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Finite element modeling of the impact of heavy vehicles on highway and pedestrian bridge decks

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Abstract

Collisions of over-height vehicles, such as tipper trucks or exceptional convoys, with highway and pedestrian bridge decks can compromise the safety of road users and cause major economic losses due to road closures required by structural inspections and urgent repairs. Several studies proposed to reduce the probability of occurrence of such events by using steel pedestals, static road signs or impact detection systems. In spite of these preventive solutions, bridge decks are still frequently impacted by heavy vehicles as a result of the densification of transportation networks. In this study, a practical finite element approach is proposed to investigate the key parameters influencing the dynamic response of a bridge deck subjected to an impact from an excavator or other heavy construction equipment trailed on a flatbed truck. The developed finite element models are used to carry out a parametric study on vehicle-bridge systems with varying properties such as the lateral stiffness and mass of the bridge deck, and the mass and the velocity of the colliding vehicle. It is first shown that contact compliance is a critical factor that should be selected carefully after several numerical tests supported by engineering judgment. The obtained results confirm that dynamic effects are key factors to be taken into account when studying vehicle-bridge collisions. The trends characterizing the collisions between a heavy vehicle and the bridge deck are studied in terms of contact forces and their duration, the structural response of the bridge deck, as well as kinetic energy of the impacting vehicle. Some of the results obtained are compared to analytical predictions proposed in Eurocode.

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Keywords: Collision, Impact, Dynamic Loads, Bridge Decks, Finite Elements, Eurocode, Compliance, Heavy Vehicle, Contact.

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1. Introduction

Bridges are subject to extreme events such as earthquake, wind, fire, explosion or impact loads. Among these, vehicle-bridge collisions may compromise the safety of users and cause major economic losses due to road closures

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required by structural inspections and urgent repairs. As illustrated by Bayley [1], vehicle impacts are even the first cause of bridge collapses in the world, with 22% of the reported cases. Most of these failures occurred in Europe (47%) and North America (34%). For example, in 2013, on the highway between Seattle and Vancouver, a truck hit and destroyed a girder of the Skagit River Bridge, causing its collapse. The bridge, which hosted 71,000 vehicles a day, had to be rebuilt at a cost of nearly US$ 20 million [2]. About 250 vehicle-bridge collisions are reported each year in France, Germany and United Kingdom [3]. In Beijing (China), 50% of bridge decks have been struck by vehicles [4]. In the state of Massachusetts (United States), an average of 126 vehicles hit bridge decks every year between 2002 and 2013. In Texas (United States), this number reaches 172 vehicle-bridge collisions every year between 2010 and 2014. A recent example of a heavy vehicle impacting a bridge superstructure occurred in L'Assomption (Quebec, Canada) in June 2016. A truck carrying an excavator hit the bridge deck damaging several girders, as illustrated in Fig. 1. The overpass had to be closed in one direction for several months, awaiting for repair interventions. This closure had a significant effect on the local population.

Fig. 1. Impact on girders (Photo: Edouard Berton)

Finite element modelling of impact loads and their effects can provide useful insight on the effects of impact loads on bridge decks [4]. However, an appropriate level of expertise is required for an efficient and correct use of such approach. Some key modelling issues are presented in this paper. The developed models are used to carry out a parametric study to determine most important factors affecting the nonlinear dynamic response of bridges submitted to a heavy vehicle collision.

2. Vehicle impact forces according to Eurocode

Eurocode 1 (Part 7) addresses accidental loads on bridges, including collisions from road vehicles, vessels, trains, etc. [5]. It provides values for impact loads on bridge decks with vertical clearance less than h_1 (recommended value of 6.0 m), otherwise no such loading needs to be considered. The indicative static design force equivalent to an impact load on bridge decks with vertical clearance lower than h_0 (recommended value of 5.0 m) are given depending on the category of traffic. For vertical clearance between h_0 and h_1, the impact force can be multiplied by a reduction factor r_F varying from 1 to 0. An impact-equivalent static force can also be applied on the underside of a bridge deck considering an upward inclination (recommended value of 10°). The informative Annex C of Eurocode 1 (Part 7) presents guidelines to conduct simplified design of bridge superstructure accounting for dynamic effects induced by vehicle impact. Two types of impact events can be distinguished: (i) hard impact where energy is assumed to be mainly dissipated by the colliding vehicle, while the impacted structure is assumed rigid and immovable, and (ii) soft impact where the bridge deck is assumed to absorb the energy generated by the impact, while the colliding vehicle is assumed rigid. The maximum dynamic interaction force F between the colliding vehicle and the impacted structure can be estimated as [5]

$$F = v\sqrt{k\,m} \tag{1}$$

in which v and m denote the velocity (m/s) and the mass (kg) of the colliding vehicle, respectively, whereas k represents the equivalent elastic stiffness (N/m) of the vehicle or the bridge structure for hard or soft impacts, respectively. This equation is based on the equality between kinetic energy of the colliding vehicle, and the strain energy developed in the impacted structure. The predictions of Eq. (1) will be compared later to results from finite element analyses. In the next section, the finite element modelling approach proposed to investigate the collision between a vehicle and a bridge deck is described.

