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Impact effect analysis for hangers of half-through arch bridge by vehicle-bridge coupling

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Abstract. Among the destruction instances of half-through arch bridges, the shorter hangers are more likely to be ruined. For a thorough investigation of the hanger system durability, we have studied vehicle impact effect on hangers with vehicle-bridge coupling method for a half-through concrete-filled-steel-tube arch bridge. A numerical method has been applied to simulate the variation of dynamic internal force (stress) in hangers under different vehicle speeds and road surface roughness. The characteristics and differences in impact effect among hangers with different length (position) are compared. The impact effect is further analyzed comprehensively based on the vehicle speed distribution model. Our results show that the dynamic internal force induced by moving vehicles inside the shorter hangers is significantly greater than that inside the longer ones. The largest difference of dynamic internal force among the hangers could be as high as 28%. Our results well explained a common phenomenon in several hanger damage accidents occurred in China. This work forms a basis for hanger system's fatigue analysis and service life evaluation. It also provides a reference to the design, management, maintenance, monitoring, and evaluation for this kind of bridge.

Keywords: half-through arch bridge; hanger; bridge surface roughness; vehicle-bridge coupling; impact effect

1. Introduction

Half-through arch bridge has been widely built in China in recent decades. The hanger system is one of the most important bearing members in this kind of bridge, and the safety of the bridge is directly related to the operation conditions of the system. However, the durability of hanger system is known to be the weakest in the bridge. In recent years, several damage accidents of half-through arch bridge have occurred in China, such as the Nanmen Bridge (Fig. 1) in Yibin, Sichuan (November 7, 2001), the Kongquehe Bridge (Fig. 2) in Korla, Xinjiang (April 12, 2011), the Gongguan Bridge (Fig. 3) in Wuyishan, Fujian (July 14, 2011), etc. These accidents are directly caused by the failure of the hanger system. As matter of fact, a detection test was conducted on the Kongquehe Bridge in 2008, and the conclusion is that "the total tension in hangers is less than the half of design value (3400 kN), the hanger system meets the strength requirement" (Jiang and Zainula 2008). However, the hanger fracture happened just three years later. So, the durability of hanger system has attracted more attention of scholars and engineers.

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In these fracture accidents in hangers above, there is an obvious common characteristic, that is, the damage occurs in the shorter hangers, or the first occurs in the shorter hangers. Through the research on the fracture accident of Nanmen Bridge, Kong (2003) believes the temperature, corrosion, and fatigue are the main factors leading to short hanger fracture. Yao's (Yao *et al.* 2002) conclusion is that the short hanger fracture in Nanmen Bridge was caused by the accumulation of fatigue damage under the long-term alternating loads. For the Gongguan Bridge accident, the preliminary conclusion by the investigator is that the long-term overload caused the hanger fatigue fracture. As the key components, hanger fracture will induce the tensions re-distribution among other hangers and even the bridge collapse (Zhu and Yi 2011).

(a) (b)

Fig.1 The photo of collapsed Nanmen Bridge

Fig. 2 The photo of collapsed Kongquehe Bridge

Fig. 3 One of the PLVM of the undamaged structure

Malm and Andersson (2006) researched the hanger behavior of a railway arch bridge. His conclusion is that the distribution of strain over hanger cross-section is nonuniform obviously when the trains pass through the bridge, and about 60 percent of alternating stress amplitude in hangers is caused by vehicle-bridge vibration. Obviously, the reasonable results for this impact effect can't be obtained unless taking the vehicle-bridge coupling dynamic into account. Huang (2005) studied the dynamic characteristics and impact coefficient of arch bridge, and obtained a series of theoretical achievements. Li *et al.* (2010) analyzed the impact effect on bridge deflection and internal force in hangers by taking the road surface roughness, vehicle speed and structural damping into consideration. Based on the frequency and impact coefficient analysis for half-through arch bridge, Gu and Xu (2002) described the mechanical behavior and failure mechanism of the short hanger, and put forward some improvement suggestions. Zhu and Yi (2012) studied the nonuniformity of impact coefficient of hangers for half-through and through arch bridge, and further analyzed the influence on the impact coefficient by structural damping, road roughness, vehicle weight and speed. Many studies show that the impact coefficient of hangers induced by vehicle load is different at different locations (Li *et al*. 2012).

