Damage location diagnosis of urban rail transit bridge based on vehicle-induced vibration responses

Hao Liu, Dongliang Zuo and Kun Zhang*
School of Civil Engineering, Dalian Jiaotong University, Dalian, 116028, China
*Corresponding author's e-mail: chinazhangkun@163.com

Abstract. For the urban rail transit bridges, vehicle load has obvious repeatability and regularity, and the vibration amplitude of the bridges under the vehicle action is much larger than that during the period of not being open to traffic, which is more conducive to the appearance of structural damage. This paper attempts to use vehicle-induced vibration responses to diagnose damages for urban rail transit bridges. Firstly, the vehicle-rail-bridge coupling finite element model was established based on the engineering background of a typical urban rail transit bridge. Then, through dynamic time history analysis, the vibration responses of bridge and vehicle before and after damage were obtained. Finally, the sensitivity to damage of acceleration responses from measuring points on both bridge and vehicle was compared, and a damage diagnosis method based on the difference of acceleration responses from different measuring points of bridge and vehicle structure was proposed. The results show that the difference of acceleration response between the measured points of bridge, wheelset and bogie before and after damage can be used to locate damage, and the vehicle-induced vibration data as a medium can provide a new way for rapid diagnosis of damage location for urban rail transit bridges.

1. Introduction

Because of the advantages of low cost and low energy consumption in operation, the proportion of bridges in urban rail transit lines is increasing. For urban rail transit bridges, the vehicle loads have the characteristics of fixed position, same mode of action and similar magnitude of action, and they have obvious repeatability and regularity. The vibration responses of the bridge structure are a series of similar non-stationary time-history signals when each train passes through, and the vibration amplitude of the bridge structure is much larger than that of the case without vehicle loading. Moreover, some structural damage forms of urban rail transit bridges only appear when the train passes. Therefore, the vibration responses of bridges and vehicles under are hopeful to become a medium for diagnosing the health status of urban rail transit bridges.

With the rapid development of urban rail transit, more and more studies were focused on the interaction among various subsystems of vehicle-rail-bridge in the process of bridge structure design and operation. From the development history of vehicle-rail-bridge interaction research, it can be seen that in the process of vehicle simplification, the main forms include moving concentrated force, moving mass, moving harmonic force, moving spring mass system, and so on. Among them, the method of simulating vehicle load by moving spring mass system is widely used in the study of vehicle-rail-bridge coupling vibration because of its better calculation accuracy and efficiency[1-5].

Based on this, a three-span continuous beam in a metro line is used as the engineering background in this paper. The vehicle-rail-bridge coupling finite element model is firstly established with ANSYS.
software. Vibration responses of the bridge and vehicle under train load is obtained by dynamic time history analysis. The feasibility of diagnosing bridge damages from vehicle-induced vibration responses of the bridge and vehicle is studied by comparing the changes of vibration response from different measuring point before and after bridge damage.

2. The establishment of finite element model for vehicle-rail-bridge coupling system

2.1. Engineering background
In this paper, a continuous girder bridge with three spans of 30+30+30 m is selected as the research object. Its main girder is single box, single chamber and equal cross-section box girder. Its cross-section sizes include roof width of 10m, thickness of 20cm, bottom width of 5m, thickness of 50cm, box girder height of 180cm. The rail is steel rail of No. 60, double track. The lower structure is a rectangular vase pier with a height of 14m and a cross-section size of 2.5×1.8m. Bored cast-in-place pile with a diameter of 1m and a length of 40m is used as the foundation.

2.2. Establishment of finite element models for bridge and tracks
The purpose of this section is to establish a finite element model of bridge and track structure in order to provide a reference model for the subsequent calculation of bridge and car body vibration response based on vehicle load. In order to improve the calculation efficiency of the subsequent transient analysis, we only take the box girder and rail parts as the main body of the finite element model of bridge structure. The lower structure is simplified as a constrained bearing, which is opposite to the top of pier. Linear displacement and angular displacement constraints corresponding to the actual direction are applied to simulate the box girder joints. The BEAM188 element with customizable cross section is selected to model the continuous box girder and rail respectively. The cross section of the box girder and rail defined according to the actual size is shown in Figure 1. The length of box girder element is 0.5 meter. The whole box girder model contains 180 elements and 181 nodes. The material of box girder is C50 concrete, and its material parameters are density of 2500 kg/m$^3$, Poisson's ratio of 0.2 and elastic modulus of 34.5 GPa. The bridge is a double-track bridge with a gauge of 1.435 m and a gauge of 4 m. The material of rail is steel. The main material parameters include elastic modulus of 2.06GPa, Poisson's ratio of 0.3 and density of 7800kg/m$^3$.

