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Dynamic Analysis of Multi-Span Bridges under Moving Wheel Loads

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Abstract

This work is aimed at presenting response studies for the dynamic analysis of various types of RC bridges. The emphasis is to provide an evaluation of the 'impact factor', which is often used to incorporate the dynamic effects in conventional analyses of bridges. After interpreting the results from numerical formulation with theoretical results, a detailed parametric study is performed in this work to investigate some important details of the behavior of Deck Girder, Balanced Cantilever and Continuous Bridges based on dynamic analysis under the moving loads. Various aspects of the dynamic response of RC bridges are studied, comparing with the conventional static structural analysis and changing the vehicular velocity, damping ratio and number of spans. The resulting effects on bridge deflection, bending moment and shear are observed.

Keywords: Emphasis • Conventional methods • Deflection • Balanced cantilever • Continuous bridges

Introduction

Reinforced Concrete (RC) bridges are extensively used in the city roads, highways and rural areas. The durability, economy and aesthetic beauty of RC bridges make them an attractive option for the highway bridges. The advancement of technology of construction and pre-stressing has increased their use further. The structural analysis and design of bridge provide a challenging project featuring various branches of Civil Engineering. An important part of this study is the evaluation of the conventional method of structural analysis of bridges. A comparison of the design forces and deflections from the static and dynamic analysis of bridges is made and the validity and limitations of the static analysis is studied. The structural analysis for bridges rarely goes beyond the conventional methods of static structural analysis. The dynamic effects of moving loads are believed to be considered by incorporating an 'impact factor' with the static load analysis, which is considered irrespective of the type of structure or the velocity and arrangement of the moving wheel loads [1]. This work presents a more rational dynamic analysis of various types of bridges, i.e., the simply supported deck girder bridge, the balanced cantilever bridge as well as multi-span continuous bridge, providing a more thorough and rational evaluation of the dynamic impact factor for single- axle load and for the multi-wheel HS20 loading, an AASHTO standardized arrangement of wheel loads.

Materials and Methods

Impact factor and dynamic effects

TAs mentioned, the live load analysis of bridges has traditionally followed the static analysis method with an impact factor suggested to incorporate the effect of dynamic effects or sudden application of moving loads [2]. Detailed procedure for the static analysis of beams and trusses for wheel loads has been outlined in several texts including the widely used one by while the application to RC bridges is included in texts on reinforced concrete of a number of design books on RCC bridges.

The impact factor differs between various design codes but they follow the general formula of a non-dimensional unit, which is a decreasing function of the loaded length of bridge. No other parameter, like the vehicular speed, the number of spans or the structural damping factor is incorporated in the formula. Although this approach is widely used in the analysis and design of RC and steel bridges, a number of papers have been written to investigate the need for a more rigorous dynamic analysis. Among recent works on this topic are a series of papers by Yang and co-workers, Yau and co-workers on the impact effect on simple and continuous bridges due to high-speed vehicles [3]. These papers studied such effects as the vehicle-bridge interaction, riding comfort, resonant velocity, effect of the number of spans etc. Significant works on this topic also include papers by and others on the resonance on continuous bridges, on dynamic interaction between moving train and bridge, while used modified vibration functions for the study on multi-span bridges under moving loads [4].

Theoritical dynamic analysis for single moving load

In order to verify the numerical method used in this work, the results for a simple case are compared with known theoretical results [5]. The midspan deflection of a simply supported beam due the movement of a single wheel is obtained theoretically in this section. The theoretical formulation is taken from Table 1 shows the comparative theoretical and numerical values of maximum midspan deflections for simply supported beams of different lengths and structural properties. A moving wheel load of 70 kN, and traveling velocities of 25, 50 and 100 km/hr are chosen for the comparison. The convergence of the numerical study is also shown in the table by increasing the number of elements from 4 to 8 in each case.

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Table 1. Results for one wheel on simply supported beam.

