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AN ASSESSMENT OF THE INFLUENCE OF DYNAMIC INTERACTION MODELLING ON PREDICTED CHARACTERISTIC LOAD EFFECTS IN BRIDGES

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ABSTRACT

Traffic loading crossing a bridge is simulated to analyse the correlation between the worst static and dynamic load case. The worst static cases are obtained through a Monte-Carlo simulation using weigh-in-motion (WIM) data from a typical European route. The bridge model is a two-lane 20 m long single span structure discretised into plate elements. The truck model is composed of bar, mass, damping, spring and rigid elements. The road profile is generated stochastically from power spectral density functions. The dynamic interaction between bridge, truck and road profile is solved using a Lagrange multiplier technique. Dynamic amplification factors are obtained for the critical static loading cases, which for a two-lane 20-m bridge is due to meeting events between two five-axle trucks. Results are compared to the Eurocode recommendations.

KEYWORDS: Bridge dynamics, Traffic loading, Simulations, Eurocode, Weigh-In-Motion.

1. INTRODUCTION

Modern bridge design codes are derived by combining traffic flow simulations with principles of structural safety to determine the maximum loading to which a structure may be subjected during its lifetime. A major shortcoming of existing codes lies in the manner in which they have taken account of the dynamic magnification of the static effect resulting from the interaction between the moving vehicle and the structure. Generally, multipliers are applied to characteristic extremes (i.e. load effect values with a specified probability of exceedance) determined from simulation. However, such values take no account of the dynamic characteristics of the bridge, the truck or of the interaction between the two systems. Clearly, this approach, which ignores a combination of probabilities, can lead to excessively conservative designs and structural assessments.

In the derivation of the Eurocode normal load model for bridge design, the dynamic load induced on bridges by free flowing traffic was obtained through the application of a Dynamic Amplification Factor (*DAF*) to the worst static case obtained from extrapolating load effects using free flowing simulations constructed from weigh-in-motion data (O'Connor 2001). The main shortcomings of this approach is that determination of the dynamic amplification for the free flowing traffic only takes account of the shape of the influence line and one other variable, i.e. bridge length. As so many parameters are being ignored, this approach is very conservative.

In this paper, static analysis is initially performed using WIM data to determine the critical loading events, which yield characteristic values for the selected structure. These critical loading combinations are modelled dynamically taking into consideration the interaction between the vehicles and the structure using the finite element software NASTRAN. Typical truck dynamic parameters are employed. The bridge model is a 20 m long single span simply supported structure. Dynamic amplification factors are obtained for a combination of static weights, speed and axle spacings corresponding to a single traffic event and to the critical static loading cases. The influence of vehicle, road and bridge parameters on the response of the bridge is discussed. For the bridge case under study, a dynamic amplification of 1.2 is to be applied according to the Eurocode (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 lowest impact factor for a simply supported bridge, if road conditions, bridge damping or mass ratio are considered in the calculations, this additional 20% due to dynamics can be reduced. Additionally, for a two-lane bridge the worst static case is described by a two-truck meeting event and the dynamic amplification factor can be reduced due to the lower probability of frequency matching. Significantly, the simulated bridge response shows that the worst static and dynamic effects do not necessarily occur for the same loading case. These considerations can lead to significant savings when assessing a structure where site-specific maximum design load effects are determined from measured traffic data and experimental bridge dynamic characteristics.

2. STATIC SIMULATIONS

The static simulations were performed using the program CASTOR-LCPC developed at the Laboratoire Central des Ponts et Chaussées (Eymard and Jacob 1989). Loads effects were calculated as the program moved the vehicles along the bridge, lane by lane, preserving the axle

loads and spacing as well as the vehicle spacing recorded on site or simulated, depending upon the simulation scenario. Level crossing histograms were calculated in real time during the simulations. These histograms are a useful means of extrapolating a load effect to a period longer than the recording period. In addition to recording the histograms of level crossings the program also records the times at which each level exceedance took place. Is it therefore possible through post-processing of the results of simulations to determine from the traffic records, the vehicles combinations which were involved in each exceedance of a given threshold. Table 1 provides an example of five such occurrences determined from the simulated data for the two lane bi-directional 20m simply supported span under consideration in this paper. It is clear that in each case the critical loading events occur when two heavily laded five-axle vehicles meet on the structure.