![Figure 1. Cross section of box girder and No. 60 rail for the urban rail transit bridge](attachment:figure1.png)

The bridge junction and rail junction are coupled by the degree of freedom, and the rail is consolidated on the bridge deck. Then, combined with the actual engineering situation, the longitudinal and vertical displacement of the continuous box girder is restrained at one end, the vertical displacement of the bridge is restrained at the other end, the rotation displacement of the longitudinal bridge is restrained at both ends, and the linear displacement of the vertical bridge is restrained only at the middle support. The rail-bridge finite element model established by the above modeling process is shown in Figure 2.
2.3. Establishment of vehicle finite element model

This paper focuses on the vehicle-induced vibration response of urban rail transit bridges under vehicle loads, including the vertical acceleration of the key nodes of the bridge structure, as well as the acceleration of various parts of the car body. According to the structural characteristics and calculation requirements, the vehicle structure is simplified appropriately. In the vehicle model, the vehicle system is simplified to one-half of the vehicle structure composed of mass, spring and damping, and the effects of the stiffness and damping of the primary and secondary springs between different mass blocks are considered. In this paper, a mass-spring-damper vehicle model is built based on the prototype of B-type Metro train. The main parameters of the train are shown in Table 1[6]. The simplified model of train load vibration is shown in Figure 3. Among them, M₁ is wheel set mass, M₂ is bogie mass and M₃ is full load vehicle mass; K₁ and K₂ are vertical suspension stiffness coefficient of vehicle primary system and vertical suspension stiffness coefficient of vehicle secondary system respectively; C₁ and C₂ are vertical suspension damping coefficient of vehicle primary system and vertical suspension damping coefficient of vehicle secondary system respectively. Although some factors affecting the vibration of the vehicle are ignored, this vehicle model can accurately simulate the vertical excitation load when the train passes the bridge.

| Name                                         | values |
|----------------------------------------------|--------|
| Vehicle body quality (no-load)/t             | 22.4   |
| Vehicle body quality (full load)/t           | 39.54  |
| Bogie quality (Power Bogie)/t                | 3.52   |
| Wheelset quality /t                          | 1.539  |
| A series of vertical suspension stiffness (per axis) / (MN/m) | 1.7    |
| A series of vertical suspension dampers (per axis)/ (kN·s/m) | 10     |
| Secondary vertical suspension stiffness (per axis)/ (MN/m) | 0.45   |
| Second-system vertical suspension damping (per axis)/ (kN·s/m) | 60 }
In ANSYS transient analysis, the moving vehicle load composed of mass-spring-damper system is applied to the bridge by the displacement contact method [7]. The interaction between the vehicle and the bridge is realized by the contact element, and the dynamic time-history response of the train passing through the bridge is obtained.

3. Damage location diagnosis for bridge based on vehicle-induced vibration response

The three-span urban rail transit bridge established in the second part is taken as the benchmark model in this part. The damage condition of the bridge is simulated by reducing the stiffness of some elements. The simulated damage element locates at one third of each bridge span, and the damage degree of the element is set as a 20% reduction of the stiffness of the element. The vibration responses of bridge and vehicle before and after damage are obtained by dynamic time history analysis. The feasibility of bridge damage diagnosis based on vehicle-induced vibration responses is studied by comparing the changes of vibration response of each measuring point before and after damage. The running speed of the train is 40km/h. The sampling rate of the responses are 100Hz.

3.1. Damage location diagnosis based on bridge vibration response

Three measuring points are respectively arranged on the midspan of each span of the bridge to study the sensitivity of bridge vibration responses to damage. Figure 4 shows the time history differences between the accelerations of each span from the intact and damaged bridge with unit stiffness of each span decreases by 20%, respectively.

