The influences of coupling beam device on the collision response between cable-stayed bridge and its approach bridges

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Abstract

Human beings always suffer huge lost in natural disasters, particularly earthquake, which directly brings catastrophic consequences. Aimed at this, scholars intensify relevant facilities and perfect the structure of affected buildings at all aspects. Regarding earthquake, measures are taken to increase the strength of some earthquake prevention materials and change the construction spot or structure that are in-conformity with the seismic safety evaluation. Bridge, as an important composition of communication, calls for improvement for its earthquake prevention. To begin with, the paper discussed the difference between the dynamic characteristics of cable-stayed bridge and its approach bridges. A bridge was applied as research object, and the influences of coupling beam device on the collision response between cable-stayed bridge and its approach bridges were investigated by analyzing the models, ground motion input, seismic influences and bridge structure parameters. Furthermore, several improvement suggestions were put forward. The research provided reference for the construction of cable-stayed bridge with ideal dynamic characteristics and theoretical basis for reducing damages that induced by the collision of cable-stayed bridge and its approach bridges.

Keywords: approach bridge, cable-stayed bridge, coupling beam device, collision

1 Introduction

Over the years, various seismic disasters are not caused one-time at the beginning of the earthquake, but result from the superposition of many factors that intensify catastrophic level. Among the factors, traffic jam obstructs the operation of rescue in time. The rescue of Kobe earthquake in Japan in 1995 and Wenchuan earthquake in China in 2008 was directly delayed due to the collapse of the approach bridges that adjacent to the main bridge of Nishinomiya Harbor Bridge and the approach bridges of Zipingpu reservoir bridge, respectively. To defense seismic disasters, scholars in China and abroad conducted research on cable-stayed bridge with great effort, and what exciting is abundant achievement has been made, which greatly assists the later research. However, the collision between cable-stayed bridge and its approach bridges and the anti-collision measures are seldom studied. In practical, because of the large difference between the dynamic characteristics of cable-stayed bridge and the connected approach bridges, when they are impacted by earthquake that presents longitudinal acting force, inverted-vibration is likely to occur and even the collision response of the main bridge and its adjacent approach bridge beams, and therefore the expansion joints are damaged and the beams collapse [1, 2].

In Japan and America, previous research has been made on the methods for reducing the collision of adjacent beams at expansion joints and inhibiting the relative displacement between adjacent beams and between pier and beam [3-6]. While, in China, there is no systematical and intensive research on the anti-collision measures between cable-stayed bridge and its approach bridges. In addition, there are no specific stipulations about this in currently implemented seismic code. Therefore, it is extremely essential to systematically investigate the collision response between main bridge and its approach bridges and the anti-collision measures, collect relevant parameters, and analyze their influences on the collision response of cable-stayed bridge and approach bridges. Aimed at this, the authors analyzed the bridge, and studied the influences of the elastic coupling beam device on the collision response of cable-stayed bridge and the approach bridges.

2 Analysis of models and ground motion input

Twin tower cable-stayed bridge with steel box girder of 84+75+70+818+124.5+233.5 m is applied as the main bridge, the structure of prestressed concrete continuous box girder with constant section of 5×50 m is used for the approach bridges, and D1600 expansion joints are adopted. The pier column, main tower and main beam are simulated using three-dimensional beam elements, in which single beam mechanical model and spatial truss element are used for the main beam and the stay cable, respectively. As the stiffness of the structure is influenced by the cable sag and dead load effect, it has to be considered as well. The elastic modulus of the cable is corrected using Ernst formula. The fixed pier is the middle-pier that close to the main bridge, and other piers slid in longitudinal direction and is fixed in transverse direction of the bridge.

In the analysis, a 5% of structural damping ratio is applied. To reduce the relative displacement between adjacent beams at the expansion joints and the collision response of approach bridges and main bridge, the coupling beam device demonstrated in Figure 1 and the expansion joint model in Figure 2 are set. The nonlinear force-

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deformation relationship of the stretching shrinking unit is

$$F = \begin{cases} k_r(\Delta_S - S) & \Delta_S - S \geq 0 \\ 0 & \Delta_S - S < 0 \end{cases}. \tag{1}$$

