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Development of a numerical model for bridge–vehicle interaction and human response to traffic-induced vibration

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ABSTRACT

The perceptible vibration of composite steel girder bridges under live loads is an important design consideration in today's bridges, which have longer spans and lighter decks than older bridges, and have with limited damping. Although, in accordance with the bridge design codes, the strength design and the deflection control of these bridges are covered fairly well, vehicle movement on the bridge may still cause vibrations that are too strong from the viewpoint of pedestrians. This investigation presents a comprehensive numerical model for studying bridge–vehicle interaction and the resultant perceptible vibration. 3D finite element models are developed for trucks, road surface and the composite girder bridge itself. Truck parameters include the body, the suspension and the tires. The bridge is treated as a 3D composite steel girder bridge on a simply-supported span. A parametric study is performed to identify the effect of various parameters on the vibration of the bridge, such as vehicle speed, neoprene stiffness, the effect of the aspect ratio (ratio of height to length) of steel girders, vehicle type, continuity of the deck slab on top of the pier and the initial bounce of the vehicle due to road surface roughness. The results have been expressed in the form of human perceptibility curves (graphs of perceptible vibration acceleration versus vibration frequency). This study finds that the bridge response is significantly influenced by the vehicle speed, stiffness of the elastomeric pad, continuity of the RC deck slab at pier and the ratio of vehicle weight to total weight of the superstructure, especially for values greater than 10%. In order to validate the proposed interaction model, dynamic field tests were performed on a simple span composite steel girder bridge, located downstream of Karkheh River Dam in Iran, which has significant vibrations under moving truckloads. The results show that the inclusion of features such as increasing the aspect ratio of steel girders and decreasing the number of expansion joints of the RC slab in the design has major effects on the reduction of perceptible vibration.

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1. Introduction

A bridge's vibration due to moving traffic is important for two reasons. First, the stresses are increased above those due to static load application. This is normally accounted for by the "impact factor" or "dynamic load allowance" in the design [7,8,14]. The second reason is that excessive vibration may be noticeable to persons on the bridge. Although not related to issues of safety, this may have the psychological effect of impairing public confidence in the structure and, therefore, demands consideration at the design stage [16].

In the pseudo-static design of structural members, the basic assumption is that the load acceleration applied to the structure is zero and the response of the structure is also free from acceleration, so that at each loading step, there is sufficient time to establish a balance between the external effective forces and the internal resistance elastic forces while inertia forces are zero. Most common situations can be classified as such since the dynamic involved is too low to produce any meaningful inertia effects. However, there are many situations in which the loading and the response are dynamic, such as vehicle/train bridges and rotary machine foundations (foundations that support centrifugal and reciprocating machines) [19,22,23].

The impetus for analyzing the effects of moving loads on bridge structures was the rapid development of railroad transportation in the nineteenth century and the growing need for constructing bridges to help with the expansion of the industrializing world. While the first 100 years of the investigations are interesting historically, more notable studies occurred in the second half of the twentieth century and up to the present. Past studies have shown that the dynamic response of a bridge depends on the dynamic properties of the vehicle, the dynamic properties of the bridge, and the bridge's pavement roughness. Vehicle properties include

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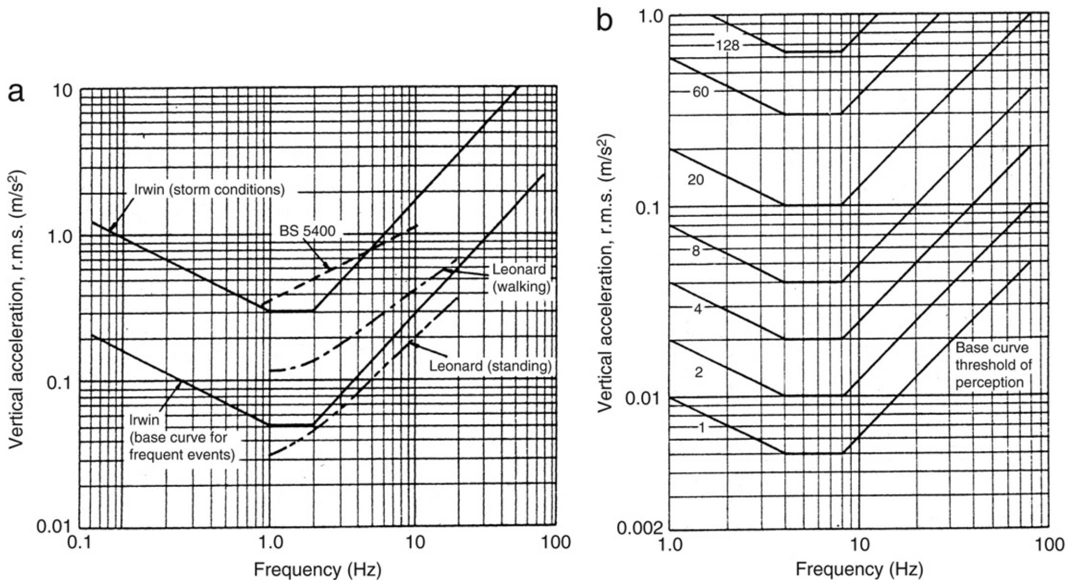