In this study, our main purpose is to investigate the differences in the impact effect between the longer and shorter hangers for a half-through arch bridge under the vehicle load by vehicle-bridge coupling. The bridge model and vehicle model are developed respectively. Road roughness is simulated according to China standard. Based on these models, the vehicle-bridge coupling analysis is conducted. The variation of dynamic internal force (stress) in hangers under different vehicle speed and road surface roughness is simulated, compared, and evaluated. Our results well explained a common phenomenon in several hanger damage accidents occurred in China. The research forms a basis for hanger system's fatigue analysis and service life evaluation. It also provides a reference to the design, management, maintenance, monitoring, and evaluation for this kind of bridge.

2. The model of vehicle-bridge coupling

2.1 The bridge model

The bridge to be analyzed is a half-through concrete-filled-steel-tube arch bridge on China national road No.G203. The elevation setup and dimensions are shown as in Fig. 4. The three dimensional finite element model is developed in which the concrete-steel interaction in arch rib is considered. In order to guarantee the precision of the model, (1) the influence of main modeling factors on the static and dynamic response of structure is analyzed in detail; and (2) the finite element model is revised by comparing the static and dynamic response calculated with field test results (Shao and Sun 2012). As a multi-DOF system, the bridge model is described in following equation

$$[M]\{\ddot{\delta}\}+[D]\{\dot{\delta}\}+[K]\{\delta\}=\{F\} \tag{1}$$

where, $[M]$, $[D]$, $[K]$ are mass, damping, and stiffness matrix, respectively. $\{\ddot{\delta}\}$, $\{\dot{\delta}\}$, $\{\delta\}$ are acceleration, velocity, and displacement, respectively. $\{F\}=\{F_g\}+\{F_v\}$ is bridge load vector, $\{F_g\}$ is vehicle weight, $\{F_v\}$ is the force caused by vehicle movement, it varies with the moving of the vehicle on the bridge.

Rayleigh damping is used in the model (Leitão *et al*. 2011)

$$[D] = \alpha[M] + \beta[K] \tag{2}$$

where, α =0.26, β=0.01.

2.2 The vehicle model

So far, many researchers have studied the theory and method for vehicle-bridge coupling from different aspects (Oliva *et al*. 2013, Wu and Law 2010, Zhang and Xia 2013, Han *et al.* 2014, Zhu *et al*. 2014). These studies have achieved rich results in development of vehicle models and iterative algorithm. Huang *et al.* (2010) studied specially on vehicle model influence to the impact coefficient in vehicle-bridge coupling analysis. His conclusion is that several kinds of vehicle models are able to reveal the general characteristics of coupling vibration response. Through the trial and comparison of the models, the 1/2 vehicle model as shown in Fig. 5 is adopted in this study. In the model, M is the mass of the vehicle body, J is the mass moment of inertia of the vehicle body, m_i is the mass of vehicle frame and wheels, k_{ij} is the stiffness, and c_{ij} is damping. The vehicle vibration is described in following equation

$$[M_v]\{\ddot{z}\}+[D_v]\{\dot{z}\}+[K_v]\{z\}=\{F_v\} \tag{3}$$

where $[M_v]$, $[D_v]$, $[K_v]$ and $\{F_v\}$ means mass matrix, damping matrix, stiffness matrix and external incentive vector, respectively. $\{\ddot{z}\}$, $\{\dot{z}\}$ and $\{z\}$ means generalized acceleration, speed, and displacement matrix, respectively.

The total weight for the vehicle model in this example is 20000kg, Vehicle model parameters: M=17500 kg , J=42480 kg·m^2 , m_1=m_2=1250 kg , k_{t1}=k_{t2}=2.0×10^7 N/m , k_{s1}=k_{s2}=1.0×10^7 N/m , c_{t1}=c_{t2}=1.0×10^5 N·s/m , c_{s1}=c_{s2}=4.0×10^4 N·s/m.