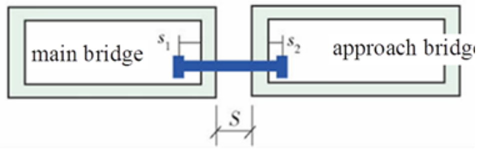

FIGURE 1 Coupling beam device

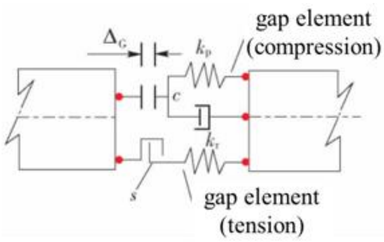

FIGURE 2 Model of expansion joint

Where the initial gap of the restrainer is S (see Figure 2, S=S_1+S_2); the relative departure displacement of adjacent beams at the expansion joint in earthquake is Δ_S; the stiffness of the coupling beam device is k_r (k_r=βk_m); the stiffness ratio of pulled coupling beam device to pier column is β, which is also called the stiffness ratio of the coupling beam device, k_m=k_1k_2/(k_1+ k_2); and the equivalent horizontal anti-push rigidity of the left and right beams are k_1 and k_2 respectively. The nonlinear force-deformation relationship of the contact element is

$$F = \begin{cases} k_p(\Delta_c + x_S) & \Delta_c + x_S < 0 \\ 0 & \Delta_c + x_S \geq 0 \end{cases}, \tag{2}$$

where the initial gap of the expansion joint is Δ_G, which is 80 cm in the calculation due to the practical engineering demand; the contact stiffness is k_p, which is determined by the structure of expansion joint and a standard k_p=6.5GN/m is applied [7-12]. A damper is used to simulate the energy lose in collision process, and the size of the damper is associated with the restitution coefficient e in the collision, which is e=0.65 in the analysis. The damper parameters are calculated using e and formula (3) and the masses of the adjacent beams at expansion joint are m_1 and m_2 in formula (3).

$$\xi = \frac{-\ln e}{\sqrt{\pi^2 + (\ln e)^2}},\quad c = 2\xi = \sqrt{k\frac{m_1 m_2}{m_1 + m_2}}. \tag{3}$$

To more effectively investigate collision response, the seismic waves measured in II and III fields are used in the analysis, and they are used as the ground motion input loads [10]. Table 1 specifically lists the selection conditions for seismic waves.

TABLE 1 Typical seismic waves

Field type	Earthquake	Magnitude	Recording station	PGA/g	amplitude modulation coefficient
II	Northridge-01	6.69	LA-Baldwin Hills	0.2388	2.51
	Landers	7.28	Fort irwin	0.1223	4.91
	Gazli, USSR	6.80	Karakyr	0.7175	0.84
III	imperialValley-02	6.95	El Centro Array #9	0.2148	2.79
	Chi-Chi, Taiwan	7.62	TCU053	0.2227	2.69
	Northridge-01	6.69	LA-Temple & Hope	0.1261	4.76

3 Influences of different seismic waves

The stiffness of coupling beam device is 60 MN/m; the expansion gas is 160 cm; and the initial gap of restrainer is 0.6 m due to the special function of free shrinkage of the main beams at two ends of the expansion joints. As shown in Table 1, the seismic waves are input and the seismic response of the structure is calculated using nonlinear time-history analysis method to compare the difference of the seismic responses with and without coupling beam between the main bridge and its approach bridges. The ratio of lower tower column height to total tower height, and the ratio of peak collision forces of adjacent beams at expansion joint with and without coupling beam device are demonstrated in Figure 3. Figure 4 and Figure 5 illustrate the maximum bending moment and shear ratios of the fixed pier bottom of the approach bridge. Figure 6 displays the maximum relative displacement ratio at the two sides of expansion joint. The ratios in Figures 3~6 are average values under the effect of six waves. In Figures 3~18, λ is the ratio of the seismic responses with and without restrainer; and each figure caption presents the measured seismic response, including collision force, displacement and bending moment.