Table 1. Example of critical meeting truck events

Case (^e)	GVW (kN)	W1 (kN)	W2 (kN)	W3 (kN)	W4 (kN)	W5 (kN)	Spd. (m/s)	Dir.	Hr.	Min.	Sec	Sec /100
1	409.07	68.67	105.94	77.49	77.49	77.49	21	1	16	23	59	91
	404.17	30.41	112.81	86.32	86.32	86.32	22	2	16	23	59	95
2	431.64	51.99	130.47	82.40	82.40	82.40	21	1	5	21	54	74
	411.03	46.10	141.26	73.57	73.57	73.57	24	2	5	21	54	97
3	441.45	51.99	119.68	89.27	89.27	89.27	27	1	20	20	0	71
	432.62	49.05	98.1	94.17	94.17	94.17	24	2	20	20	0	80
4	395.34	31.39	140.28	73.57	73.57	73.57	24	2	15	21	8	58
	446.35	74.55	105.94	87.30	87.30	87.30	27	1	15	21	8	65
5	407.11	45.12	135.37	74.55	74.55	74.55	23	2	17	29	17	63
	429.67	46.10	124.58	85.34	85.34	85.34	26	1	17	29	17	74

(^e) Five-axle articulated trucks with axle spacings 3.6, 5.6, 1.2 and 1.2 m.

In this paper the prediction of the characteristic extreme load effects was performed using the Extreme Value Type I (Gumbel) and Type III (Weibull) distribution. Figure 1 illustrates the results of extrapolations performed for varying periods. In determining the extreme values for the free flowing scenario a dynamic amplification factor of 1.2 has been applied to the static load effects as previously discussed. It is observed that the characteristic extremes predicted by the Weibull extreme value distributions are consistently lower than those predicted by the Gumbel I distribution. This is due to the mathematical formulation of the two distributions with the former bounded in the extreme and the latter is unbounded. For this reason, some authors consider the Weibull distribution more appropriate to predict extreme load effects for short spans (Bailey 1996, O'Connor 2001).

3. DYNAMIC SIMULATIONS

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 favourably to

bridge measurements on site (Brady et al. 2002, Lutzenberger & Baumgärtner 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.

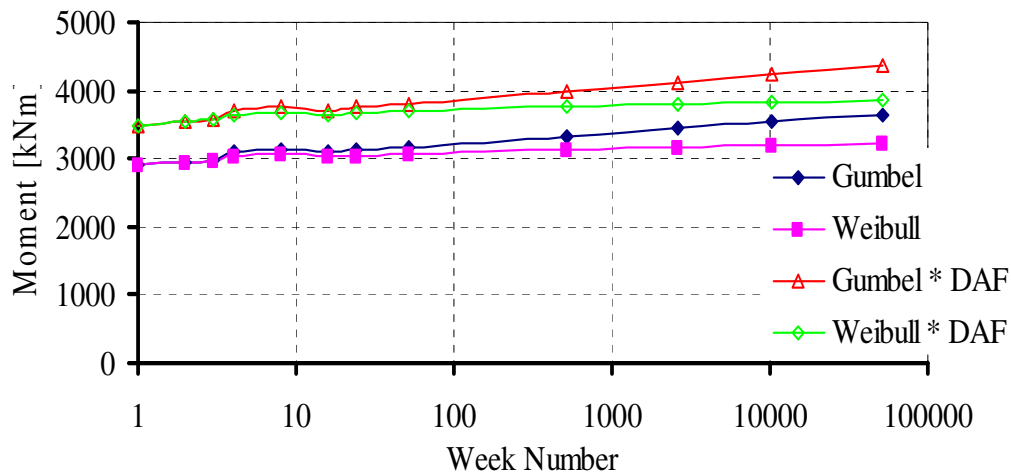


Fig. 1. Extreme simply supported moment at midspan ($DAF = 1.2$).

