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The Impact of a Bump on the Response of a Bridge to Traffic

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Abstract

There are numerous studies on the dynamic amplification factors caused by traffic flow on a bridge. For short- and medium-span bridges, the road profile appears as a dominant parameter on the bridge dynamic response. In theoretical investigations, the road profile is usually modelled as a stochastic random process. However, this approach does not take into account the high irregularities that are prone to develop in the connection of the bridge to its approach, as result of a damaged expansion joint and/or differential settlement. Most of research on dynamic amplification due to traffic has focused in bending moment effects. This paper uses planar vehicle-bridge interaction models to assess the increase in shear effects at the supports that a bump prior to the bridge may cause. Results for a range of bumps, bridge lengths, traffic configurations and road conditions are discussed.

Keywords: Vehicle, bridge, dynamics, shear, expansion joint, highway

1 Introduction

The condition of the road profile is a major factor influencing the response of the bridge to a passing vehicle [1] as well as specific location of particular bumps [2]. [3] shows the best way of reducing dynamics effects due to a bump is by removing it. However, there are certain types of discontinuities that frequently appear on the road profile before a bridge, i.e., at the expansion joint. Either because expansion joints are the weak point of bridges [4] and are easily damaged or differential settlements occur between the bridge and the abutment, it is not rare to have a significant discontinuity at this location. Any step on the road surface influences the vehicle dynamics and subsequently the bridge response too.

In [5, 6, 7], it can be seen how a single bump or ramp can be positioned in some critical locations where the bridge response due to a moving vehicle will be of major

significance. In [8], combinations of bump characteristic (i.e., height and length) and vehicle speed can result in very high dynamic effects. There are also investigations on fatigue effects on bridges due to damaged expansion joints [9, 10], and experimental and computer simulations with emphasis on slab deflection [11]. However, the effects of dynamic shear forces at the supports have not received much attention.

1.1 Shear

Bridges are more likely to fail in bending than shear after significant plastic deformation has developed under excessive dynamic traffic load [12]. Brittle failure mechanisms such as shear failures are not so frequent, but if an accurate assessment is needed or if there was signs of cracking initiating close to the support, the applied shear force and structural shear strength will require immediate attention. For the accurate determination of the total shear force on the structure, it will be necessary to take into count the effects of damaged expansion joints.

In vehicle-bridge dynamic field the study of the shear forces has not been treated many times. However some interesting articles can be found, like [13] where shear impact factors of 10% are proposed for curved steel box girder bridges, as well as in [14] that studies beams for non-linear bending and shear properties. Another research that includes shear analysis is [15] for two-span continuous beam subjected to high speed 2DOF sprung vehicles, obtaining a maximum of 10% dynamic amplification for a variety of speeds and profiles.

The Eurocode traffic load model is based on the statistical combination of static traffic load effects and dynamic amplification factors (DAFs). The latter have been derived from numerical simulations and the average values for global effects are shown in Figure 1 [16] for one, two and four loaded lanes. In Eurocode 1 [17], an additional DAF is recommended near expansion joints, $\Delta\phi$, and applied to all loads, given in Equation (1):

$$\Delta\phi = 1.3 \cdot \left(1 - \frac{D}{26}\right) \quad (1)$$

where D is the distance in meters of the cross-section under consideration from the expansion joint.

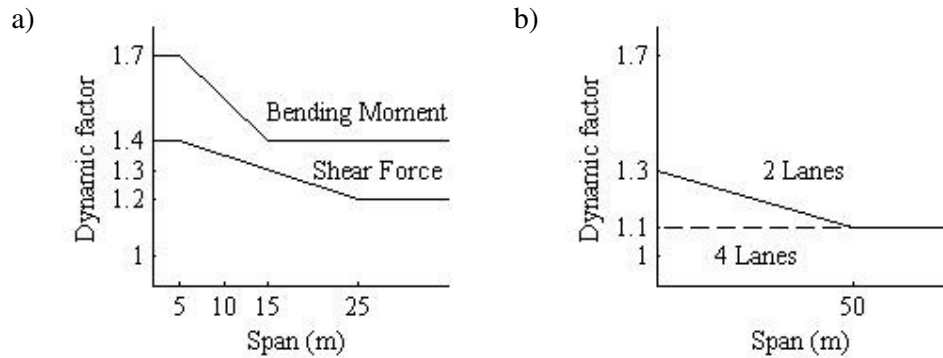


Figure 1: Average global dynamic factors; a) One loaded lane; b) Two and four loaded lanes

Weigh-In-Motion (WIM) records have shown that extremely heavy vehicles, such as cranes, are becoming more and more frequent in normal traffic [18]. These extreme vehicles represent the critical traffic load for simply supported bridges and short to medium spans. This paper reviews the dynamic effects of large cranes on the shear load effect in short to medium span bridges and compares them to typical 5-axle articulated trucks. For this purpose, shear load effects are obtained for a range of vehicle-bridge interaction (VBI) parameters varied using Monte Carlo simulation.

