Effect of five versus two axle moving trucks on structural dynamic performance of frame bridges

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Abstract. Recent advances in analysis, and design approaches led to a considerable reduction of the structural elements' size and weight. Heavy multi-axle trucks are now standardized in North America, and elsewhere, the traffic speed and the average number of trucks passing bridges have dramatically increased. For the purpose of the design and/or assessment of bridge structures, it is imperative to evaluate the static deformations, frequency, vibration amplitudes, and dynamic deformation patterns of new and aged bridges due to the new five-axle versus the old two-axle design trucks. This study investigated the effects of using a recent standard multi-axle design truck on the dynamic performance of a frame bridge. It presents a comparison of the bridge dynamic performance under 2-axle and 5-axle moving trucks. A two-dimensional nonlinear finite element model is used to model the frame, and trucks are modelled as a multi-degree of freedom dynamic system integrated with the bridge model. It is found that the model is able to capture the local dynamic excitation and oscillations results from the high variation of the stiffness and mass of the bridge components.

1. Introduction

Recent advances in design approaches have driven to a major reduction of the weight and size of the structural elements. On the other hand, heavy multi-axle trucks are now standardized in North America and elsewhere, and the traffic speed and the rate number of vehicles passing bridges have considerably increased. For the purpose of the design and/or assessment of bridge structures, it is necessary to assess the static deformations, frequency, vibration amplitudes, and dynamic deformation patterns of bridges due to the new five-axle versus the old two-axle design trucks.

Frame bridge type was developed in the mid-twentieth century as a cost-effective and attractive alternative to the conventional arch bridge, which required massive abutments and significant excavation/grading to accommodate its relatively high profile. A concrete rigid frame bridge's strength originated from the rigid connection of the vertical abutment walls with the horizontal deck slab, resulting in a shallow mid-span section. The frame bridge type has a unique ability to redistribute loads throughout the structure until it reached a balance if any one element of the bridge is overstressed. Its immense strength and rigidity provide additional safety to the structural system. The result is a bridge that provides greater structural strength and redundancy than other types of bridges such as reinforced concrete slab-on-girders bridges. However, the frame bridge's sensitivity to traffic-induced vibration would be increased due to its structural continuity. By the 1940s and 1930s, frame bridges became more common to use for grade separations and river crossings. Medium and short span rigid frame concrete
bridges are widely employed rail/roadway grade separations in urban areas with constrained right-of-ways or with minimal vertical and/or horizontal clearances.

This study aims at investigating the effects of using a recent standard multi-axle design vehicle on the structural behavior of frame bridges. It aims to compare the bridge’s dynamic performance under 5-axle versus 2-axle moving trucks. In this study, the frame bridge is modeled as a rigid frame using a two-dimensional nonlinear finite element model. The trucks are modeled as a multi-DOF dynamic system incorporated with the bridge model.

2. The bridge structure modelling and traffic load modelling

Modelling the effects of dynamic interaction between trucks and bridge systems has been of interest to bridge engineers [1-4]. The vehicle is introduced as a multi degrees-of-freedom (DOF) system united with the structure (bridge) into a unified dynamic system represented by the differential equation of motion. All the mentioned studies considered only the bridge superstructure ignoring the effects of substructure stiffness and superstructure-substructure connection on the vibration pattern and amplitude. Consequently, previous studies results have not addressed: (i) the significant effects of the traffic load on the dynamic behavior of the substructure; or (ii) the effect of the variation of substructure stiffness and the bridge structural system internal boundary conditions or continuity on the dynamic behavior of the superstructure. In this study, an RC frame bridge structure under a moving truck is modelled as two dimensional structural systems using the finite element analysis. Three types of analysis are carried out: static analysis, free vibration dynamic analysis, and time history dynamic analysis.

A flowchart of a finite element model approach (FEMA) developed in [5] is shown in Figure 1. The approach includes performing static analysis and time history analysis of the applied (traffic) load. FMA employs nonlinear analyses of the structure under traffic load, where all the bridge structural elements matrices (mainly stiffness, mass and damping) are updated at each new location throughout the truck movement over the bridge deck. As the truck moves, the loads on each bridge element vary. Then, the static analysis is performed on the bridge structural elements to compute the elements’ mass and stiffness, and hence estimate the damping as it is assumed proportional to the element mass and stiffness. The instantaneous global dynamic matrices are then assembled into the equation of motion in every step of integration of the time history analysis.