2.3 Simulation of road surface roughness

Road surface roughness is described by the following displacement power spectral density given by China national standard GB7031-86 (1986)

$$G_d(n) = G_d(n_0)\left(\frac{n}{n_0}\right)^{-\omega} \tag{4}$$

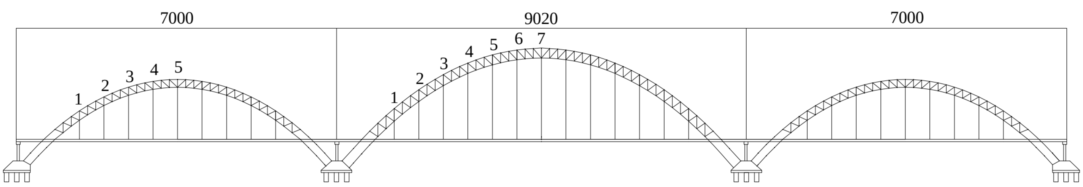


Fig. 4 The elevation of the arch bridge (Unit: cm)

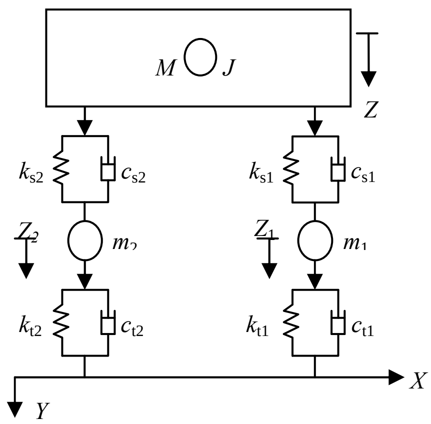


Fig. 5 Model of vehicle

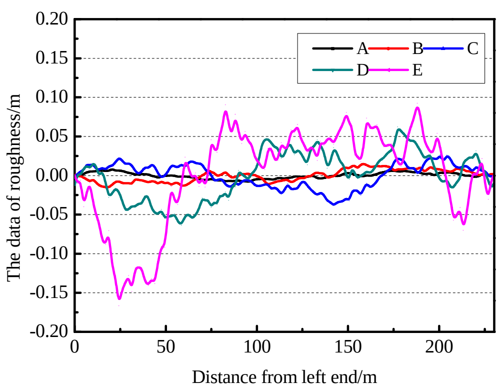


Fig. 6 Road surface roughness

in which, n is spatial frequency, the unit is m^{-1}, $n_0 = 0.1\mathrm{m}^{-1}$ is reference spatial frequency. $G_d(n_0)$ is the coefficient of road surface roughness depending on the roughness grade. $G_d(n)$ is the displacement power spectral density. ω is frequency index. A set of samples of the road roughness of levels A ~ E is shown in Fig. 6.

2.4 Vehicle-bridge coupling iteration method

First, the road roughness is applied to vehicle model as the displacement excitation. Assuming the wheels keep in contact with the bridge deck, vehicle wheel load at contact point is then calculated. The position of contact point changes with time based on the vehicle speed. Then, vehicle wheel load is applied to the corresponding position of bridge model to calculate vertical deflection of bridge deck. The next round of calculation can be started by adding the deflection to the roughness. The iteration is conducted by repeating the above process until two successive deflections meet the requirement of precision. The detailed process is shown in Fig. 7. This iterative algorithm has many advantages such as clear in concept, good in generality, and ease of programming.

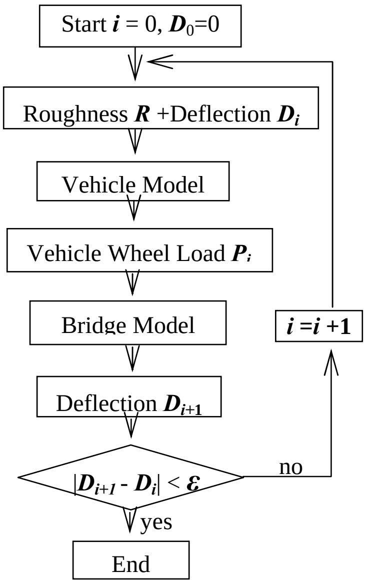
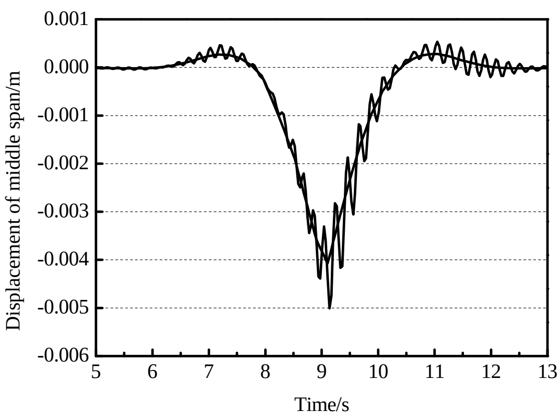