Fig. 1. (a) Human response to the vertical component of bridge vibration, (b) Combined direction criteria curves for vibration in buildings.

the self-weight, physical dimensions, and mechanical properties of the suspension system and the tires. Bridge properties include the mass, flexural stiffness, span length, and elastomeric bearing characteristic. The pavement roughness is determined by the surface condition of the approach and the bridge [1]. Some researchers suggest that other parameters, including the ratio of live load to dead load, tire stiffness and suspension stiffness, vehicle speed and bounce on suspension, also affect a bridge's dynamic response to the passage of a vehicle [2,3,13,14,37].

In theory, bridge response cannot be separated from the vehicle loading, since the response of a real bridge affects the wheel loads that initiate the original response. Therefore an iterative analysis is required at each time step to ensure compatibility between the suspension, the bridge deflections and the interacting forces. A number of theoretical studies have been performed for road vehicles and rail vehicles in which multi-degrees-of-freedom vehicle models have been used in conjunction with theoretical road surface profiles and elastic bridge models in order to model the interactions between bridge and vehicles, and thus to obtain the bridge responses [9,28,36,37].

Today, thanks to the powerful computers and the availability of advanced numerical methods, two- or even three-dimensional numerical modeling of bridge vibrations is within reach. Such an analysis however is not performed by most of the medium-sized consulting firms for two reasons; firstly it requires a high level of expertise that may need to be sourced from outside of the firm, and secondly it is time consuming and therefore costly. For these reasons, engineers prefer to have some in-house rules that help them with minimizing the vibration of bridges. The current study is an attempt in that direction.

In this study, the main goal is to provide basic rules and design guidelines for the design of steel girder bridges, based on numerical simulation of bridge–vehicle interaction, including dynamic modeling of vehicle, composite steel girder bridge and Neoprene bearings. An existing bridge on Karkheh River, which suffers from excessive vibrations of the deck, was selected for the study. Human perceptibility curves were graphed and different parameters affecting vibration perception were studied. Based on the parametric study, several simple design rules are presented for reducing/preventing the vibration problems of composite steel girder bridges. These rules are straightforward enough to be used by design engineers, eliminating the need for them to perform a full dynamic analysis such as this one.

2. Human response to bridge vibration and human perceptibility base curve definition

Human beings are surprisingly sensitive to vibration and are often disturbed by intensities that are well below those required to overstress the structures they inhabit or use. Therefore, in the design of structures, human response to vibrations caused by frequent sources of dynamic loading, e.g. wind, or the passage of vehicles, should be regarded as a serviceability limit state. Extreme loading, e.g. due to earthquakes, would be considered an ultimate limit state, and dynamic stress should be kept below the levels likely to cause collapse.

Because of their structural form, being wide but shallow in depth, bridges are predominately susceptible to vertical, torsional and coupled mode vibrations [30], all of which induce a vertical component of vibration in the bridge's deck. The only exception is the wind-induced horizontal oscillation occurring in very long suspension bridges [6].

In general, several factors influence the level of perception and the degrees of sensitivity of people to vibration. Among them, one can note position of the human body, excitation source characteristics, exposure time, floor and deck system characteristics, level of expectancy and type of activity engaged in [11,15,21,38]. Higher values of vertical motion are acceptable in bridges, when compared to residential or office buildings, because users are out in the open and are more aware of the presence of wind or traffic. Furthermore, people crossing a bridge are exposed to vibration for a relatively short period of time.

Smith [6] presents the work of Irwin, who suggested a base curve for acceptable human response to the vibration of a bridge under frequent forms of loading. This is shown in Fig. 1(a). For comparison, ISO combined direction criteria curves for transient vibration in buildings are shown in Fig. 1(b). Since the magnitude of acceptable vibration depends on the circumstance (such as exposure time and type of activity engaged in), ISO suggests specifying satisfactory vibration levels in terms of multiples of a base curve. In this graph, which is the base curve (shown with index 1), curves corresponding to index values 1, 30–90, 60–128 and 90–128 represent base curves for critical working areas (such as hospitals and precision laboratories), residential buildings, offices and workshop places, respectively [11,38]. According to ISO, at vibration magnitudes below the relevant curve, complaints

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