Speed km/hr	Length m	Unit mass kg/m	Method of analysis	Midspan deflection cm
25	15	150	Theory	-3.42
			Num(4)	-3.47
			Num (8)	-3.47
50	15	150	Theory	-3.48
			Num(4)	-3.49
100	15	150	Num(8)	-3.48
			Theory	-5
100	18	250	Num(4)	-5.03
			Num(8)	-5.03
			Theory	-9.55
			Num(4)	-9.49
			Num(8)	-9.5

Structural models used for the numerical analyses

In this work dynamic analyses have been carried out for Deck Girder (called DGB in this study), Balanced Cantilever (BCB) and Continuous Bridges (CB). The cross-sectional and material properties of the bridges have been based on values assumed for typical RC members. Figures 1-4 show the side elevations and cross-sectional properties of the bridges under study. It may be mentioned here that although the sectional properties of BCB and CB are usually variable, they are chosen to be constant in this study for simplicity [6]. The Deck Girder bridge used here is 15 m long, while the Balanced Cantilever as well as Continuous bridge are both 65 m long. For both, the first and last span-lengths are 20 m but the middle span is 25 m long [7]. The difference between the BCB and CB is the presence of two internal hinges that make the BCB statically determinate. For all the bridges, the deck slab is 15 cm thick while the girders are 30 cm wide with clear spacing among them being 1.45 m each.

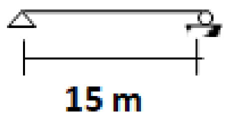

Figure 1. The Deck Girder Bridge (DGB).

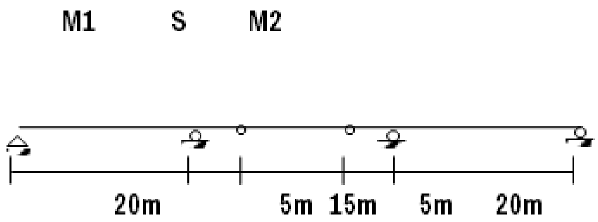

Figure 2. The Balanced Cantilever Bridge (BCB).

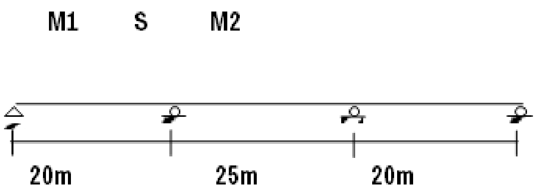

Figure 3. Continuous Bridge (CB).

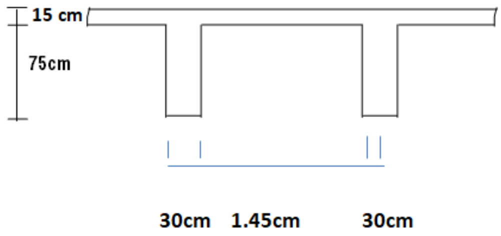

Figure 4. c/s Area of slab-girder system.

Results and Discussion

Static load analysis

From the static analysis the deflections and bending moments are found when the HS20 loading is moved on the bridges. Although the load is dynamic (i.e., moving) the effects of inertia forces are ignored in a purely static analysis.

Dynamic load analysis

The deflections and bending moments are also obtained from dynamic analysis by moving the HS20 load over the bridges and considering in the dynamic analysis the inertia effects; i.e., the mass as well as damping. For the Deck Girder Bridge the deflection and moment at midspan are chosen for comparison. Thus the maximum deflections are negative and bending moments are positive, which is typical of simply supported beams. However, in addition to the significant magnification of moments due to dynamic effects (especially when V=100 km/hr), the presence of significant negative moment for the undamped case suggests a possibly risky design condition, because using static analyses the DGB is designed for positive moments only [8]. But for the Balanced Cantilever bridge the deflections are compared at the midspan of the structure (M2), the positive bending moment at middle of the left span (M1) while the negative moments are calculated at the support Similar sections are chosen for the Continuous bridge as well. The importance of dynamic analysis is apparent from the results and impact factors presented in Tables 2 and 3. In these cases, the dynamic results are often significantly greater than the static results particularly for the faster moving vehicle (V=100 km/hr). Several of the impact factors are much greater than even the upper limit (0.30) of the impact factor suggested by AASHTO. However, this is not so for the slower vehicular speeds.

Table 2. Results from static and dynamic analyses.

