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Dynamic response of a train–bridge system under collision loads and running safety evaluation of high-speed trains

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ABSTRACT

Based on the authors' previous work, an extended study of the train–bridge system under collision loads is presented. A continuous bridge with box girders is considered as a case study. The dynamic responses of the bridge and the running safety indices of the train on the bridge under three types of collision loads are analyzed. Large responses of the bridge induced by collision strongly threaten the running safety of trains. An assessment procedure is proposed for the running safety of high-speed trains on bridges subjected to collision loads, and related threshold curves for train speed versus collision intensity are defined.

1. Introduction

Bridges are indispensable structures for crossing rivers, bays and other railway or highway lines, while sometimes they also become man-made obstacles against water flow or traffic underneath. With the rapid expansion of the infrastructure network in the past decades, more crossings are generated being the cause of many bridge collapse accidents due to vessel, vehicle and other collisions [1–4].

The factors producing bridge collapses can be divided into two categories: man-made and natural. The man-made factors include design faults, construction mistakes, collisions (by vessels, automobiles and trains), overload, etc. The natural factors include earthquakes, water flow (flood, scouring, etc.), wind, collisions (by floating floes or other objects), environmental deterioration (temperature, corrosion, etc.), etc. According to the statistics by Dong et al. [2] based on 502 bridge collapse accidents in 66 countries, there were 91 caused by various collisions (by vessels 56, trucks and trains 33, ice-floes 2). Only preceded by earthquakes, collisions constitute 18% of the total bridge collapses, as shown in Fig. 1. A similar investigation by Wardhana and Hadipriono [3] on 503 bridge collapses in the United States from 1989 to 2000 indicated that the most frequent causes of bridge failure were attributed to floods and collisions. Collisions from trucks, barge/ships and trains were responsible for 11.73% of the total bridge failures. A review by Hartik et al. [4] on 114 bridge failures in the United States over a 38-year period (1951–1988) showed that 17 events (15%) of them were due to truck collisions. These statistical data show that collision has become one of the leading causes for bridge failures.

When a collision load acts on a bridge pier or a girder, it may cause dislocation of bearings and girders, uneven deformation or fracture of expansion joints and even collapse of girders, resulting in serious accidents, as studied by many researchers [5–8]. For high-speed railway bridges, however, even if there is no girder collapse, the vibrations and displacements induced by the collision may deform the track and make it unstable. When the collision is intense and the train speed is high, the running safety of the train on the bridge may be seriously affected, and in the most serious case, the train may even derail from the track. The running safety is assessed by several indices: the derailment factor, the offload factor and the lateral wheel–rail force, which will be defined in detail in section 3.3.

There have been many studies focusing on the coupled vibration of the train–bridge system, and also its behavior under earthquake and wind loads [9–19]. However, up to now only a few papers have been published on the vibration of the train–bridge system induced by a collision load and its influence on the running safety of the train [20–22].

In a previous paper of the authors [22], a dynamic analysis model was established for the coupled train–bridge system subjected to a collision load. The dynamic responses of a

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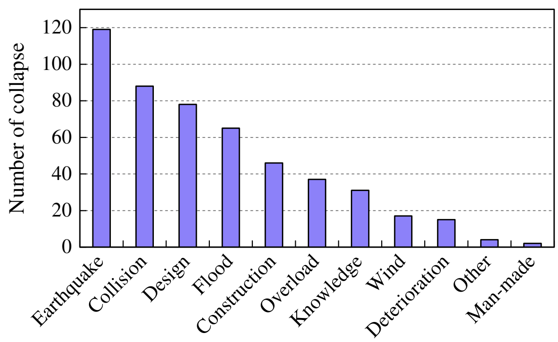

Fig. 1. Statistics of 502 bridge collapses in 66 countries.

7×32 m simply-supported railway bridge crossed by the high-speed China-Star train were analyzed when the bridge was subjected to ice-floe collision loads. Running safety indices of the high-speed train on the bridge were preliminarily evaluated.

For a bridge, the collision load considered in the design may be a vessel, an ice-floe, a vehicle or a train, and sometimes more than one of them. Since various collision loads have different properties, the dynamic responses of the bridge and their effects on the running safety of high-speed trains might be different. Moreover, a same collision load may exert different effects on the running safety of different types of trains on the bridge, which was already noticed during the dynamic analysis of high-speed railway bridges in China, when several types of trains were considered. To better study these differences, as a continuation of the authors' previous paper [22], this paper presents a more extensive and systematic study of the train–bridge system subjected to different collision loads. A continuous bridge with $(32+48+32)$ m box girders is considered as an illustrating case study. This bridge located in the cold region of China may suffer an ice-floe collision in winter and as well a vessel collision in summer, so both the two loads were considered in the design. Response histories of an ICE-3 high-speed train running over the bridge subjected to three types of collision loads are simulated. The displacement and acceleration responses of the bridge at pier-top and mid-span, and the running safety indices, such as the derailment factors, offload factors and lateral wheel/rail forces, of the train on the bridge are analyzed. A systematic parameter analysis is performed to study the influences of the type and running speed of the train, and the type and intensity of the collision load on the running safety indices. Based on these results, an assessment procedure for the running safety of high-speed trains on bridges subjected to collision loads is proposed, and related threshold curves for train speed versus collision intensity are defined.