3. Finite element modeling

This section describes the construction of the 3D finite element (FE) models and analyses conducted to characterize a collision between a heavy vehicle and a bridge deck. The modelled heavy vehicle consists of a truck trailer carrying an excavator or other similar heavy construction equipment. The truck flatbed is modelled as a rigid shell, sliding over the road surface. For simplicity, the top of the shovel arm of the excavator is represented by a rigid rectangular plate, modelled using shell elements, and connected to a nodal mass through rigid links, as illustrated in Fig. 2 The top part of the excavator is attached to the base of the trailer using rigid links to account for lever arm effects during impact. The bridge deck is modelled as a rectangular slab using 3D solid elements. The finite element mesh of the deck is optimized for computational efficiency. It varies from very refined at the vertical face of the slab, where contact occurs, towards a progressively coarser mesh at the other side of the bridge deck. This simplified modelling approach of the vehicle and the impacted structure was adopted to avoid accounting for the complex geometrical details of various heavy construction equipment and bridge decks, while preserving the general validity of the results. Frictionless contact elements are defined on the plate at the top of the excavator, and on the front vertical face of the bridge deck. Frictionless contact elements are also introduced at the interface between the truck flatbed and the road surface. A contact surface compliance factor is considered as will be discussed later. All materials are assumed elastic and large displacements are considered. The implicit Bathe time integration method is used [6]. In this scheme, each time step Δt is divided into two sub-increments. In the first one, unknown variables are solved at a time $t + \gamma \Delta t$, where γ value is 0.5. In the second sub-increment, unknown variables are solved at both times t and $t + \gamma \Delta t$.

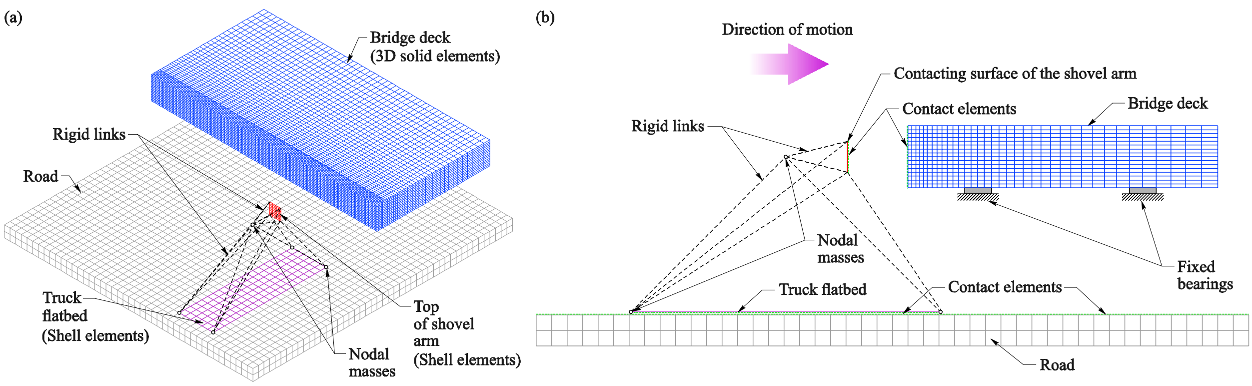
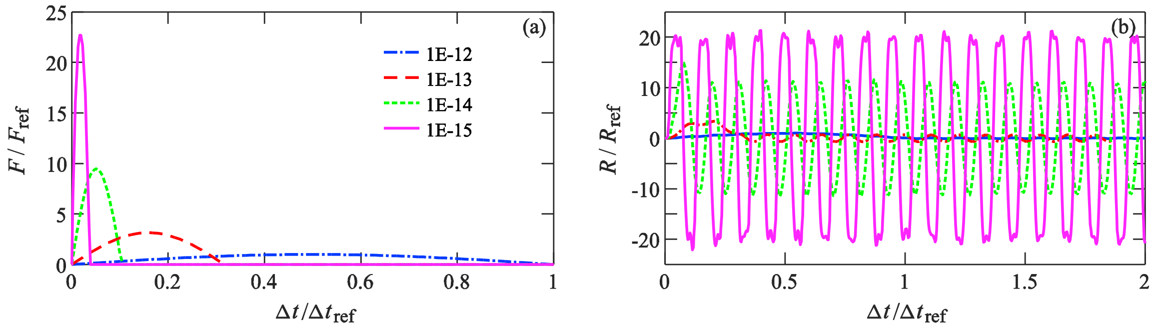


Fig. 2. Finite element models of a heavy vehicle impacting a bridge deck: (a) 3D view, and (b) 2D view.

