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Abstract
Five-axle trucks produce the critical load cases for the design of short span bridges. This paper uses theoretical simulations to analyse the effect of a five-axle articulated truck on the dynamic response of a short-span bridge. Three-dimensional finite element bridge and truck models are developed with NASTRAN software. The bridge model is a 20 m long single span structure discretised into isotropic plate elements. The truck model is composed of bar, mass, damping, friction, spring and rigid elements. The road profile is generated stochastically from power spectral density functions. Then, the dynamic interaction problem between bridge, truck and road profile is solved using a Lagrange multiplier technique. Dynamic amplification factors are obtained for a combination of static weights, speed, road roughness and damping and compared to the Eurocode recommendation.

1. Introduction

Highway bridges are continuously subjected to heavy traffic loads. The impact factors caused by these loads are very important as they limit the life of the bridge. Generally, the motion of a truck has two main frequency components: a body frequency in the range 1.0 to 4.5 Hz and a wheel frequency around 15 Hz. One of these truck frequencies can match the bridge frequency and excite the dynamic forces applied to the bridge. This frequency matching in combination with poor road condition of the bridge surface and/or a large discontinuity prior to the bridge (e.g. a joint or a bump due to settlement of the abutments) causes high impact factors. Additionally, the influence of the unevenness of the approach is more important in short span bridges, where dynamic wheel forces might reach the critical bridge section before being damped out by vehicle or bridge damping mechanisms. This paper discusses the influence of vehicle, road and bridge parameters on the response of short-span bridges.

2. Vehicle-Bridge Interaction

A program developed by González (2001) is used to study the dynamic response of a bridge crossed by a heavy truck. The formulation is based on a Lagrange multiplier technique that represents the compatibility condition at the contact points using a set of auxiliary functions (Cifuentes 1989). The approach is extended to treat more complex problems by manipulating...
the global stiffness matrix. The definition of the interaction forces is adapted to the finite element package NASTRAN (1997). The solution provided by this model has compared favorably to bridge measurements on site (Brady et al. 2002, Lutzenberger & Baumgartner 1999). Prior to calculations, the program requires from the user three types of input:
- The bridge finite element model.
- The truck finite element model, including geometry, mechanical characteristics, speed, length of the approach, initial position, path of the vehicle on the bridge, etc. More than one vehicle can be specified.
- The definition of the road surface, given by measurements or generated stochastically from power spectral density functions for a particular road class.

The inputs considered in the study at hand are described in the following subsections.

2.1 Bridge Model

A 20 m single span bridge structure is simply supported at both ends. Figure 1(a) shows a layout of this slab model. Traffic direction is parallel to the \( x \)-axis. The deck has a uniform rectangular cross-section 1.0 m deep and it is supported on four bearings at each end. Typical properties of prestressed concrete are assumed (2500 kg/m\(^3\) unit weight, \( 35 \times 10^6 \) kN/m\(^2\) modulus of elasticity and 0.15 Poisson’s ratio). A static analysis is carried out to determine the influence line of longitudinal strain at midspan. The influence line due to a 1 kN axle load travelling along one lane (inner and outer wheels following a path 1.5 m and 3.5 m offset from the bridge centre line) is represented in Figure 1(b).

![Slab Finite Element Model: (a) Mesh (dimensions in m), (b) Influence line of longitudinal strain at midspan (T is the distance in m from the edge of the bridge driving lane)](image)

**Figure 1** - Slab Finite Element Model: (a) Mesh (dimensions in m), (b) Influence line of longitudinal strain at midspan (T is the distance in m from the edge of the bridge driving lane)

The natural frequencies and mode shapes are an indication of how the bridge will respond to a dynamic excitation. The bridge will then naturally vibrate at these frequencies. The main modes of vibration over the frequency range of interest (from 0 to 30 Hz) are represented in Figure 2. Bridge damping is considered to be 1.3% unless otherwise specified.
Figure 2 - Modes of Vibration of the Slab: (a) 1\textsuperscript{st} mode (4.2 Hz), (b) 2\textsuperscript{nd} mode (10.8 Hz), (c) 3\textsuperscript{rd} mode (16.8 Hz) and (d) 4\textsuperscript{th} mode (25.7 Hz)

2.2 Truck Model

A five-axle articulated truck model has been developed for the simulations. The model is represented in Figure 3. The five-axle truck has a typical configuration with a rear tridem and axle spacings 3.6, 5.8, 1.2 and 1.2 m, which are mean values obtained from a weigh-in-motion survey on the A196 French motorway (Grave 2002).