2. Analysis model

The dynamic analysis model is established by adding the collision load applied on the bridge pier as an external excitation to the train–bridge coupled system model [19,23], as shown in Fig. 2.

In the model, the bridge is simulated by a finite element model, the train vehicles by multi rigid-bodies with elastic connections, and the wheel–rail relationship is assumed as close contact, without detach during the movement of the wheel on the rail. In the analysis, it is assumed that there is no relative displacement between the track and bridge deck, and the elastic effect of the track system is also neglected. The track irregularities are taken as system input that determine the relative displacement between wheel-sets and rails.

The equations of motion for the train–bridge system subjected to a collision load can be expressed as:

$$\begin{bmatrix} \mathbf{M}_{vv} & 0 \\ 0 & \mathbf{M}_{bb} \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{X}}_v \\ \ddot{\mathbf{X}}_b \end{Bmatrix} + \begin{bmatrix} \mathbf{C}_{vv} & \mathbf{C}_{vb} \\ \mathbf{C}_{bv} & \mathbf{C}_{bb} \end{bmatrix} \begin{Bmatrix} \dot{\mathbf{X}}_v \\ \dot{\mathbf{X}}_b \end{Bmatrix} + \begin{bmatrix} \mathbf{K}_{vv} & \mathbf{K}_{vb} \\ \mathbf{K}_{bv} & \mathbf{K}_{bb} \end{bmatrix} \begin{Bmatrix} \mathbf{X}_v \\ \mathbf{X}_b \end{Bmatrix} = \begin{Bmatrix} \mathbf{F}_{vb} \\ \mathbf{F}_{bv} \end{Bmatrix} + \begin{Bmatrix} 0 \\ \mathbf{F}_c \end{Bmatrix} \quad (1)$$

where **M**, **C** and **K** are mass, damping and stiffness matrices of the train–bridge system, $\mathbf{X}$, $\dot{\mathbf{X}}$ and $\ddot{\mathbf{X}}$ are displacement, velocity and acceleration vectors, respectively; $\mathbf{F}_{vb}$ and $\mathbf{F}_{bv}$ are interaction forces between vehicle and bridge, and the subscripts v and b represent vehicle and bridge, respectively. The components of these matrices

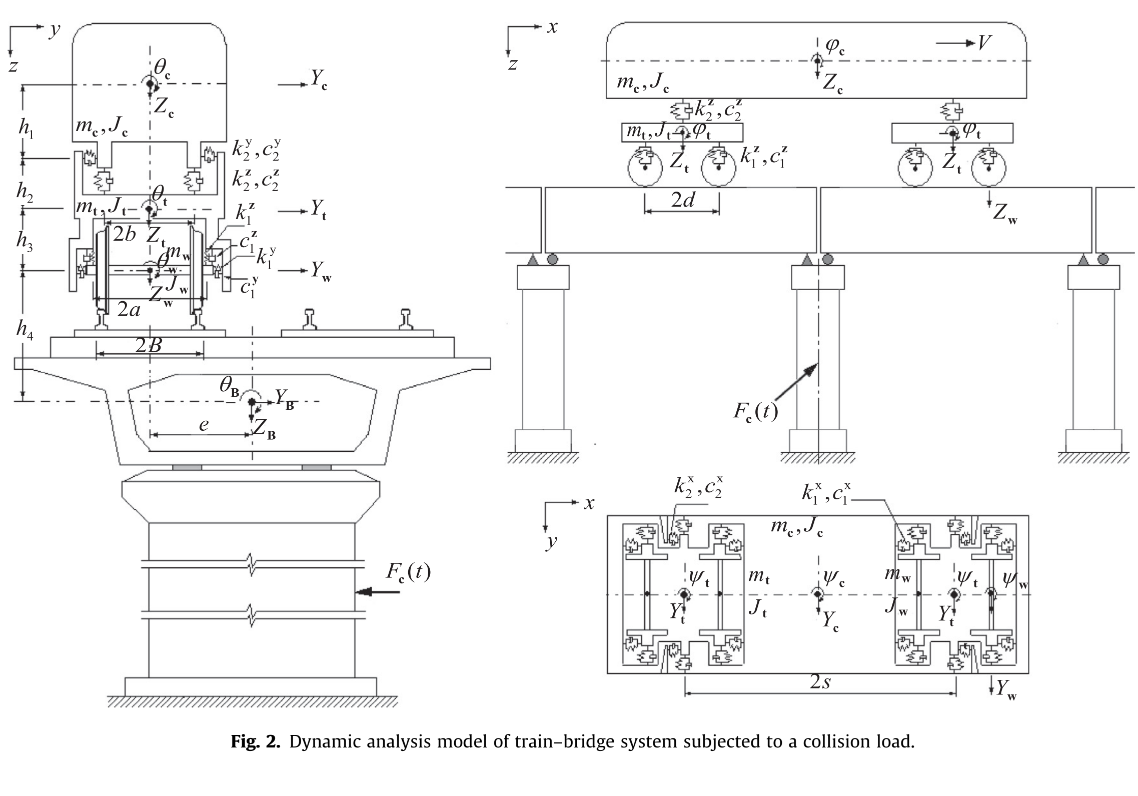

Fig. 2. Dynamic analysis model of train–bridge system subjected to a collision load.