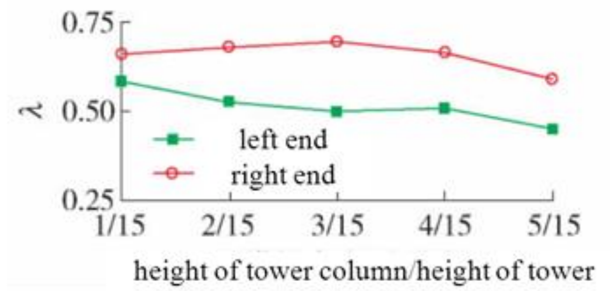

FIGURE 3 Variation of collision force at expansion and contraction joint

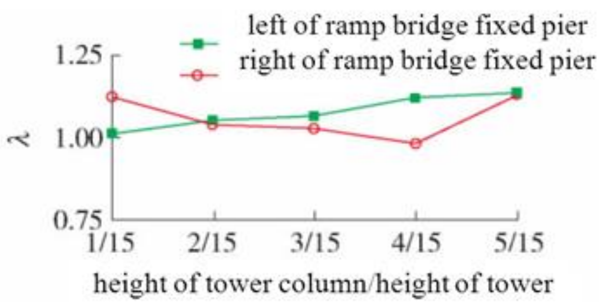

FIGURE 4 Variation of bending moment on key section of the bridge

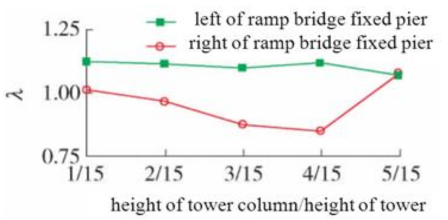

FIGURE 5 Variation of shear force on key section of the bridge

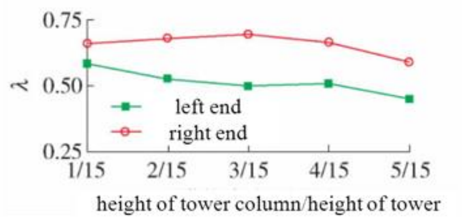

FIGURE 6 Variation of relative displacement at expansion joint

1) As shown in Figure 3, the peak collision forces at the both expansion joints are significantly decreased by the pulled coupling beam devices set between the adjacent beams at the expansion joints. It is observed that the peak collision forces at left and right expansion joints reduce by up to 50% and 28%, respectively. Obviously, the collision force of adjacent beams is influenced and reduced by the pulled coupling beam device set between the adjacent beams at the expansion joints, thus protecting the expansion joints.

2) Figure 4 and Figure 5 indicate that the maximum bending moment and shear force at the fixed pier bottom of the two sides of the approach bridge are slightly influenced by the pulled coupling beam device set between adjacent beams at the expansion joints, with variations within±10%.

3) It is seen in Figure 6 that the maximum relative displacements at the two expansion joints reduced significantly, because of the influence of the pulled coupling beam device set between the adjacent beams at the expansion joints. The relative displacements at the left and right expansion joints decrease by up to 52% and 27%, respectively. It indicates that the arrangement of pulled coupling beam device between the adjacent beams at expansion joints significantly reduces the relative displacement of the adjacent beams, protects the expansion joints thereby, and avoids the damages caused by the collapse of approach bridge beams.

4) The coupling beam device improves the influences of the ratio variation of the lower tower column height to the total tower height on the seismic collision response of the cable-stayed bridge; the reductions of the collision force ratio with and without coupling beam device and the ratio of the relative displacement of the beam end are influenced by the increase of the ratio of lower tower column height to total tower height. The ratio of the internal force response of the fixed pier of the approach bridge with and without coupling beam device is also influences by the ratio of lower tower column height to total tower height without regulation.

4 Influences of structural parameters

To investigate the influences of the structural parameters of the pulled coupling beam device on the collision of the bridge, the major structural parameters were varied to analyze their influences on the collision.