The commercial software ADINA [6] was used to construct the finite element models and perform the nonlinear dynamic impact analyses. Some of the results are presented and discussed in the next section.

4. Results and discussion

This section presents selected results from the nonlinear dynamic analyses conducted using the finite element models described previously. To facilitate the presentation and interpretation of the results, the following reference properties are introduced: Mass of the bridge deck $M_{\text{ref}} = 1000$ tons; the static lateral stiffness of the bridge deck $K_{\text{ref}} = 1.6\times10^{10}$ kN/m; the mass of the impacting vehicle $m_{\text{ref}} = 10$ tons and its initial velocity $v_{\text{ref}} = 20$ m/s (72 km/h). The results corresponding to these properties will be denoted by the subscript 'ref' in what follows. Contact surface compliance, which accounts for the softness of the contact surfaces, can have a major influence on impact characteristics, namely induced contact forces and load duration [7]. A null compliance value corresponds to a perfectly rigid contacting surface. Assuming a non-null compliance value means that some interpenetration, i.e. overlap, is allowed between the contactor and the target surfaces. In general, a certain value of compliance has to be included in the models to avoid numerical instabilities. However, there is no systematic method, other than trial and error, to determine the appropriate amount of compliance to be considered as this depends on the type of dynamic impact problem being solved. A starting value of about 10^{-4} is generally selected, and then diminished depending on the results. In the present case, compliance values larger than 10^{-11} induce complete continuous overlap between the vehicle and the bridge deck, i.e. contact interfaces are not detected. Accordingly, a compliance factor $C_{\mathrm{ref}} = 10^{-12}$ is considered, as well as lower compliance values of 10^{-13}, 10^{-14} and 10^{-15} to evaluate the effects on the results. Figure 3 illustrates the variation of the nondimensional vehicle-bridge contact force F/F_{ref} and bridge deck reactions R/R_{ref} as a function of nondimensional duration $\Delta t/\Delta t_{\mathrm{ref}}$ of the impact. As can be seen and as expected, a smaller value of compliance induces larger contact forces and reactions in the bridge superstructure. These results emphasize the high sensitivity of the impact response of the bridge to the selected values of compliance, i.e. F/F_{ref} and R/R_{ref} increase from 1 to 22.7 and 1 to 20, respectively, when the compliance factor is decreased from 10^{-12} to 10^{-15}. The duration of impact is also significantly affected by the selected value of contact compliance, i.e. a reduction of $\Delta t/\Delta t_{\mathrm{ref}}$ from 1 to 0.04 when the compliance factor is decreased from 10^{-12} to 10^{-15}. Figure 3(b) reveals the larger



fluctuations of the reaction forces at the bridge bearings, i.e. structural response, as contact compliance is lower. Such fluctuations correspond to more significant impact-induced dynamic effects propagating within the bridge deck.

Fig. 3. Effects of contact surface compliance on: (a) contact forces, and (b) bridge deck reactions.

Figure 4 (a) illustrates the effects of contact compliance on the nondimensional kinetic energy $E_{\mathrm{k}}/E_{\mathrm{k,ref}}$ of the vehicle. In all cases, the kinetic energy of the vehicle decreases from a maximum value corresponding the pre-impact initial velocity of the vehicle, to a null value at the most intense phase of the impact, i.e. null relative velocity, and then to a restituted post-impact value. It is observed that smaller values of contact compliance, i.e. 10^{-14} and 10^{-15}, induce a lower post-impact kinetic energy of the vehicle, i.e. $E_{\mathrm{k}}/E_{\mathrm{k,ref}} = 0.95$ and 0.65 respectively. On the opposite, the vehicle totally recovers its initial impacting kinetic energy when larger values of contact compliance are adopted, i.e. 10^{-12} and 10^{-13}.