From Figure 4 (a), it can be seen that the acceleration difference of each measuring point in the first span is obviously larger than that of the other two spans, no matter which span is damaged. This is because the initial displacement of the bridge is zero. At the initial moment when the vehicle load is applied, the impact effect of the vehicle load from scratch causes the vibration acceleration of the first span of the bridge to be larger, so the difference of acceleration between the measured points on the first span can not locate the damage of the first span and other spans. Figure 4 (b) shows that, when the damage occurs in the second span, the difference of acceleration in the second span is obviously higher than that in the other two spans. It can be seen from Figure 4 (c) that, when the damage occurs in the third span, the difference of acceleration in the third span is obviously higher than that in the other two spans. The above results show that, except for the first span, the acceleration response difference of the other span of the bridge can locate which span the single damage of the bridge occurs.

3.2. Damage location diagnosis based on vehicle vibration response

In this part, the vibration accelerations of wheelset, bogie and vehicle body mass are taken as the research object, and the difference between acceleration of each damage condition and that of intact structure is analyzed. The sensitivity of acceleration of each measuring point on the vehicle to damage is determined by comparing the variation law of acceleration difference. Figure 5 shows the acceleration difference time history curves of wheelset, bogie and vehicle body before and after the 1/3 span of each span of the bridge is damaged with 20% reduction of element stiffness.
Figure 4. Difference in acceleration from bridge after and before one third of each span is damaged

Figure 5. Difference in acceleration of vehicle after and before one third of each span is damaged

As can be seen from Figure 5 (a) and (b), when a single damage occurs at one third of the span of the bridge, the difference of the acceleration response between the wheelset and the bogie occurs obviously when the vehicle passes through the damage location of one third of the other spans (corresponding to 3.75s and 6.45s), except for the first span, because in the first span, the difference of the acceleration response between the wheelset and the bogie occurs obviously no matter if damage exists. When the vehicle has just entered the bridge, it produces a large impact load on the bridge, so the difference of acceleration at the first span position has a great change, which can not be used to identify the damage. Figure 5 (c) shows that the difference of acceleration response at the measured points on the car body is small, and there is no obvious change at the damage location. The above results show that, in addition to the first span, the specific location of the damage on the other span can be diagnosed by using the measured responses from wheelset and bogie.
4. Conclusions
Based on the engineering background of a urban rail transit bridge, this paper establishes a vehicle-rail-bridge coupling model. By simulating the different damage conditions of the bridge, the sensitivity of the acceleration response of the bridge measuring points and the vehicle body measuring points to the damage of the bridge is proved. A damage location method based on the difference of acceleration response of measuring point of the bridge and vehicle structure is proposed. The results show that except for the first span when the train crosses the bridge, the amplitude variation of the acceleration difference at the measuring points in the other span of the bridge can be used to locate which span the damage occurs, while the difference of the acceleration response between the wheel-set measuring point and the bogie measuring point in the vehicle system is more sensitive to the damage, and the specific location of the damage can be identified. It is proved that using the vehicle body vibration data as the medium can provide a new way for rapid diagnosis of damage location of urban rail transit bridges.

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References
[1] Ju B G 2015 Damage Diagnosis Study for RC Simple Supported Girder Bridges Based on Vehicle-Bridge Coupling Vibration (Harbin: Harbin Institute of Technology)
[2] Tian Q 2015 Identification of Bridge Damage Based on Bridge Dynamic Response Difference and Lifting Wavelet Transform (Tianjin: Tianjin University)
[3] Zhan L 2010 Damage Identification for Multi-Supported Beam Based on Wavelet Analysis (Qinhuangdao: Yanshan University)
[4] Zhang X D 2015 Resonance Response Analysis of Bridge Structures Under Vehicle-Rail-Bridge Coupling of High-Speed Railway (Wuhan: Huazhong University of Science and Technology)
[5] Li X P 2016 The Research on the Damage Identification of the Continuous Beam Bridge Under Moving Loads Based on Wavelet Analysis (Zhengzhou: Zhengzhou University)
[6] Chen Y B 2015 Moving System and Structure Interaction Analysis and Simulation by ANSYS (Shijiazhuang: Shijiazhuang Railway University)
[7] Wang X M 2016 Structural Dynamic Analysis and Application with ANSYS (Beijing: People's Transportation Press)