4.1 INFLUENCES OF INITIAL GAP OF THE COUPLING BEAM DEVICE ON THE SEISMIC RESPONSE OF THE STRUCTURE

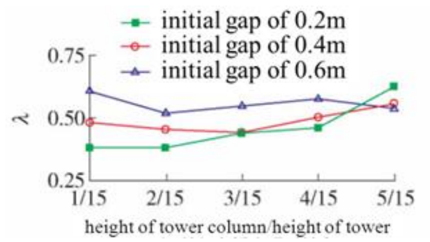

FIGURE 8 Collision force variation at left expansion joint caused by collision

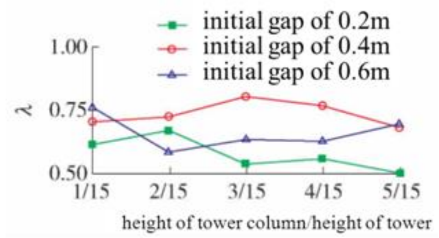

FIGURE 8 Collision force variation at right expansion joint caused by collision

The initial gap Δ_G of the pulled coupling beam device is set to be 0.2, 0.4, and 0.6 m respectively and the stiffness is 60MN/m. Based on Table 1, the influences of the initial gap on the seismic collision response are analyzed by calculating the response using nonlinear time-history analysis method. For cable-stayed bridges of different heights of gravitational center, the influences of the initial gap variation on the maximum collision forces at left and right expansion joints are demonstrated in Figures 7 and 8; the influences on the maximum relative displacement are illustrated in Figures 9 and 10; and the influences on the maximum bending moment of the fixed pier of the approach bridge are shown in Figures 11 and 12. In Figures 3~6, all the ratios are the average values under the effect of six waves.

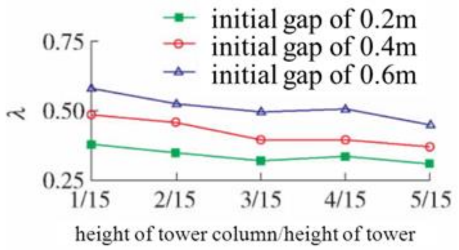

FIGURE 9 Relative displacement variation at left expansion joint resulted from collision

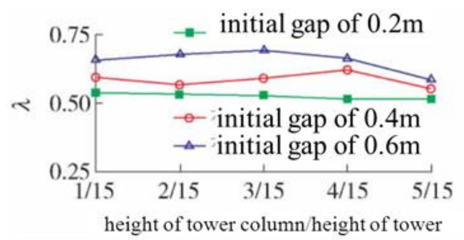

FIGURE 10 Relative displacement variation at right expansion joint induced by collision

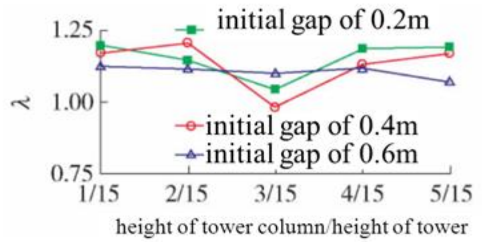

FIGURE 11 Variation of bending moment of fixed pier of left approach bridge caused by collision

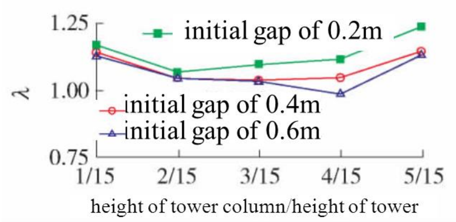

FIGURE 12 Variation of bending moment of fixed pier of right approach bridge caused by collision

1) Figure 7 and 8 illustrate that: 1. the collision force between adjacent beams can be reduced and therefore protecting expansion joints by varying the initial gap in certain range; 2. in general, the reduction of the collision force is influenced by the decrease of the initial gap of the coupling beam device; 3. after setting the pulled coupling beam device, the collision force is irregularly influenced by the height of gravitational center of the cable-stayed bridge.

2) Figure 9 and 10 show that 1. the relative displacement of adjacent beams is reduced significantly and the expansion gap is therefore protected by varying the initial gap in a certain range; 2. the relative displacement at both expansion joints decreases with the decrease of the initial gap.

3) It is observed in Figure 11 and 12 that 1. the maximum seismic demands for the bending moments the fixed piers at both sides of the approach bridge are influenced by the initial gap of the pulled coupling beam device. As the initial gap varies in certain range, the demand for bending moment changes as well with slight amplification; 2. when the initial gap is 0.6 m, the peak collision forces on both sides increase slightly and evenly.

In summary, a reasonable initial gap of the pulled coupling beam device ranges from 0.4 m to 0.6 m.

4.2 INFLUENCES OF STIFFNESS OF THE COUPLING BEAM DEVICE ON THE SEISMIC RESPONSE OF THE STRUCTURE

With a coupling beam device that presents stiffness of 30, 60, and 120 MN/m and an initial gap of 0.6 m, the seismic responses of the structure are calculated based on Table 1. Then the seismic responses of the main bridge and the approach bridge with and without coupling beam device are compared, to analyze the influences of the stiffness of the pulled coupling beam device on the structure.