2 Simulation Model

2.1 Vehicle

The vehicle models are represented as lumped masses joined to the road or bridge surface by spring-dashpot systems, which simulate the suspension and tyre responses. Figures 2a and 2b show sketches of the 5-axle truck and crane vehicle respectively. The main difference between both models is the presence of a hinge in the articulated truck allowing it to be more flexible than the crane. In addition, the number of axles, spacing and loads are different for both models. The vehicle responses are obtained using a planar model following [19], that presents the equations of motion for a general articulated road vehicle, with variable numbers of wheels for the tractor and semitrailer. Similar vehicle models have been widely used in the literature [20], [21] representing vehicle-bridge interaction with a reasonable degree of accuracy [22].

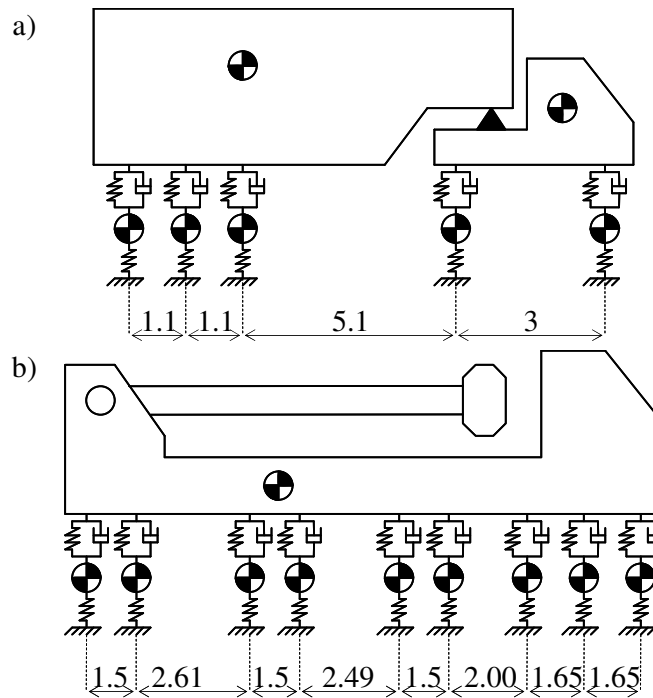


Figure 2: Vehicle model sketch a) 5-axle truck; b) Crane

The 5-axle truck represents a typical European lorry previously used in [23] and [24]. Whereas the 9-axle crane has been implemented using body masses, axle spacings and loads available from crane manufacturer specifications and WIM data, other parameters such as suspension and tire properties have been taken from the literature for a similar vehicle by [25], and [26] that provide results from extensive experimental tests. The dynamic properties of both vehicles are summarised in Table 1.

2.2 Beam

The bridge is modelled as a simple supported Euler-Bernoulli beam with constant cross section and mass per unit length for length L , as shown in Figure 3.

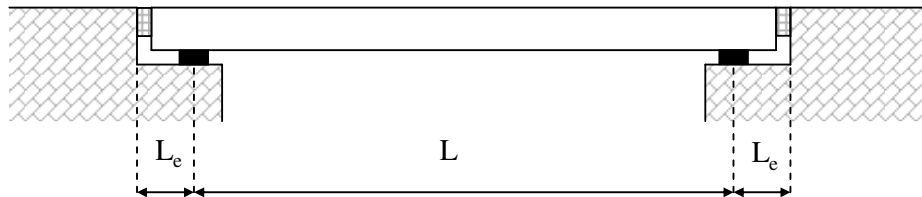


Figure 3: Bridge model

5-axle truck		
Masses (kg)	Tractor	4500
	Semitrailer	31450
	Tractor front axle	700
	Tractor rear axle	1100
	Semitrailer axles	750
Suspension stiffness (kN/m)	Tractor, front	400
	Tractor, rear	1000
	Semitrailer	750
Suspension damping (kNs/m)		10
Tyre stiffness (kN/m)	Tractor, front	1750
	Tractor, rear & semitrailer	3500
Crane		
Masses (kg)	Body	101250
	Axles	750
Suspension stiffness (kN/m)		1200
Suspension damping (kNs/m)		40
Tyre stiffness (kN/m)		1500