2.1. The bridge structure model

A rigid frame bridge is a bridge in which the superstructure and substructure are rigidly connected to act as a continuous unit. Menially, the bridge’s continuous structural system is formed by rigid joints between the two parts: the superstructure and substructure. This continuity leads to vibration waves propagating across the whole bridge if it is exposed to highly vibration excitations. The framed bridge structure is divided into three major components: the superstructure component representing horizontally and the two substructure components representing vertically or diagonally. The bridge
structure is modelled using with two nodes and, and the three parts of the structure are assembled as a two-dimensional structural system; each of the bridge parts was considered as a composite section. The self-weight of each element is modeled as a uniform gravity load. The bridge damping matrix of the bridge is assumed linearly proportional to its stiffness and mass matrices.

2.2. Modelling the vehicle

2.2.1. Two-axle moving truck. A two-axle moving truck is modeled as a 2-DOF system: rotation and vertical displacement. The two axles of the truck are assumed to be in contact with the bridge structure (superstructure), where (i) the vertical vibration of the truck is only considered, and (ii) The force load of the truck-bridge system is taken as a point load moving along the superstructure. The governing equations of the moving dynamic system and the bridge are presented by [1].

2.2.2. Five-axle moving truck. The five-axle vehicle representing the CHBDC design truck [6] is modeled as a multi-degrees of dynamic freedom system (MDFM-DS). The vehicle MDFM-DS has eight independent degrees of freedom. The mass, damping, and stiffness matrices of the vehicle are adopted from [7]. It is considered that the five axles of the truck remain in contact with the bridge superstructure at all times. Only the vertical vibration is considered. The governing equations of the dynamic system and the bridge are adopted from [1]. The vehicle and the dynamic bridge systems are integrated into one dynamic system. A step-by-step integration method is used to solve the resulting matrix equation of motion.

3. Case study

A concrete frame bridge built in 1964 has been selected for the following case study. The bridge structure is modelled as a dynamic system subjected to a moving load. The bridge has (i) a central span of 28.8 m and two “overhang” side spans of 13.71m each of a single reinforced concrete rigid frame bridge, and (ii) two inclined walls. The connections of support are (i) rollers at the ends of “overhang” side spans of the superstructure; and (ii) pinned at the inclined concrete walls connection to the foundation. The rigid frame section has a variable thickness over each component. The frame bridge longitudinal section is shown in Figure 2. As the bridge was designed in 1964, the compressive strength of the concrete ($f_c$) is 20MPa, and the truckload is designed according to AASHO H20-516-44; however, the detailed characteristics design of the considered bridge is beyond the scope of the paper work. Two design truckloads have been used in this study to compare the dynamic performance of the bridge: (i) two-axle moving truck which has 34,400kg mass, where 30,000 kg is the body mass, 2,800 kg is the front axle mass, and 1,400kg is the rear axle mass. The truck mass moment of inertia is 2.63 x 105 kg.m², the stiffness of each axle is 5,363 kN/m and the axle spacing is 6.91 m [8]; and (ii) five-axle moving truck which represents the design truckload of CHBDC CL625 [6].

On the other hand, it is imperative to ensure the originality and accuracy of the results obtained from the DFEM of this concrete rigid frame bridge under traffic load; therefore, convergence studies have been conducted as shown in Section 3.1 and 3.2 where the truck speed is equal to 100km/h.

3.1. Bridge structure under a two-axle moving truck

Two convergence studies have been conducted for the concrete rigid frame bridge under a two-axle moving truck, for both convergence studies. The convergence study 1 of the structure under a two-axle
moving truck is shown in Figure 3a; in this convergence, the number of superstructure elements (NE) is constant, and the integration points number (NI) is changed from 5 to 100. It can be seen that the variation/fluctuation in the deformation behavior is insignificant after NI=30. In case of second convergence, NI is considered to be specified as NI= 80, and the element numbers (NE) differs from 10 to 120, Figure 3b. The results become stable after NE =20, and the dynamic deflection change becomes negligible as a result of increasing the number of elements, Figure 3b. In this case, it is observed that further increase of the number of elements and/or the number of integration points to a reasonably high number would not result in a round-off error, which reflects the high numerical stability of the model.

![Location of front axle(m) vs Deflection(mm) for NI=5 to 100](image1)

![Location of front axle(m) vs Deflection(mm) for NE=10 to 120](image2)

Figure 3. (a) Convergence study 1 of the frame bridge under a two-axle moving truck; (b) Convergence study 2 of the frame bridge under a two-axle moving truck.

3.2. Bridge structure under five-axle moving truck

For a five-axle moving truck, which represents the design truckload of CHBDC CL625, similar convergence studies have been conducted; however, the minimum length of the element segment should be greater than the axle width tire, which is equal to 0.25 as specified in [6]. In this case and for convergence study 1, the NE is constant (NE= 80), and the NI changes from 5 to 80. Figure 4a displays the deformation behavior below the truck's third axle along the span length of the superstructure for variable NI. It is clear that after NI = 30, the variation in the deformation is very minor. In convergence study 2, the integration point numbers is stable (NI= 50), and the element numbers is changed from 20 to 100. As shown in Figure 4b, the results become stable after NE =40, and the dynamic deflection change becomes negligible as a result of increasing the number of elements.