1) Figure 13 and 14 indicate that 1. the collision force of adjacent beams is influenced by the stiffness of the pulled coupling beam, that is, to vary the stiffness in a certain range, the collision force is decreased effectively and the expansion joints are protected thereby; 2. the variations of the peak collision forces on left and right sides are different under the influence of the stiffness of the pulled, and a stiffness of 60 MN/m is reasonable; 3. the height of gravitational center of cable-stayed bridge poses significant but irregular influences on the collision force reduction effect of coupling beam device of different stiffness.

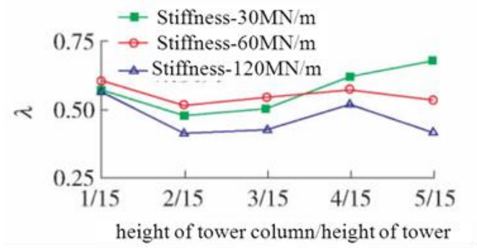

FIGURE 13 Collision force variation at the left expansion joint caused by collision

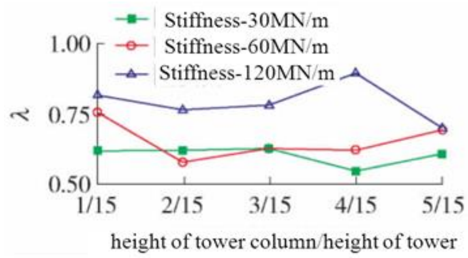

FIGURE 14 Collision force variation at the right expansion joint caused by collision

2) Figures 15 and 16 show that 1. different stiffnesses of the pulled coupling beam device show different influences on the bending moment of the fixed pier bottom of the approach bridge at both sides; 2. the maximum seismic demand for the bending moment of fixed pier bottom of left and right approach bridges changes with the variation of the stiffness of the pulled coupling beam device, and 60 MN/m is reasonable for the stiffness.

3) It is demonstrated in Figures 17 and 18 that 1. the relative displacement of adjacent beams is decreased and the expansion joints are protected when the stiffness of the pulled coupling beam device ranges in a certain scope; 2. with a large stiffness of the pulled coupling beam device, the relative displacement at both expansion joints reduces correspondingly.

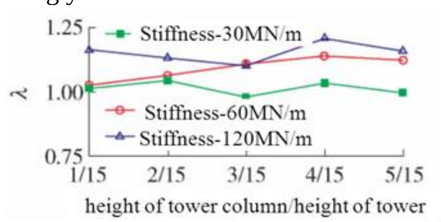

FIGURE 15 Variation of bending moment of the fixed pier bottom of the left approach bridge caused by collision

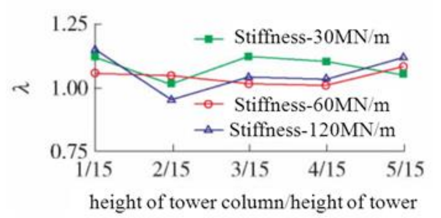

FIGURE 16 Variation of bending moment of the fixed pier bottom of the right approach bridge caused by collision

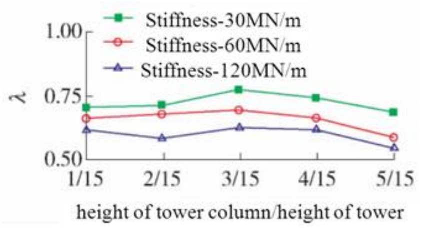

FIGURE 17 Variation of relative displacement on the left side induced by collision

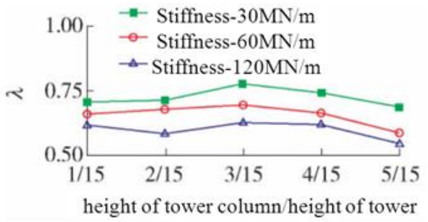

FIGURE 18 Variation of relative displacement on the right side induced by collision

5 Conclusions

1) By setting pulled coupling beam device between the adjacent beams at expansion joints, the relative displacement of adjacent beams and the peak collision force are significantly reduced, and the collision of the approach bridge and the cable-stayed bridge is effectively controlled.

2) The stiffness of the pulled coupling beam device shows huge influences on the relative displacement and peak collision force of adjacent beams and the seismic demand for bending moment of fixed pier of approach bridge, while slight influences on the displacement of the approach bridge beams.

3) When pulled coupling beam device is set between the adjacent beams at expansion joints, the displacement of approach bridges beams and the seismic demand for bending moment of fixed pier of the approach bridges vary in different conditions.

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