Transverse Mechanical Behavior of Hangers in a Rigid Tied Arch Bridge under Train Loads. II: Dynamic Magnification Factor

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Abstract

The transverse vibration of the rigid hanger in a rigid tied arch bridge which is common concerned in bridge engineering, and the dynamic magnification factor of transverse vibration for rigid hangers under train loads is needed to be explored. Based on the Dashengguan Yangtze River Bridge, this paper investigates the transverse vibration of rigid hangers in the rigid tied arch bridge under train loads from two foci. Firstly, the finite element model of the rigid tied arch bridge and the sub-model of each hanger of this bridge are established within ANSYS environment. The dynamic characteristics analysis of the whole bridge and each hanger are presented. Secondly, the dynamic amplification factors of transverse vibration of hangers in 2 field load cases are presented by nonlinear dynamic analysis. The conclusions show that generally the resonance between hangers and main girder is unlikely to happen in a rigid tied arch bridge and the dynamic amplification factors of transverse dynamic displacements at short rigid hangers are required to be paid more attention. This work also gives a suggestion which lays a foundation for the better design, maintenance and long-term monitoring of hangers in a long-span rigid tied arch bridge.

Key words: High-speed trains; Rigid hangers; Tied arch bridge; Dynamic magnification factor

Introduction

The vibration of long span rail bridge is serious under high speed train. As a typical project of tied arch bridges, the Dashengguan Yangtze River Bridge was constructed on the Beijing-Shanghai high-speed railway line of China due to its large stiffness, less usage of steel and the good capability in span compared to other types of bridge (for example the cable-stayed bridge and the suspension bridge) with the same span.

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Therefore, its long-term performance is required to be investigated.

From the viewpoint of structural dynamics theory, the tied arch bridge is a complex dynamic system consisting of the arch ribs, hangers and main girders; the tied arch bridge has complicated mechanical behaviors under the external excitation. A series of studies about the vibration of the tied arch bridge have been published. The dynamic characteristics of the tied arch bridge in construction (Kang et al. 2013) and in service (Li et al. 2008; De Backer et al. 2014; Wang et al. 2014) are the research basis for the bridge's dynamic mechanical behaviors. To study the dynamic characteristics and responses of the arch bridge under the traffic load, many researchers (Ju and Lin 2003; Yang and Lin 2005; Yoshimura et al. 2006; Kong et al. 2006; Huang, 2012) established the finite element (FE) model of the steel tied arch bridge, studied the nonlinear vibration responses of the whole bridge, and determined the parameters which affect the dynamic responses under high-speed train loads. On the other hand, some researchers investigated the long-term dynamic performance of the tied arch bridges based on their structural health monitoring (SHM) systems (Afonso Costa and Figueiras 2012; Li et al. 2012).

Hangers are one of the main load-bearing components in a long-span bridge (Deng et al. 2015), and the mechanism of influence of high-speed train loads on the hangers' vibration must be clarified. The present paper focuses on the transverse dynamic mechanical behavior of hangers in the rigid tied arch bridge under train loads. The transverse and torsional vibration of the main girder is generated due to the wind load and train load, and then the transverse bending and the shear deformation of hangers are presented especially obvious on the long hangers at the middle position of a span. The end of rigid hangers are fixed with the main girder, the vibration of rigid hangers are largely affected by the vibration of main girder under the train load; therefore in the present work, the transverse vibration of hangers is required to be studied based on the nonlinear dynamic analysis from the view of the system of rigid hangers and the main girder in the FE model.

In the present work, the dynamic characteristics analysis of the whole bridge and their hangers are presented. The space distribution of dynamic magnification factor of transverse dynamic displacements of hangers in 2 load cases are calculated.

Dynamic Characteristics Analysis for bridge FE model

The dynamic characteristic (mode frequency and mode shape) is the base of structure vibration. Table 1 shows results of modal parameters of the first six modes based on the FE model and the field test (Meng et al. 2015); it can be seen that the numerical modal parameters based on the FE model are close to the measured results, which show that the FE model can be used in the structural dynamic analysis.

As can be seen in Table 1, the first 3 mode shapes obtained from the Dashengguan Yangtze River Bridge FE model are transverse mode shapes or mode shapes including transverse vibration. The 4th to 6th mode shapes are vertical mode shapes. These two vibration modes will affect the vibration of hangers. It can be concluded that the modal parameters results of the first 6 modes based on the FE model are close to the field test results (Meng et al. 2015).
Table 1. Comparison of the modal parameters of the first six modes of the whole bridge