To further assess the effects of compliance, it is also important to evaluate induced contact overlap, i.e. interpenetration. The sensitivity of nondimensional contact overlap d/d_{ref} to compliance factors is illustrated in Fig. 4 (b). It is clearly seen that interpenetration increases with higher compliance values. However, acceptability of maximum interpenetration values should be assessed in relation with anticipated maximum normal contact stresses, given by the ratio of contact overlap over compliance, i.e. d/C. This discussion confirms the importance of conducting several numerical tests, supported by engineering judgment, to select appropriate values of contact compliance in the investigation of vehicle-bridge collisions. Based on the above considerations, a value of $C_{\mathrm{ref}} = 10^{-12}$ is adopted for the rest of the paper.

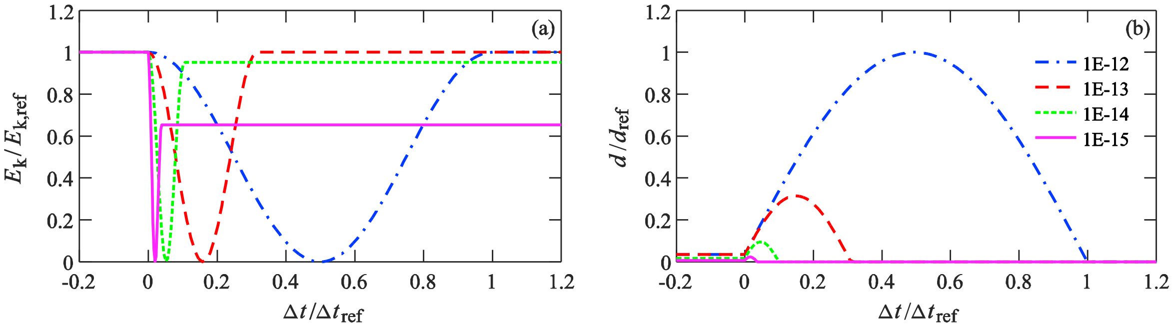


Fig. 4. Effects of contact surface compliance on: (a) kinetic energy of the colliding vehicle, and (b) contact overlap

To investigate the effects of lateral stiffness of the bridge deck, the maximum nondimensional contact forces F_{max}/F_{ref} are computed for different values of nondimensional lateral stiffness K/K_{ref} varying from 10^{-5} and 10^{15}. The obtained results are illustrated in Figure 5(a). It is seen that maximum contact forces reach a maximum beyond a certain value of bridge deck lateral stiffness, i.e. $K = 0.1K_{ref}$. The predictions of the simplified approximation in Eq. (1) are also plotted on the same figure for comparison purposes. As can be observed, the agreement between the trends of finite element results and the analytical predictions is satisfactory for nondimensional lateral stiffness values below $0.1K_{ref}$. Trend discrepancies between predictions of Eq. (1) and finite element results become more important for stiffer bridge decks, i.e. higher values of K/K_{ref}. Figure 5(b) presents the nondimensional maximum contact forces generated by the same colliding vehicle of mass m_{ref} impacting bridge decks having the same lateral stiffness K_{ref}, but with masses varying from $0.1M_{ref}$ to M_{ref}. The constant maximum contact forces obtained confirm the negligible influence of the mass of the bridge deck, which is significantly larger than the vehicle mass, on impact response. Such influence is also neglected in the approximation of Eq. (1).

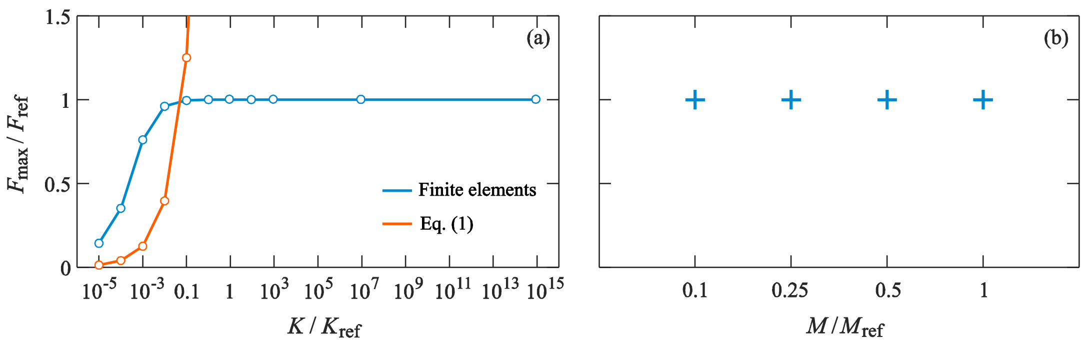


Fig. 5. Sensitivity of maximum contact forces to: (a) the lateral stiffness of bridge deck, and (b) its mass.