Table 1: Truck and Crane Mechanical Parameters

Table 2 summarises properties of mass per unit length and second moment of area for a number of bridge spans employed in the simulations. These properties are based on bridge cross-sections made of T beams, Y beams and Super-Y beams depending on the bridge span [27]. Bridge responses will be simulated for a total number of 51 spans (values are interpolated for those spans not included in Table 2), with 3% structural damping and a Young's Modulus of $3.5 \cdot 10^{10} \text{ N/m}^2$.

Type	Length (m)	Mass per unit length (kg/m)	Second moment of inertia (m^4)	Natural frequency (Hz)
T beams	9	16875	0.1139	9.43
	12	22500	0.2757	7.14
	15	28125	0.5273	5.66
	18	33750	0.9197	4.73
	21	39375	1.4470	4.04
Y beams	23	17419	1.1133	4.44
	27	19372	1.7055	3.78
	31	21650	2.4651	3.26
Super-Y beams	33	20952	2.9327	3.19
	37	22552	3.9425	2.84
	43	24952	5.7957	2.42

Table 2: General characteristics of the bridge models

2.3 Road Profile and Damaged Expansion Joint

The profiles are generated as a random stochastic process described by a power spectral density functions as specified in ISO recommendations [28]. Road classes can be varied from A ('very good') to E ('very poor'), although well maintained highway pavements are assumed in this paper and only class A profiles have been employed.

The damaged expansion joint was modelled using three different shapes shown in Figure 4 [27],

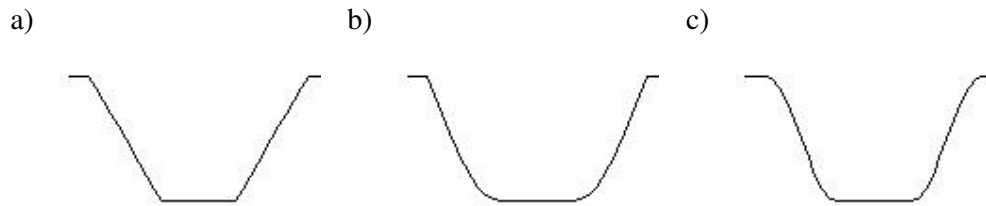


Figure 4: Bump shapes

The appropriate value for bump depth has been chosen following expansion joints road network surveys from Japan [9, 10] and Portugal [4]. In this paper, 2 cm deep bumps represent average damaged expansion joints, and 4 cm is the maximum depth considered. These bumps are located at 0.5 m from bridge support to account for the usual beam overhang; L_e in Figure 3. Figure 5 gives the profile resulting from combining a class 'A' road profile and a 4 cm deep bump.

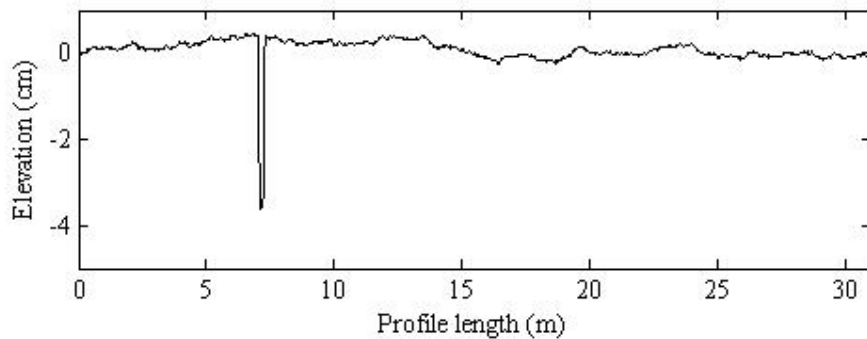


Figure 5: Road profile example with 4cm deep bump

2.4 Solution

The coupled vehicle and bridge system can be solved using standard numerical techniques. In this paper Wilson- θ integration scheme [29] was adopted. For the shear stresses calculation in the beam, the so called combined method outlined by [30] was used. In this paper the shear forces are computed for points very close to, but not at, the supports of the beam because calculations involve the bending

moment first derivative. Dynamic Amplification Factor (DAF) is defined as the maximum total load effect (maximum of both supports) over the corresponding maximum static load effect.