<table>
<thead>
<tr>
<th>NO.</th>
<th>Numerical results</th>
<th>Field test results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency (Hz)</td>
<td>Mode shape</td>
</tr>
<tr>
<td>1</td>
<td>0.45964</td>
<td>vertical-symmetric, transverse-antisymmetric, longitudinal floating</td>
</tr>
<tr>
<td>2</td>
<td>0.52906</td>
<td>transverse-antisymmetric</td>
</tr>
<tr>
<td>3</td>
<td>0.68201</td>
<td>transverse-symmetric</td>
</tr>
<tr>
<td>4</td>
<td>0.81154</td>
<td>vertical (great response presents at Beijing side)</td>
</tr>
<tr>
<td>5</td>
<td>0.81284</td>
<td>vertical (great response presents at Shanghai side)</td>
</tr>
<tr>
<td>6</td>
<td>1.0710</td>
<td>vertical-symmetric</td>
</tr>
</tbody>
</table>

Fig.1 Comparisons between the first 3 natural frequencies of the hangers and the first 50 natural frequencies of the whole bridge
Dynamic Characteristics Analysis of the Hangers

Fig. 1 shows the first $n$ ($n = 1, 2, 3$) orders natural frequencies based on the FE model of each hanger and the comparisons with the $1^{\text{st}}$, $10^{\text{th}}$, $20^{\text{th}}$, $30^{\text{th}}$, $40^{\text{th}}$ and $50^{\text{th}}$ order natural frequencies of the whole bridge.

In Fig. 1, $B_i$ represents the value of the $i$th natural frequency of the whole bridge model. The sections of hangers 1 and 21 are H-section, while the sections of hangers 2~20 are box section. It can be seen from Fig. 2: (1) for Dashengguan Yangtze River Bridge, the natural frequencies of hangers with box section are related to the length of hangers; (2) the frequency of hanger 1 is so small that the frequency curve at hangers 1 and 2 is not continuous, and the main reason is: hanger 1 is the shortest one with small deformation capacity, and it will be damaged easily and even destroyed if it is too rigid (i.e. with large frequency), so hanger 1 employs H section and thus its frequency is far smaller than the other hangers with box section; (3) the first order natural frequency of the hangers with box section in the middle position of a span is close to the $20^{\text{th}}$ order natural frequency of the whole bridge, and the first order natural frequency of the hangers with H section at the arch foot is close to the $50^{\text{th}}$ order natural frequency of the whole bridge. Therefore, the resonance between hangers and the whole bridge is unlikely to happen.

Transverse Dynamic Magnification Factor of the Hangers

In structural nonlinear vibration theory, the transverse vibration of hangers in a rigid tied arch bridge is generated due to the main girder’s vibration induced by the eccentric train loads. The interaction of hangers and main girder in the rigid tied arch bridge results in the complex dynamic responses.

Figs. 2~3 show the dynamic magnification factors of transverse displacements for the hangers within the 6 load cases; in which Figs. 2~3 (a) show results of hangers in span 1 and Figs. 2~3 (b) show results of hangers in span 2.

![Fig. 2 Dynamic amplification factors of transverse displacements for hangers in load case 1](image-url)
It can be found from Figs. 2~3 that:

(1) for transverse displacement of the hangers, the maximum of dynamic magnification factor appears at these short hangers located near the mid-piers (hangers 19~21 in span 1, hangers 1~3 in span 2) in load cases 1, 2, which was also indicated in the work of Shao et al. (2015).

(2) the row nearest the loading track has the greatest dynamic amplification factor (2.6802) of transverse displacement, which indicates moving train loads have greater impact effect on the transverse vibration of the nearby hangers.

Conclusions

An accurate FE model of a rigid tied arch bridge called Dashengguan Yangtze River Bridge and its FE sub-models of every hanger are established. The dynamic characteristics analysis of the whole bridge and each hanger are presented. The dynamic amplification factors of transverse dynamic displacements of hangers in 2 load cases are calculated by nonlinear dynamic analysis. Some conclusions can be summarized as follows:

(1) The dynamic characteristics analysis of the whole bridge and each hanger shows that: for such a representative long-span rigid tied arch bridge, generally the resonance between rigid hangers and main girder is unlikely to happen. The interaction of rigid hangers and the arch bridge does not lead to the hangers’ significant vibration. The minimum of first natural frequencies of the rigid hangers is generally far greater than the first several orders of natural frequencies of the whole long-span arch bridge; therefore, generally the hangers of the rigid tied arch bridge will not suffer a sudden failure due to the resonance of hangers and main girder.

(2) The maximum of dynamic magnification factors for transverse dynamic displacement appears at the short hangers at the arch foot; the hangers in the row nearest from the loading track have the greatest dynamic amplification factors of transverse displacements.

A suggestion is given as follows. In the design, the maintenance and the long-term monitoring of a long-span rigid tied arch bridge, the transverse dynamic responses,
stability and fatigue performance of hangers are required to be paid more attention, the transverse vibration of short hangers close to the arch foot need be pay more attention.

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