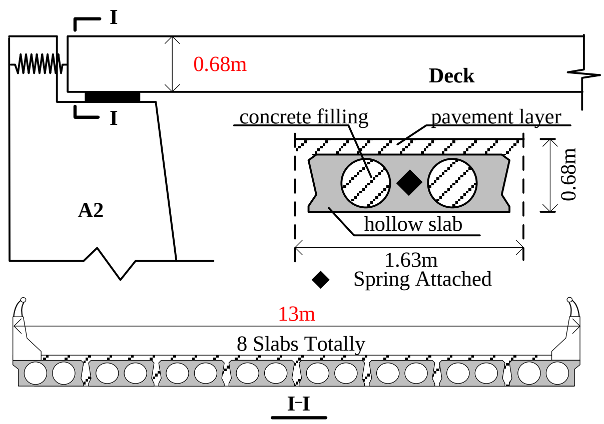


Fig. 11 Pounding Condition of 1st Pounding

keeps varying during the poundings. Fig. 11 aims to describe the size of joint area. The joint area of the deck has a thickness of 0.68m and a length of 13m, so the area of joint is 8.84m^2. Each single slab is attached a pounding spring and each spring represents a unit pounding area. Each span has 8 hollow slabs, including pavement layer and concrete filling shown in the section view of single slab, so the unit pounding area of slab is calculated as 1.1m^2 (A_s below) in Fig. 11. A_s will be used in the discussion on poundings in next part.

During the 1st pounding, the deck pounds to the abutment with all joint area as shown in Fig. 10 formerly. The pounding condition can be shown in Fig. 12. Fig. 12 (a) shows the condition of the max pounding force in the 1st pounding. The deck pounds into the abutment with 1.6mm and there is a small rotational angle of 0.002°. Max force of the 1st pounding reaches 16.4MN, shown in Fig. 12 (b). As being stated above, the damage degree of members is related to the stress that the members suffer. The definition of stress can be expressed as follows:

$$\sigma_{P(ave)} = \Sigma P_i / nA_S \tag{1}$$

Here, $\sigma_{P(ave)}$: Average stress by poundings; ΣP_i: Total pounding load; n: Number of springs that provide resistance; A_s : Unit pounding area stated above.

The 1st pounding is a whole area pounding, in which all 8 pounding springs provide resistance, so the pounding area is the whole joint area of 8.84m^2. Shown in Fig. 12 (b), the average stress by the 1st pounding is calculated as 1.9MPa (=16.4MN/8.84m^2), which just reaches 9.2% of the compressive strength of deck (C30 concrete, f_c'=20.1MPa). Besides, the corner C (obtuse corner of deck at A2 side) gets the max value of stress of 2.2MPa (=2.4MN/A_s), which is 10.8% of the compressive strength. Thus, the stress by 1st pounding is just about 10% of compressive strength so the bridge members may not suffer serious damage. Damage mechanism is supposed in Fig. 13. When the deck collides to the abutment, the slab on abutment may move back. However, with the resistance by roadbed and back earth, the abutment slab will trend to be lift from the roadbed as shown in Fig. 13 (a) and the side view in Fig. 13 (b) for simple. Actually, as shown in Fig. 14, the end of the slab on abutment is raised from the roadbed by about 185mm almost evenly due to the poundings. Current analysis still cannot surely get the actual raising of 185mm at the end of abutment slab. However, it can be confirmed that the even-raising of slab end is strongly related to the 1st poundings with all joint area which also accords with Fig. 13. Also, relative displacement between the deck and abutment reaches 450mm and 350mm at corner C and D separately due to the rotation.

Similarly, the 2nd pounding happens closely to the 1st pounding so that rotational angle hasn't increased too much shown in Fig. 10 formerly. 5 springs (in totally 8 springs) provide resistance and the pounding condition is shown in Fig. 15 (a). The max force of pounding reaches 9.5MN at corner C. Based on Formula (1), the stress at this part is calculated as 8.6MPa (=9.5MN/A_s). Also with the total pounding force of 24.5MN, the average stress reaches 4.5MPa (=24.5MN/5A_s).