3 Single Vehicle Events

The DAF for shear forces at the supports, due to the effect of a bump at the approach to the bridge, is analysed here for single vehicle events. A preliminary analysis using constant loads give an order of magnitude of the DAF values when road irregularities or bumps are not considered. Then, the additional dynamics due to the influence of the road profile and bumps on vehicle sprung models and bridge response are discussed.

3.1 Vehicle Model based on a Moving Constant Force

Using the closed form solution for a single constant load over a simply supported Euler-Bernoulli beam [30, 31], it can be shown that the dynamic amplification factors for shear at supports is in many situations larger than for bending moment at mid-span. This phenomenon is illustrated in Figure 6, where frequency ratio (FR) is defined by Equation (2):

$$FR = \frac{c}{2 \cdot f \cdot L} \quad (2)$$

where c is the speed of the vehicle, f the bridge natural frequency and L the span length.

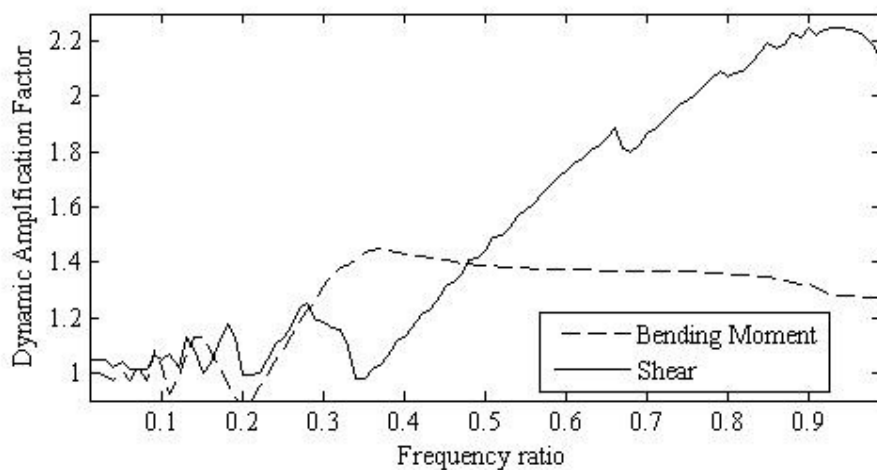


Figure 6: Dynamic amplification factors for moving constant load

3.2 Sprung Vehicle Models

Vehicles described in previous section 2.1, i.e. 5-axle truck and crane, are studied independently within a Monte Carlo simulation scheme for a wide range of bridge

spans and bump depths. Different vehicle parameters were varied within a realistic range of values, including speed, suspension and tyre mechanical properties, as well as different profiles (although within the same class ‘A’) for each event. The results showed no significant difference in bridge response when varying the bump shapes (Figure 4), and the bump shape of Figure 4b was used for the remaining simulations.

Figures 7a and 7b show the mean shear DAF at the support for 5-axle trucks and cranes respectively. The results are displayed for more than 100000 different events, classified into beam types, span lengths and bump depths. In the case of 5-axle trucks (Figure 7a) there is a clear influence of bridge length on DAF, which increases as the span decreases. Shear DAF increases significantly with bump depth. However, the influence of bump depth on DAF is hardly noticeable for the crane (Figure 7b). This is due to the larger static load effect, higher number of wheels, vehicle rigidity and moment of inertia of the crane compared to the 5-axle truck. The shear at the support is the sum of the individual effects of each axle on the bridge, and the more axles on the bridge, the less influential on DAF the dynamic effect of one of the axles going over the bump becomes.