The influence of the mass of the colliding vehicle and its initial velocity are investigated next. Figures 6(a) and (b) present the variation of the nondimensional vehicle-bridge contact force F/F_{ref} and bridge deck reactions R/R_{ref} as a function of nondimensional duration $\Delta t/\Delta t_{ref}$ of the impact generated by colliding vehicles having the same initial velocity v_{ref}, but different masses $0.5m_{ref}$, m_{ref}, $4m_{ref}$, and $8m_{ref}$. These results confirm that maximum contact force is roughly multiplied by $\sqrt{\alpha}$ when the vehicle mass is multiplied by a factor α, which agrees with the predictions of Eq. (1). Figures 6 (a) and (b) also show that impact durations increase with heavier colliding vehicles. The same type of impact responses is illustrated in Figs. 6 (c) and (d) considering impact generated by colliding vehicles having the same mass m_{ref}, but different initial velocities $0.7v_{ref}$, v_{ref}, $1.3v_{ref}$, and $1.7v_{ref}$. As predicted by Eq. (1), maximum contact force increases linearly with the velocity of colliding vehicle. Impact duration remains constant irrespectively of the initial velocity of the impacting vehicle.

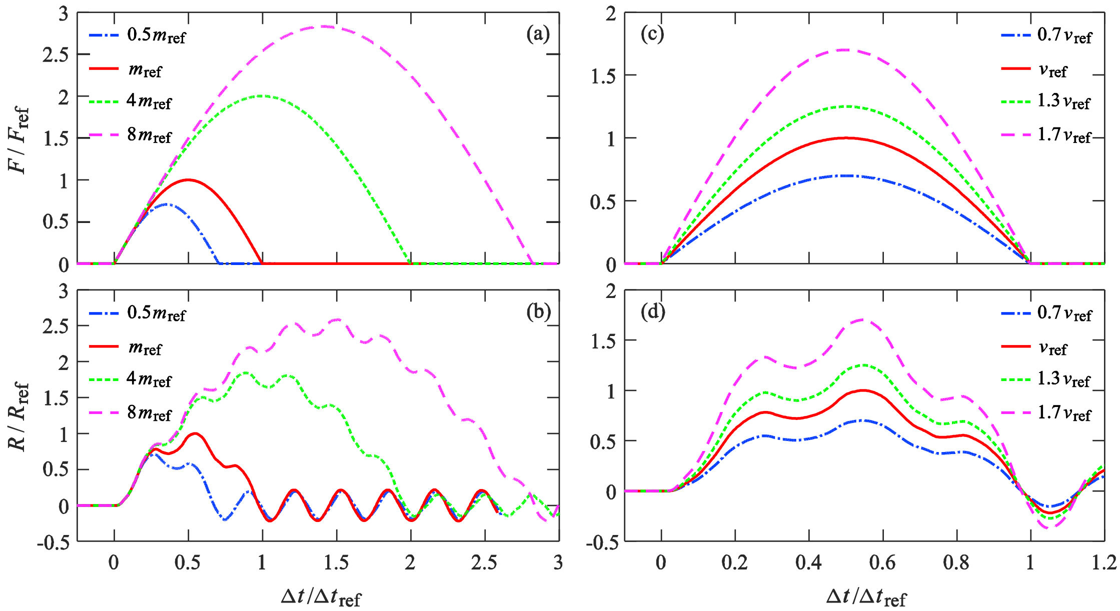


Fig. 6. Effects of vehicle's velocity and mass on collision contact forces and bridge reactions

5. Conclusions

Bridge decks are frequently impacted by heavy vehicles as a result of densification of the transportation networks. Such events can seriously compromise the integrity of bridge structure and the safety of road users. Recurrent accidents of the past few years call for a better understanding of these vehicle-deck collisions. This paper presented a finite element modelling approach to investigate the key parameters influencing the dynamic response of a bridge deck subjected to an impact from an excavator or other heavy construction equipment trailed on a flatbed truck. The following main conclusions can be drawn: (i) contact compliance is a critical parameter that should be selected carefully for such type of analyses, (ii) maximum contact force reach an upper bound limit for stiffer bridge decks, (iii) contact force is not influenced by the mass of bridge deck, (iv) heavier and faster vehicles induce larger contact forces. It is worth noting that the finite element models and the results presented in the paper were provided to mainly illustrate the basic trends describing complex impact behaviour, and to emphasize important modelling issues. The models have to be refined further to account for other key factors such as the flexibility of the impacting vehicle and the impact-induced material damage.

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