3.1 Bridge Model

A 20 m single span bridge structure is simply supported at both ends. Figure 2(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, $35 \times 10^6 \text{ kN/m}^2$ 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 2(b).

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 are represented in Figure 3. Bridge damping is considered to be 1.3% unless otherwise specified.

These modes of vibration are associated with a given frequency. 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.

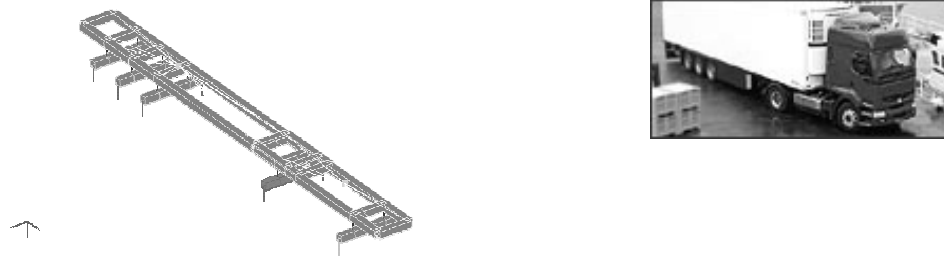


Fig. 4. Five-axle finite model of typical European truck.

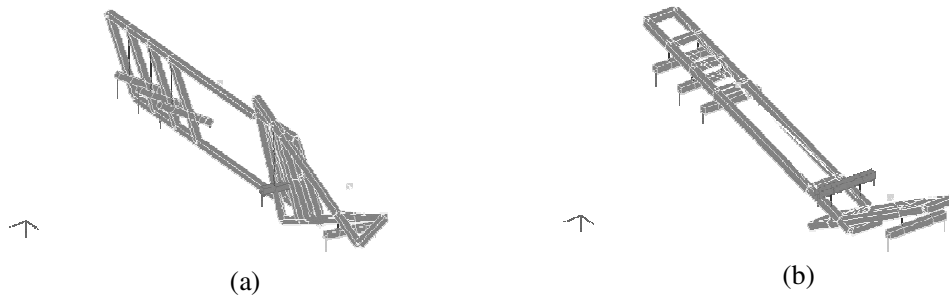


Fig. 5. First modes of vibration of five-axle articulated truck: (a) Trailer body roll and twisting of tractor frame and (b) Pitching of tractor and trailer.

3.3 Road Profile

The road condition is defined based on power spectral density functions according to ISO standards (Wong 1993). Figures 6(a) and 6(b) illustrate the bridge response for two types of road roughness and an extremely overloaded five-axle truck travelling at 70 km/h and 100 km/h respectively. The dynamic component is more important for 100 km/h and the rougher profile.

4. COMPARISON OF WORST STATIC AND DYNAMIC LOAD EFFECTS

First, the dynamic amplification factor caused by one single vehicle is subject to analysis. The influence of the ratio truck mass to bridge mass on DAF is especially relevant for short-span bridges. 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. Then, dynamic amplification factors caused by multiple vehicle presence are compared to the Eurocode

recommendations. In these runs, road conditions have been assumed to be ‘good’ (Section 3.3) unless otherwise specified.