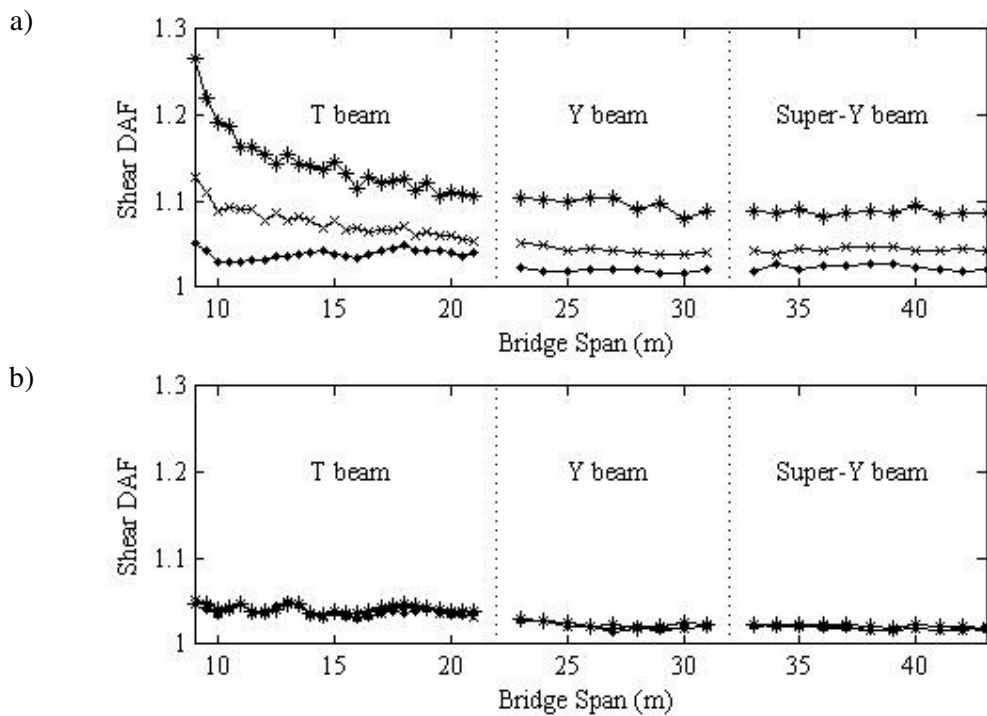


Figure 7: Mean DAF for shear force at support; a) 5-axle truck; b) Crane ("•" No damage; "x" 2 cm bump depth, "*" 4 cm bump depth)

From Figure 7, Table 3 provides the DAF values obtained for both truck models, the three bump conditions and 10, 20, 30 and 40 m span lengths.

Span (m) \ Bump depth (cm)	5-axle			Crane		
	0	2	4	0	2	4
10	1.029	1.088	1.193	1.033	1.037	1.040
20	1.040	1.061	1.111	1.034	1.037	1.039
30	1.017	1.039	1.080	1.019	1.018	1.025
40	1.023	1.043	1.096	1.018	1.019	1.023

Table 3: Mean DAF values for single vehicle events

4 Meeting Events

In the case of short span bridges (< 20 m), the critical traffic loading event consists of two heavy trucks meeting on the bridge [32]. Meeting events involving more than two vehicles are relevant for longer spans, but for a short span long vehicles' wheelbase is as long as the bridge span, making it difficult to locate more than one vehicle per lane. Therefore, this paper is focused in short to medium span lengths where the dynamic amplification due to traffic is very relevant.

Three meeting events have been defined to compare different traffic scenarios. Type I is defined for two 5-axle trucks meeting on the bridge, type II for a 5-axle truck and a crane event, and Type III for two cranes as sketched in Figure 8.

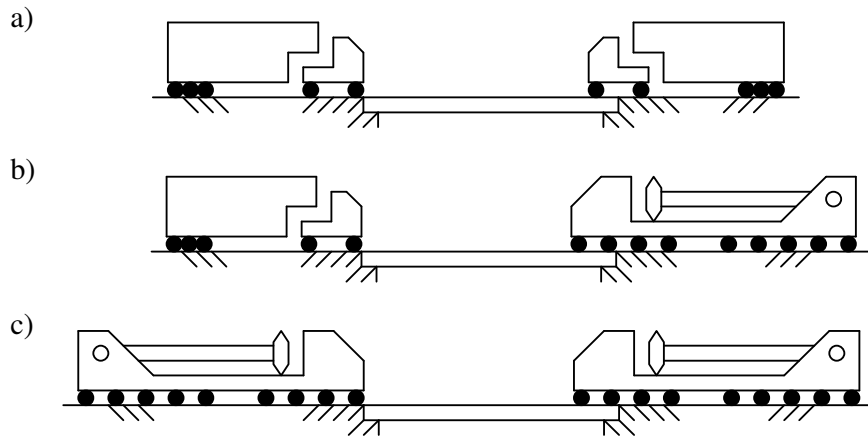


Figure 8: Scenarios of vehicle meeting events; a) Type I; b) Type II; c) Type III