![Location of 3rd axle(m) vs Deflection(mm) for NI=5 to 30](image3)

![Location of 3rd axle(m) vs Deflection(mm) for NE=20 to 100](image4)

Figure 4. (a) Convergence study 1 of the frame bridge under a two-axle moving truck; (b) Convergence study 2 of the frame bridge under a two-axle moving truck.
3.3. Performance of the bridge components under two-axle versus five-axle moving trucks

Integrating the results of the dynamic deformations for the vertical displacement under the truck axles (Figure 5a and Figure 5b) gives a view of the oscillation pattern of the frame bridge system. The vertical displacement is growing downward when the truck (two or five-axle) is crossing the bridge at a speed of 100 km/h. The deformations due to the moving of a 5-axle truck are more than double the deformations due to the moving of a 2-axle truck. When the axles pass over these connections, the exceptionally joint’s very high stiffness linking the inclined walls to the horizontal part “superstructure” reduces the vertical displacement significantly. On the other hand, in both cases of two and five-axle trucks, the sudden fluctuation and peak vibration amplitude happened when the rear axle (fourth and fifth axles in case of 5-axle truck) entered the bridge, which can be explained by (i) high mass over the truck rear axles, (ii) the possible local dynamic excitation of the two-depth part of the superstructure at the two overhangs that results in high local oscillation, and (iii) high rigidity and continuity of the bridge.

The lateral and axial displacements at the top and mid-height of the two inclined walls for both cases are shown in Figures 6a, 6b, 7a, and 7b, respectively. The figures show that when the truck is crossing the bridge: (i) the two rollers in the top supports allow the frame to sway horizontally; and (ii) the left wall moves to the right side and slightly downward, the right wall moves oppositely to the left and slightly upward. However, the lateral and axial displacements due to the heavier multi-axle truck (five-axle) are much higher than those correlated displacements due to two-axle. For instance, the lateral displacement ranged between 20mm and -20mm in the case of moving five-axle truck while it ranged between 5mm and -5mm in case of moving two-axle truck.

![Figure 5](image)

**Figure 5.** (a) The bridge superstructure dynamic deflection under 2-axle moving truck; (b) The bridge superstructure dynamic deflection under 5-axle moving truck.

![Figure 6](image)

**Figure 6.** (a) Lateral deformation of the bridge walls due to moving 2-axle truck; (b) Axial deformation of the bridge walls due to moving 2-axle truck.
4. Analysis results and discussion

It is observed that the developed DFEM is sensitive to the number of elements of the bridge superstructure and the number of integration points. In any specified application, it is required to perform convergence studies for both parameters, the number of elements, and the number of integration points. It is observed that further increase of the number of elements and/or the number of integration points to a reasonably high number would not result in a round-off error, which reflects the high numerical stability of the model.

The frame bridge considered here has a massive thickness for both the superstructure part and the inclined piers (substructures); the bridge can be considered is as way-overdesigned. That leads the bridge to avoid a dramatically high increase of the dynamic deformation. It should be mentioned that the pattern of the dynamic deflections as plotted over the bridge length looks similar to the pseudo-static deflections because it presented the peck deflection under the specified axle.

In the considered frame bridge, it can be seen that due to an increase of the truckloads, there are considerable variations in the dynamic deformations of the bridge components (superstructure and substructure); that may results in reducing/changing the load capacity of the bridge structural components when the bridge exposed to damage. The progressive increase of the traffic intensity and truckloads could contribute to increasing the dynamic deformations of bridges. That could be of high importance in the future work for slender frame bridges (where their beam-slab systems and columns, or more slender abutment/rigid slab frame bridges).

5. Summary

For the purpose of the design and/or assessment of bridge structures and due to advances in construction materials, it is always essential to evaluate the static deformations, frequency, vibration amplitudes, and dynamic deformation patterns of new and aged bridges due to the new five-axle versus the old two-axle design trucks. Therefore, the effects of using a recent standard multi-axle design truck on the structural behaviour of a frame bridge are investigated, where a comparison of the bridge dynamic behaviour due to different number of axles (2 and 5 axles) moving vehicles are presented. A two-dimensional nonlinear finite element model is used to model the frame, and trucks are modelled as a multi-DOF dynamic system incorporated with the bridge model. It is found that the model is able to capture the local dynamic excitation and oscillations results from the high variation of the mass and stiffness of the bridge components. Moreover, in case of nonlinear analysis of slender frame bridges, a progressive increase of the traffic intensity and truckloads could contribute to increasing the dynamic deformations of bridges.

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