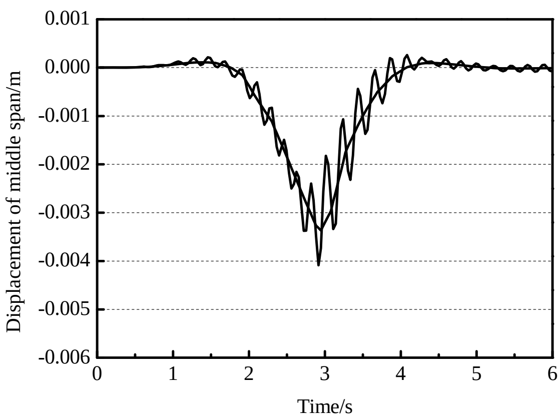
Fig. 7 The iterative process of vehicle-bridge coupling dynamics

2.5 Model modification and preanalysis

The vehicle (20000 kg) drives over the bridge at different speeds (10~60 km/h). The dynamic response of vehicle-bridge coupling is calculated at the road roughness of level C. Through comparing the response calculated from the experimental results, the bridge model is corrected and improved. The simulation results on modified model have a good match to the experiment results as listed in Table 1. The dynamic displacements of middle span are showed in Fig. 8.



(a) main span



(b) side span

Fig. 8 Dynamic displacements of middle span

Table1 Impact coefficient and frequency

	Impact coefficient		frequency /Hz	
Vehicle speed /km/h	calculation	experiment	calculation	experiment
10	1.231	1.148	4.4	4.1
20	1.379	1.349		
30	1.369	1.369		
40	1.330	1.354		

3. Impact effect analysis for hangers

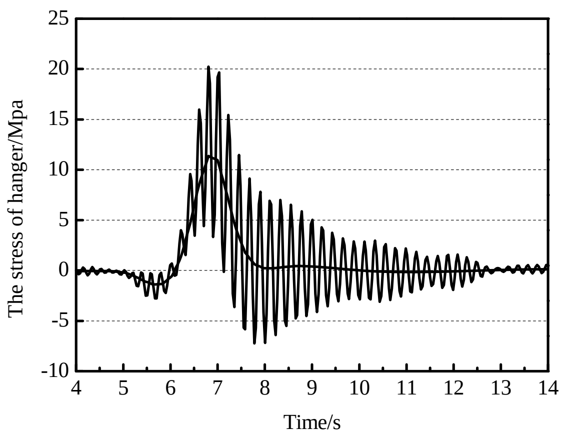
3.1 Impact effect

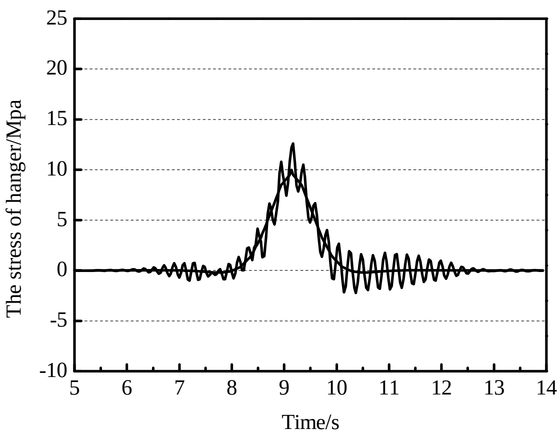
Usually, the impact coefficient $(1+\mu)$ is used to describe the magnitude of dynamic effect of the moving vehicle to the bridge. μ is defined as:

$$\mu = \frac{Y_{d\max}}{Y_{j\max}} - 1 \tag{5}$$

where, $Y_{j\max}$ is the maximum static displacement of the bridge, and $Y_{d\max}$ is the maximum dynamic displacement of the bridge.