4.1 Influence of a Bump on a Smooth Road Profile

The scenarios illustrated in Figure 8 are analysed for a wide range of possibilities allowing for:

- A variation of the meeting location, since it is unknown beforehand which is the worst possible meeting configuration in terms of total shear load effect.
- Vehicle speeds within normal highway values (50 to 120 km/h).
- Five bridge spans: 9, 12, 15, 18 and 21m.

d) Two bump depths (0 and 2 cm) to compare results for a perfectly smooth profile to a damaged one.

The results of 164000 simulated meeting events are shown in Figure 9. These figures present shear DAF values only for the event with the maximum static load effect within the analysed speeds and vehicles locations, i.e. each point represents the maximum of 4100 different speed and location combinations.

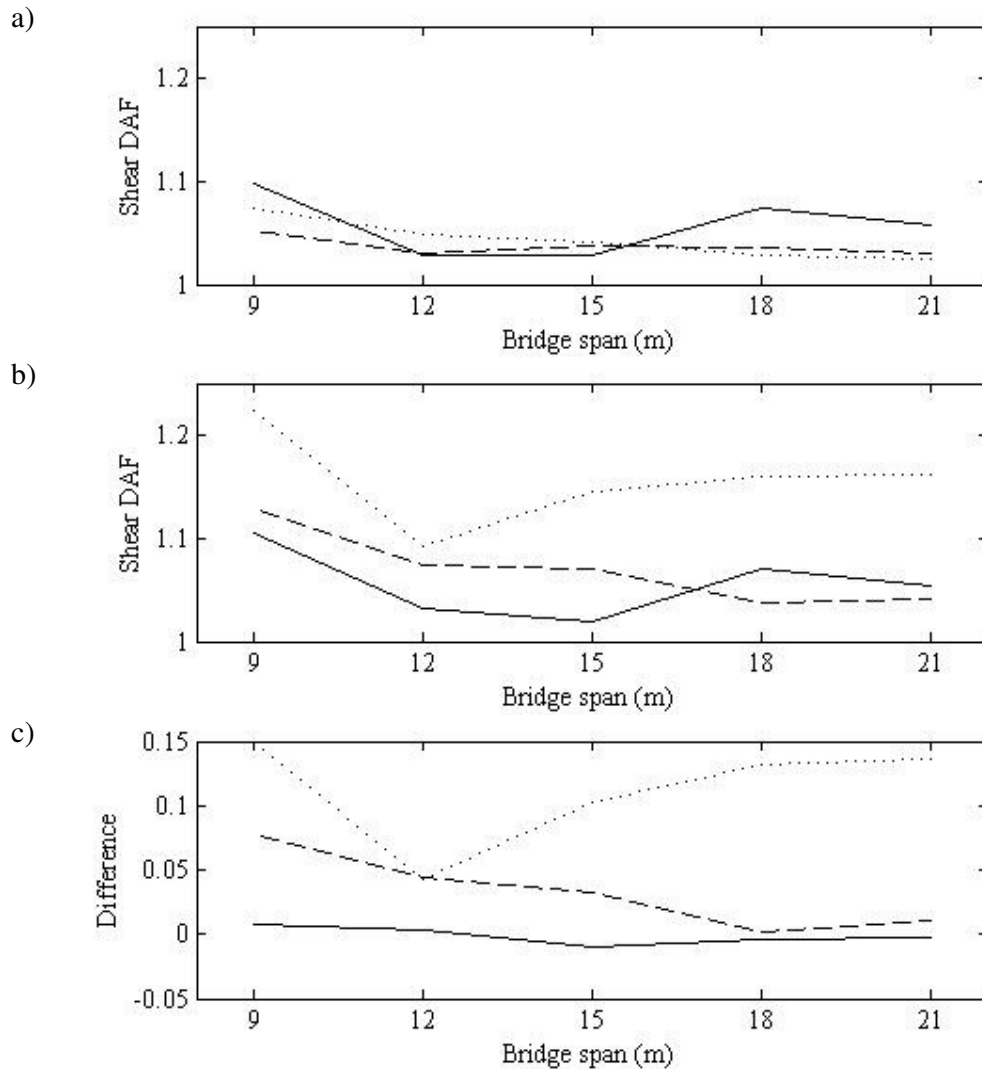


Figure 9: a) Shear DAF for smooth profile; b) Shear DAF for 2 cm bump; c) Difference (Meeting events Type I (dotted), Type II (dashed) and Type III (solid))

Figure 9c shows the small contribution of a damaged expansion joint to the shear DAF in Type III meeting events (two cranes), being Type I (two 5-axle trucks) the most susceptible to the bump depth. Table 4 provides the DAF values obtained for

the 3 truck meeting scenarios, the two bump conditions and 9, 15 and 21 m span lengths.