Authors assume that the guardrail suffers the same stress with the deck slab at same position. The guardrail (C25 concrete) at corner C may be damaged more seriously as the stress (8.6MPa) it suffers reaches 51% of the compressive strength (C25 concrete, f_c'=16.7MPa). Actually, as shown in Fig. 15 (b), the guardrail at corner C suffers concrete crushing and

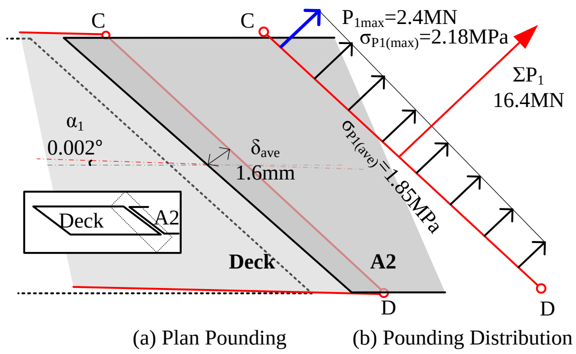


Fig. 12 Pounding Condition of 1st Pounding

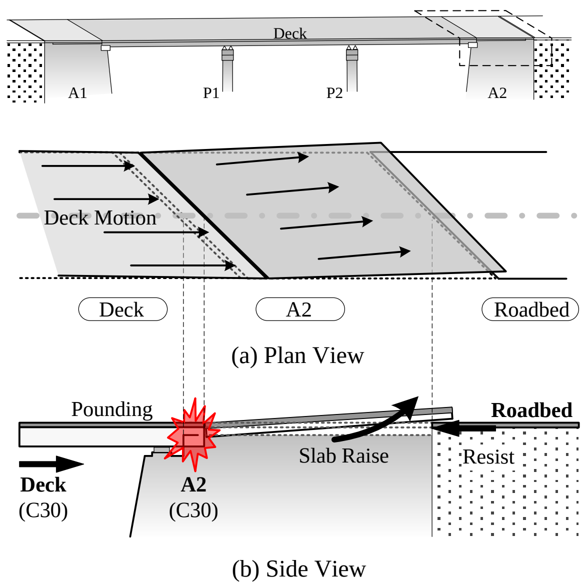


Fig. 13 Supposed Damage Mechanism

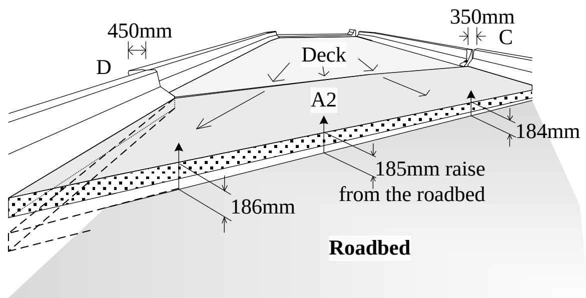
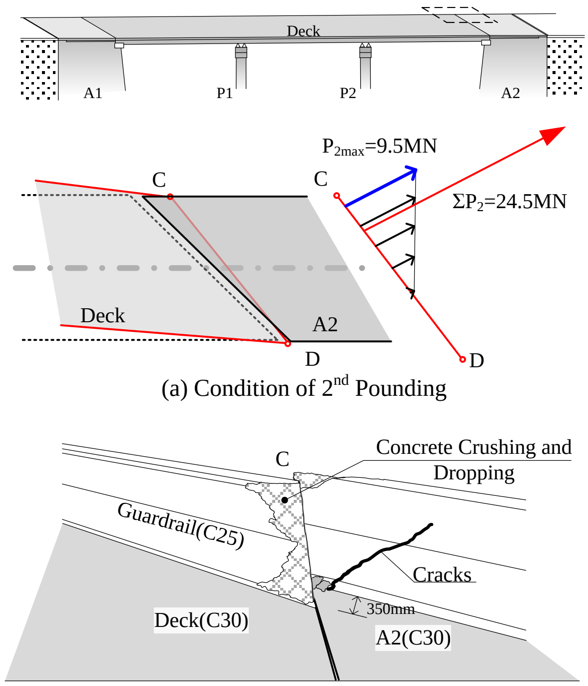


Fig. 14 Actual Damage Condition at A2

dropping, and there are some cracks on it. To sum it up, the 1st pounding gives the abutment slab a trend to dislocate, including the raising. The 2nd pounding aggravates the damage of A2 and causes the serious damage of guardrail at corner C shown in Fig. 15 (b).