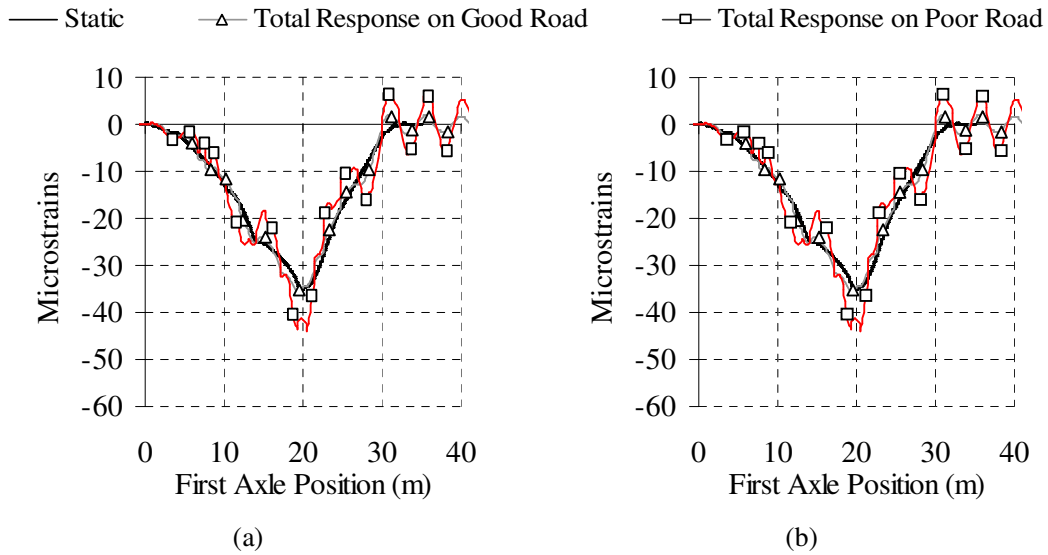


Fig. 6. Bridge response for ‘good’ and ‘poor’ road conditions: (a) Vehicle crossing at 70 km/h and (b) 100 km/h

4.1 DAF versus Mass Ratio for One Single Vehicle and different Levels of Vehicle Speed

Static and total strains are simulated for three different loading conditions (lightly, fully laden and heavily overloaded with gross vehicle weights 233, 426 and 619 kN respectively) and six levels of speed (from 50 to 100 km/h) at different locations within the bridge midspan section (Influence lines for these locations have been shown in Figure 2(b)). The bridge midspan section should be strong enough to resist the highest strain. *DAF* is obtained by taking into account the maximum total and maximum static strain for each run. In Figure 7, 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 (lightest vehicle). *DAF* decreases as mass ratio increases. The maximum strain (39.8 microstrains) takes place for the overloaded 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 (Hwang and Nowak 1991).

4.2 DAF versus Bridge Damping for One Single Vehicle and Different Road Conditions

Cantiene (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 8 shows *DAF* for different levels of damping and the case of the overloaded vehicle traversing the bridge at 100 km/h (run that 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). The high impact factors up to 1.7 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).

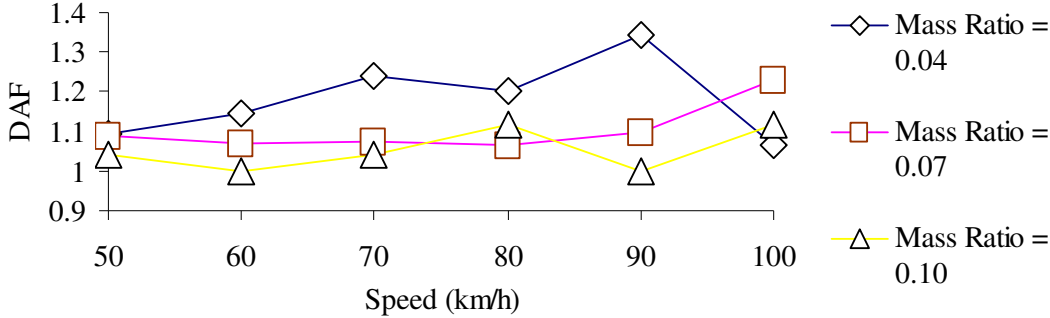


Fig. 7. Dynamic amplification factor versus speed and mass ratio.