Span (m) \ Bump depth (cm)	Type I		Type II		Type III	
	0	2	0	2	0	2
9	1.074	1.223	1.051	1.128	1.097	1.105
15	1.042	1.145	1.037	1.070	1.028	1.019
21	1.024	1.161	1.031	1.042	1.057	1.054

Table 4: Mean DAF values for meeting events and smooth surface

4.2 Influence of a Bump on a Rough Road Profile

The influence of road roughness is investigated using a Monte Carlo simulation consisting of 20000 events made of 2 vehicles meeting on the bridge. The variability for each event included different profiles, vehicle speeds, meeting locations, bump depths and bridge spans. Figure 10 shows the mean shear DAF value for all three meeting event types (Figure 8), bridge lengths and bump depths. These figures validate previous results for a wider spectrum.

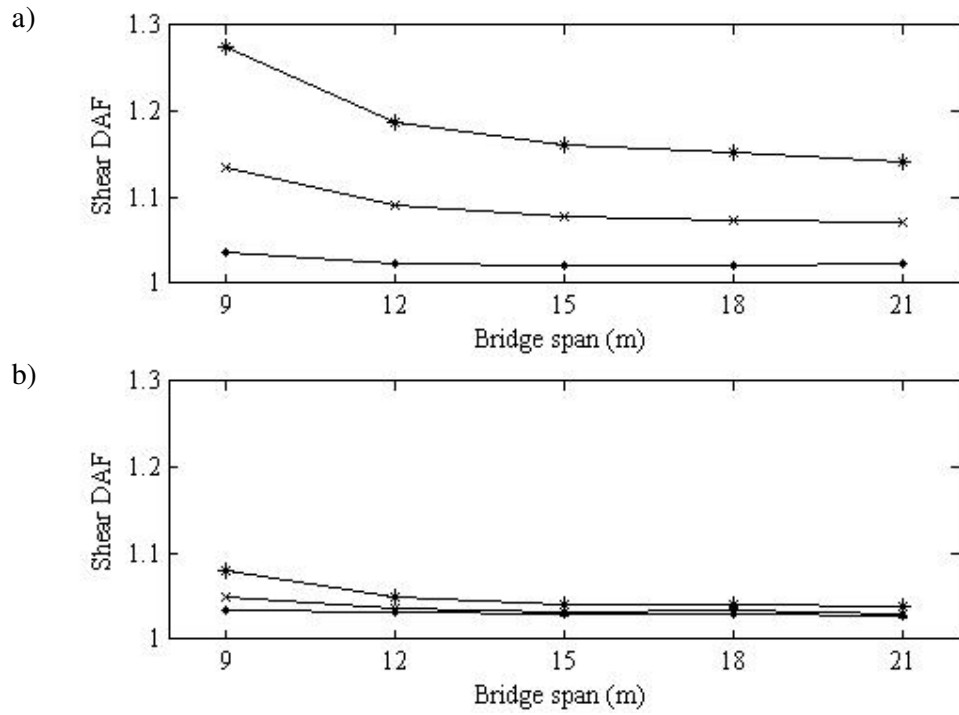


Figure 10(a & b): Mean Monte Carlo simulations results for meeting events a) Type I; b) Type II ("•" No damage; "x" 2 cm bump depth, "*" 4 cm bump depth)