Figure 3 - Five-Axle Finite Model of Typical European Truck

Three different loading conditions (empty, half and fully laden with gross vehicle weights 233, 426 and 619 kN respectively) and six levels of speed (from 50 to 100 km/h) have been used in the simulations. The mechanical characteristics of the truck have been taken from Kirkegaard et al (1997). The main modes of vibration of the fully-laden vehicle are represented in Figure 4.
Figure 4 - First Modes of Vibration of a Fully Laden Five-Axle Truck: (a) Trailer Body Roll and Twisting of Tractor Frame, (b) Pitching of Tractor and Trailer, (c) Tractor Body Roll, (d) Pitching of Tractor Body, (e) Pitching of Trailer Body, (f) Rear Axle Hop in Tractor, (g) Front Axle Hop in Tractor and (h) Front Axle Roll in Tractor.

These modes of vibration are associated with a given frequency. Figures 4(a),(b),(c),(d),(e),(f),(g) and (h) have frequencies 0.4, 0.9, 1.3, 1.88, 1.9, 12.9, 14.5 and 15.4 Hz respectively. These frequencies change depending on the truck weight and mass moment of inertia, allowing to assess the dynamic interaction with the supporting bridge. As the natural frequencies of the bridge and vehicle get closer, the dynamic response increases.
2.3 Pavement Model

The road condition is defined based on power spectral density functions according to ISO standards (Wong 1993). Figures 5(a) and 5(b) illustrate the bridge response for two types of road roughness and the fully laden five-axle truck traveling at 70 km/h and 100 km/h respectively. The dynamic component is more important for 100 km/h and the rougher profile.

![Static Total Response on Good Road Total Response on Poor Road](a)

![Static Total Response on Good Road Total Response on Poor Road](b)

**Figure 5** – Bridge Response for ‘Good’ and ‘Poor’ Road Conditions: (a) Vehicle crossing at 70 km/h and (b) 100 km/h

3. Influence of Bridge and Truck Parameters on Dynamic Amplification Factor

Dynamic amplification factor (DAF) is defined as:

\[
DAF = \frac{y_{dyn}}{y_{stat}}
\]

where \(y_{dyn}\) and \(y_{stat}\) are the maximum bridge response under dynamic and static loading with the same vehicle at a given measurement point.

The influence of the ratio truck mass to bridge mass on DAF is subject to analysis. This ratio is especially relevant for short-span bridges. If the truck mass is big compared to the bridge, the truck characteristics will govern the bridge behavior. On the other hand, if the truck mass is relatively small, the bridge dynamic characteristics will be dominant. The influence of speed and bridge damping are also investigated. Dynamic amplification is more significant at certain speeds depending on the span length and if the truck excites the bridge, the damping forces of the bridge are responsible to bring it back to its original state. If bridge damping is small, more heavy axles coming into the bridge before vibrations are damped out might cause resonance. Other truck mechanical properties (e.g., tire or suspension stiffness) have not been considered due to two main difficulties: first, they have a wide range of variation and secondly, there is not sufficient statistical information available to give a solution in probabilistic terms (Up to date, weigh-in-motion technology can only provide data on weights, axle spacing and speed). In these runs, road conditions have been assumed to be ‘good’ (Section 2.3) unless otherwise specified.
3.1 DAF versus Mass Ratio for different Levels of Vehicle Speed

Static and total strains are simulated for a range of speeds and load conditions at different locations within the bridge midspan section (Influence lines for these locations have been shown in Figure 1(b)). The bridge midspan section should be strong enough to resist the highest strain. DAF is obtained from Equation (1) by taking into account the maximum total ($y_{dyn}$) and maximum static strain ($y_{stat}$) for each run. In Figure 6, it can be observed the highest DAF is 1.34 (corresponding to 16.3 microstrains) and it is obtained for a speed of 90 km/h and a mass ratio of 0.04 (empty vehicle). DAF decreases as mass ratio increases. The maximum strain (39.8 microstrains) takes place for the fully laden vehicle travelling at 100 km/h and it has a DAF of 1.12. So, it appears clear that there is not correspondence between worst static loading case and worst dynamic amplification, and the use of the highest DAF, regardless of the vehicle weight, would produce far too conservative results.