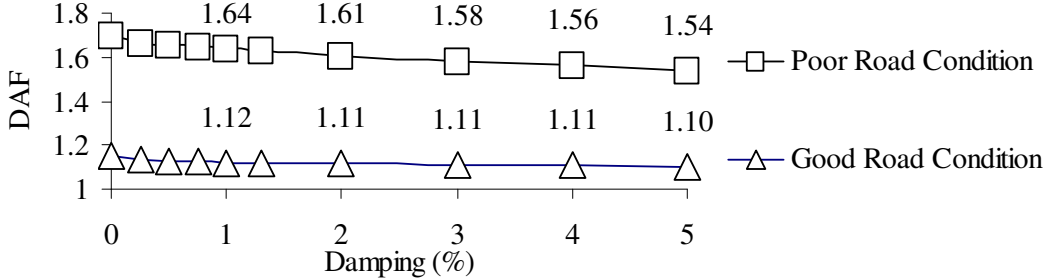


Fig. 8. Dynamic amplification factor versus damping.

4.3 DAF due to Multiple Vehicle Presence

Figure 9 plots maximum static strain and maximum total strain (static+dynamic) besides its corresponding *DAF* for each extreme loading case (due to multiple vehicle presence as defined in Section 2). In the figure, extreme loading cases are sorted from highest to lowest static strain and it can be seen how a *DAF* of 1.07 corresponds to the maximum strain this bridge should be assessed/designed for. It is noticeable how *DAF* can increase up to 1.17 for other loading cases, but using this *DAF* or the one recommended by the Eurocode (1.2) would be too conservative for the bridge under study. I.e., the maximum strain corresponding to a *DAF*=1.17 (22 microstrains) is more than three times smaller than the maximum strain obtained (74 microstrains).

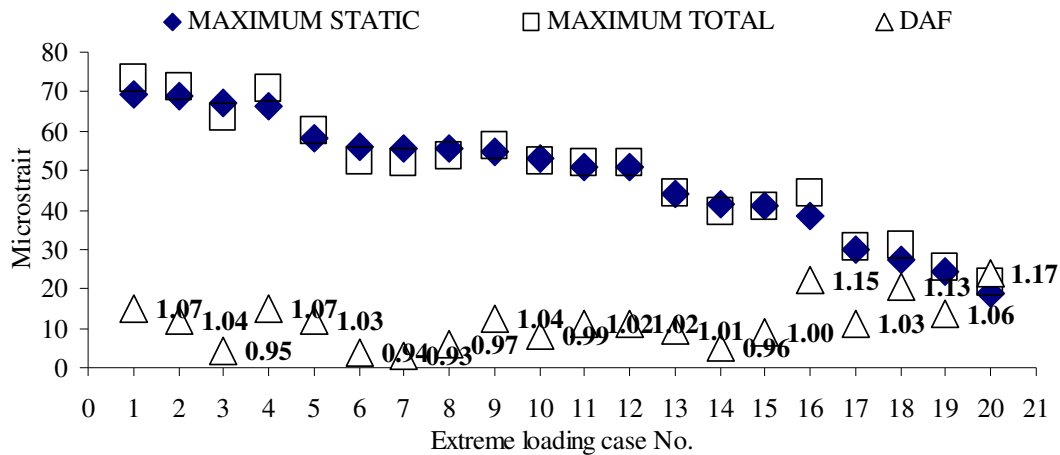


Fig. 9. Dynamic amplification factor and maximum strain versus extreme loading cases.

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. Parameters such as traffic statistics, bridge damping and mass ratio are relatively easy to obtain through field measurements and they can give an upper bound of the dynamic load to be considered. It has been seen how road condition plays a major role in dynamic amplification. The periodical maintenance of the approach and bridge pavement, the introduction of appropriate damping devices, the characteristics of the traffic 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.) 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).

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