The stresses in hangers are calculated based on the modified model at the road roughness of level C. The stress time history of the shortest (No.1) and the longest (No.7) hangers of main span are shown in Fig. 9. The figures show that the dynamic effects are significant and different between two hangers.





(a) hanger No.1 (b) hanger No.7

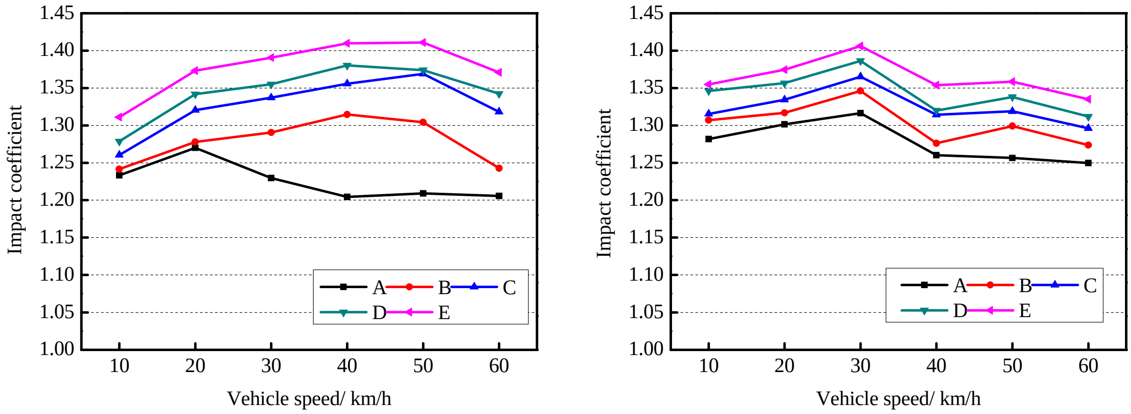
Fig. 9 Hanger stress of main span

3.2 Effect of road roughness

The impact coefficients of hanger internal force are calculated for 6 settings of vehicle speeds and 5 levels of roughness respectively. Fig. 10 shows the impact coefficients of the shortest hanger stresses of main and side span. The level of bridge roughness shows an obvious influence on the hanger stress impact coefficient. The impact coefficient increases with the decreasing of road surface roughness level.

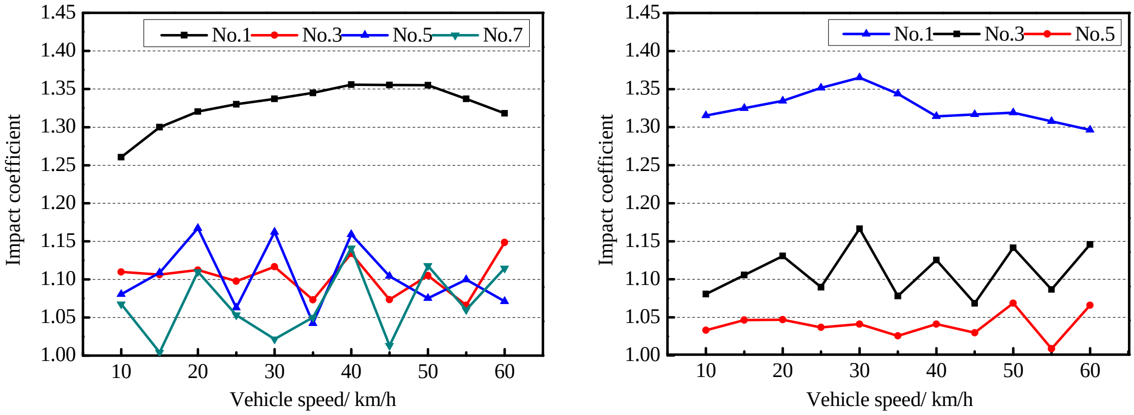
3.3 Effect of hanger length

Adopting C level of road roughness, the dynamic responses of bridge are calculated for the driving speed of 10 to 60 km/h. Fig. 11 shows the stress impact effect of hangers with different lengths.



(a) main span (b) side span

Fig. 10 The effect of roughness on hangers' impact coefficient



(a) main span (b) side span

Fig. 11 Stress impact coefficient of hangers

The stress impact coefficient of the short hanger is significantly greater than the others. This means that the short hangers have to withstand greater impact than longer ones. So the short hangers are easier to be damaged. From the above results, the hangers with different lengths (or at different position) will have a different service life. The stress impact coefficients for each hangers of main span are shown in Fig. 12.