The 3rd pounding gets the max stress of 15.4 MPa, as it is a corner pounding. It causes the most serious damage of A1 obtuse corner. This damage can be roughly explained by the different pounding condition from each pounding.

Based on the different stresses got in each pounding, authors also make a summary about the relationship between deck motion and pounding. As for straight bridges, the greater incoming velocity may cause the greater pounding force. However, as for skew bridge, it may not be true because of the rotation. At this time of analysis, the incoming normal velocity reaches 16.5cm/s, 19.5cm/s and 39.5cm/s before the 1st, the 2nd and the 3rd pounding separately, shown in Fig. 8, and they trend to increase. However, the pounding force gets the max of 24.5MN at the 2nd pounding, which is greater than the 1st pounding (16.4MN) and the 3rd pounding (17.0MN). The stress by each pounding reaches 2.18MPa (the 1st), 8.5MPa (the 2nd) and 15.4MPa (the 3rd), trending to increase. Authors consider that the incoming normal velocity should be related to the stress. Then Fig. 16 is plotted, and it shows the relationship between incoming normal velocity and the max stress by each poundings. According to the figure, the relationship appears positive correlation, in which the greater incoming velocity will cause greater stress. Actually, as it has been stated above, the local damage degree is related to the stress by poundings. The three factors (incoming velocity, stress by pounding, damage condition) are related to each other closely.



(a) Condition of 2nd Pounding

(b) Damage Cnodition

Fig. 15 Pounding Condition of 2nd pounding

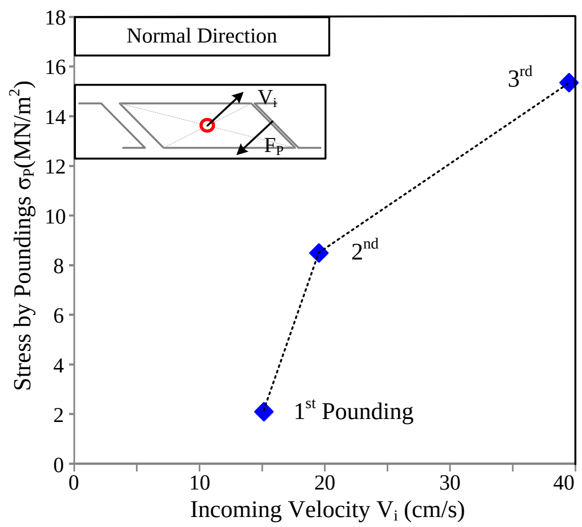


Fig. 16 Relationship of Pounding Velocity and Stress

5. CONCLUSIONS

According to dynamic analysis of Maweihe Bridge, comparison with actual damage, and discussion of failure mechanisms, following conclusions have been drawn:

(1) Large residual displacements and in-plane rotation happened on the deck. Deformation of deck center reached 315mm and 75mm in axial and transverse. Rotational angle of actual damage reached 1.32° clockwise. Side blocks and abutments were damaged to different degree due to poundings. Slab on the A2 abutment raised from the roadbed and obtuse corner of the deck was damaged seriously due to the poundings.

(2) Based on the analysis, both the 1st and 2nd pounding happened at A2 abutment. The even-stress by the 1st pounding and corner pounding by the 2nd pounding could roughly explain the raising of slab and serious damage at obtuse corner of guardrail. Besides, the great stress by the 3rd pounding could explain the cracks on the A1 abutment at downstream side.

(3) Based on the definition of pounding area, it could be inferred that relationship between normal velocity and stress by poundings appeared positive correlation. The greater incoming velocity was, the greater stress by poundings was. Furthermore, greater stress by poundings would cause more serious actual damage.

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