![Figure 6 – Dynamic Amplification Factor versus Speed and Mass Ratio](image)

3.2 DAF versus Bridge Damping for Different Road Conditions

Cantieni (1983) measured critical damping in 211 bridges and values fell within the range [0.22%, 5.73%]. The mean damping of the sample resulted 1.27%. Damping was generally lower for straight bridges, bridges with closed cross section and narrow bridges. Figure 7 shows DAF for different levels of damping and the case of the fully laden vehicle traversing the bridge at 100 km/h, which caused the highest bending strain in the previous section. DAF decreases from 1.15 if 0% to 1.10 if 5% damping in the case of a ‘good’ road profile. Dynamic amplification decreases significantly as damping increases up to 1%, but levels of damping over 1% cause a very small reduction of DAF. The influence of damping is more significant in the case of a ‘poor’ road profile, and DAF falls from 1.69 if zero damping to 1.54 if 5% damping. For the case of a ‘poor’ road profile, DAF decreases rapidly as damping increases up to 1%, and then, decreases linearly up to 5% damping. It can be seen how a road in bad condition can increase dynamic amplification by 50% or more (in this case, from 1.15 to 1.69 if zero damping).
4. **Comparison to the Eurocode**

In the Eurocode, the dynamic load induced on bridges by free flowing traffic is obtained through the application of a dynamic amplification factor. This factor is applied to the worst static case obtained from extrapolating load effects using free flowing simulations and weight-in-motion data (O’Connor 2001). The shortcoming of this approach is that it does not take into count the characteristics of the road profile, the vehicle or the bridge. When calculating DAF for free flowing traffic, it only takes into count the shape of the influence line and one variable, i.e. bridge length. As so many parameters are being ignored, this approach uses very conservative values and the maximum dynamic effect will not necessarily correspond to the maximum static effect (as seen in Section 3.1). I.e. for the bridge case under study (Simply supported, 2 lanes and 20 m long), a value of 1.2 is the amplification factor to apply according to the Eurocode. This bridge length was not chosen hazardously, as it corresponds to the lowest impact factor for a simply supported bridge (For shorter bridges, it can go as high as 1.7 for 5 m length, while for longer bridges, it increases up to a maximum of 1.4 for span lengths over 30 m). In spite of being the least conservative case of all span lengths, if road conditions, bridge damping or mass ratio are allowed in calculations, this additional 20% load due to dynamics can be reduced as shown in the previous section (i.e., for 1.3% bridge damping, ‘good’ road profile and fully laden truck, down to 12%). The high impact factors up to 1.7, obtained in Section 3.2, due to ‘poor’ road condition are unlikely to take place in a well-maintained highway pavement (In particular, integral bridges are a very beneficial design that propitiates a smooth approach without a significant unevenness). Therefore, if the bridge has more than one lane, and the worst static case is given by a simultaneous traffic event, it would be expected that the dynamic amplification factor could be further reduced due to the lower probability of frequency matching (Brady et al. 2002). It is also known the braking of a vehicle can increase dynamic amplification considerably compared to the same vehicle travelling at constant speed, but the probability of a critical loading case having to brake strongly during the bridge lifetime is minimal.
5. Conclusions

In order to satisfy the increasing demand in transport capacity, new European regulations will shortly allow heavier vehicles on the road. One major issue is to investigate if existing bridges will be able to resist the dynamic allowance required by these heavier vehicles. Standard codes of practice such as Eurocode rely on DAF’s that will lead to excessively conservative designs or unnecessary replacement of old structures. It has been seen how road condition plays a major role in dynamic amplification. Parameters such as bridge damping and/or mass ratio are relatively easy to obtain through field measurements and they can give an upper bound of the dynamic load to be considered. The periodical maintenance of the approach and bridge pavement, the introduction of appropriate damping devices and/or the consideration of particular dynamic characteristics (e.g., bridge and truck natural frequencies, damping, the influence of the transverse position of the truck related to the bridge section, etc.) in the calculations might justify a reduction of dynamic amplification in both assessment (extending the bridge life without having to bear the cost of bridge strengthening) and design stages (leading to a reduction in bridge deck section and material cost).

References