As a preliminary study and evaluation to the hanger impact effects under operation conditions, stress impact coefficient is also analyzed comprehensively based on the vehicle speed distribution model (Shi 2004) shown in Fig. 13. The impact coefficient of speed weighted is calculated. The comprehensive impact coefficients of the hangers of main and side spans are shown in Fig. 14. The comprehensive impact coefficient varies obviously and regularly with the change of the hanger length. Therefore, under the operation conditions, the dynamic stresses in shorter hangers are significantly larger than the longer one.

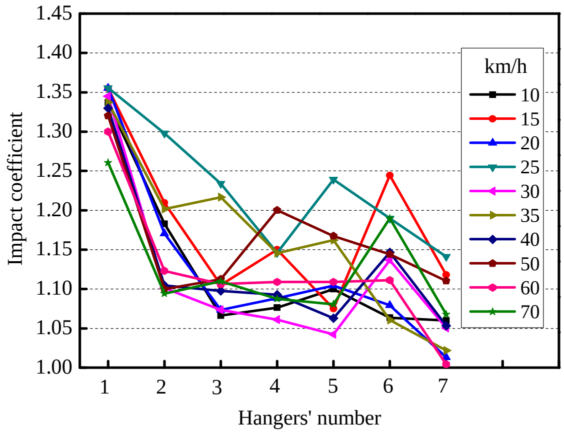


Fig. 12 Stress impact coefficient of hangers with different length

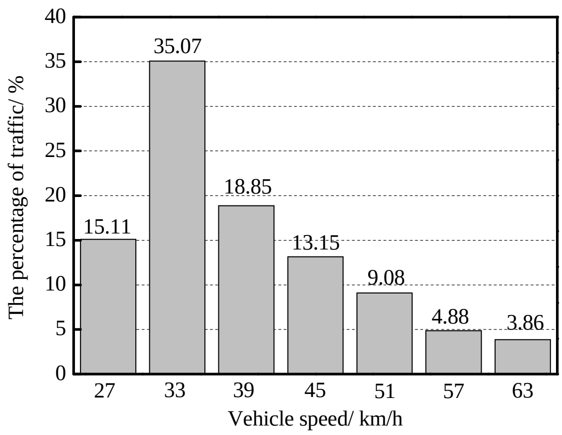


Fig. 13 Vehicle speed distribution model

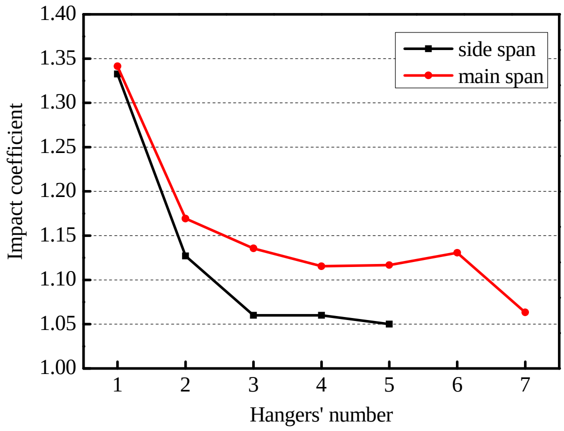


Fig. 14 Vehicle-speed-weighted impact effect of hangers

4. Conclusions

The impact effect of hangers is obviously magnified by the road surface roughness. Keeping road surface in a good condition is very important for the hangers' durability.

The dynamic internal force induced by moving vehicles in the shorter hanger is significantly greater than that in the longer ones. The largest difference of dynamic internal force among hangers is as high as 28%. The hangers with different length (or at different position) will have a different service life. Our results well explained a common phenomenon in several hanger damage accidents occurred in China.

The differences in impact effect between short and long hangers are mainly caused by differences in vertical stiffness. These differences can be diminished by the means of design so as to improve the service life of the bridge.

This work forms a basis for hanger system's fatigue analysis and service life evaluation. It also provides a reference to the design, management, maintenance, monitoring, and evaluation for this kind of bridge.

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