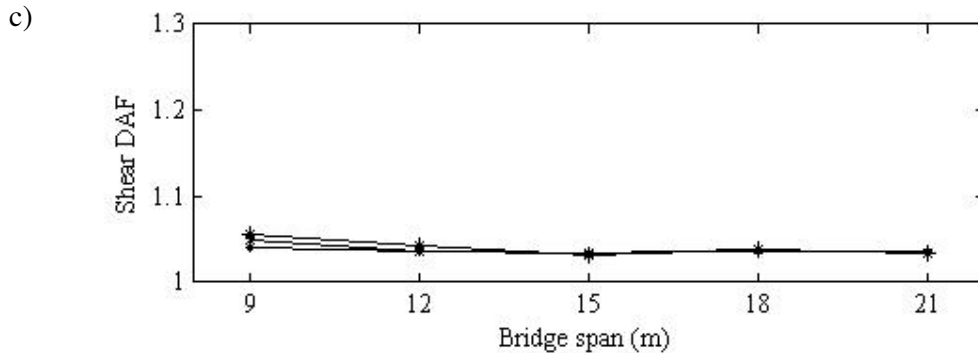


Figure 10(c): Mean Monte Carlo simulations results for meeting events c) Type III ("•" No damage; "x" 2 cm bump depth, "*" 4 cm bump depth)

Figure 11 shows the results obtained from the Monte Carlo simulation for the shortest span being analyzed (9 m), where the highest DAF values have been found. Approximate mean and standard deviation lines have been added to Figure 11, showing that both statistical indicators tend to decrease for larger static shear effects.

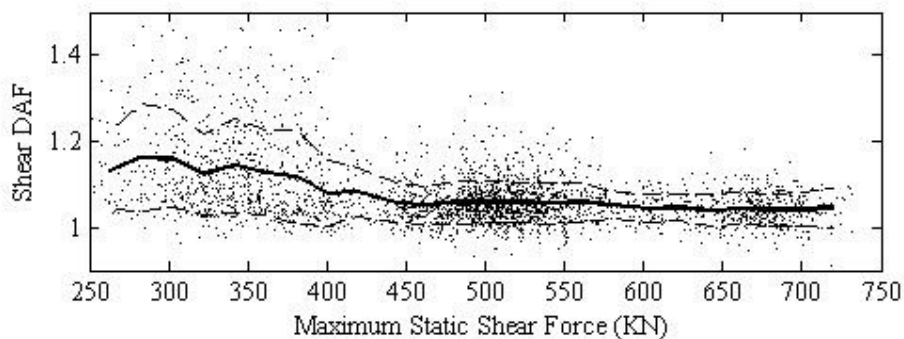


Figure 11: Meeting events Monte Carlo results for L = 9 m; particular event ("•"); mean value (solid line); +/- standard deviation (dashed lines)

Table 5 provides the mean DAF values obtained for the 3 truck meeting scenarios, the three bump conditions and 9, 15 and 21 m span lengths.

Span (m) \ Bump depth (cm)	Type I			Type II			Type III		
	0	2	4	0	2	4	0	2	4
9	1.037	1.136	1.275	1.034	1.050	1.080	1.040	1.049	1.056
15	1.020	1.079	1.160	1.029	1.031	1.041	1.033	1.033	1.032
21	1.023	1.071	1.142	1.026	1.028	1.039	1.037	1.033	1.034

Table 5: Mean DAF values for meeting events and rough surface

The Eurocode (Figure 1) is necessarily conservative because it needs to cover for many uncertainties relating to the dynamic response of a new bridge to traffic. But when assessing a bridge, the knowledge of the response of the bridge to moving loads, on the existing profile and on the traffic at the site can be used to determine a

more accurate dynamic load. This paper has shown how this load is affected by a bump prior to the bridge and how extremely heavy rigid vehicles such as cranes are less sensitive to this irregularity than 5 axle articulated trucks.

5 Conclusions

This paper has addressed the need of exploring the dynamics associated to the shear load effect. The influence of shear DAF values has been investigated by direct comparison of two vehicle configurations, a typical 5-axle truck and a crane truck, as well as some possible meetings of two trucks on a bridge. Using a numerical VBI model and Monte Carlo simulation, a sensitivity study has been carried out for many possible bridge spans, speeds, vehicle characteristics, severity of damaged expansion joints and profile roughness. The results clearly show that the highest shear DAF values occur on shorter spans and that they are directly related to the damage severity of the expansion joint. Furthermore, massive rigid vehicles with a lot of axles like cranes, that could govern the assessment of a bridge, are less influenced by large road discontinuities prior to the bridge and tend to produce significantly smaller dynamic increments on shear than 5-axle trucks. Overall, the higher the static load effect, the smaller the dynamic amplification factor for shear forces at supports.

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