Bridge Type	Velocity km/hr	Damping ratio	δ max cm	$M^{(+)}_{max}$ kN-m	$M^{(-)}_{max}$ kN-m
	Static	0%	-6.8	483.44	0
	50	5%	-7.62	525.41	-32.51
DGB		0%	-7.83	540.19	-33.73
	100	5%	-8.44	587.98	-71.93
		0%	-8.63	598.27	-89.28
	Static	0%	-16.67	679.9	-722.73
	50	5%	-18.32	751.14	-788.76
BCB		0%	-18.96	773.78	-838.99
	100	5%	-29.38	877.53	-949.41
		0%	-34.87	946.49	-1090.59
	Static	0%	-15.58	540.63	-365.96
	50	5%	-16.89	584.81	-385.64
CB		0%	-16.22	594.41	-404.31
	100	5%	-23.56	682.37	-485.19
		0%	-25.24	705.8	-521.84

Table 3. Maximum impact factors.

Bridge Type	Velocity Km/hr	Damping ratio	Impact factor for δ	Impact factor for BM	Impact factor for BM
	50	5%	0.12	0.09	0.05
		0%	0.15	0.12	0.09
DGB					
	100	5%	0.24	0.22	0.19
		0%	0.27	0.24	0.19
	50	5%	0.1	0.1	0
		0%	0.14	0.16	0.01
BCB					
	100	5%	0.77	0.31	0.14
		0%	1.09	0.51	0.35
	50	5%	0.08	0.08	0
		0%	0.04	0.1	0
CB					
	100	5%	0.51	0.33	0
		0%	0.62	0.43	0.07

The time series variations of all the results cannot be shown within the limited scope of the paper. Only the variations of bending moments for the continuous bridge are presented in Figures 5-10. The results for the static analyses as well as dynamic analyses for damped (5%) and undamped systems are shown in the figures for the two speed cases mentioned before [9]. As mentioned before, the bending moments are shown at the middle of the left span (M1) of the bridge as well as at the support (S) denoted in.

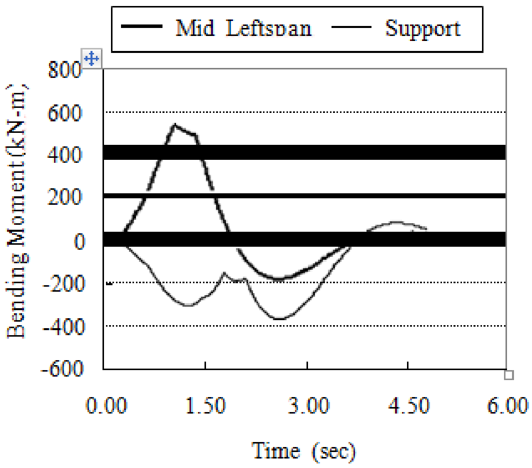

Figure 5. Bending moment for CB (Static, V=50 km/hr).

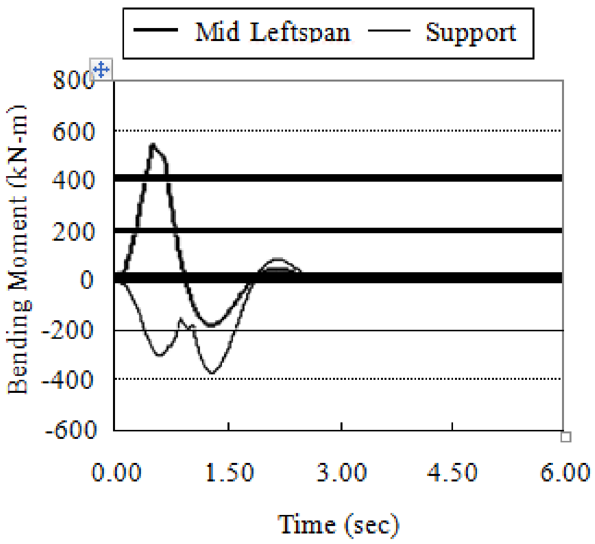

Figure 6. Bending moment for CB (Static, V=100 km/hr).

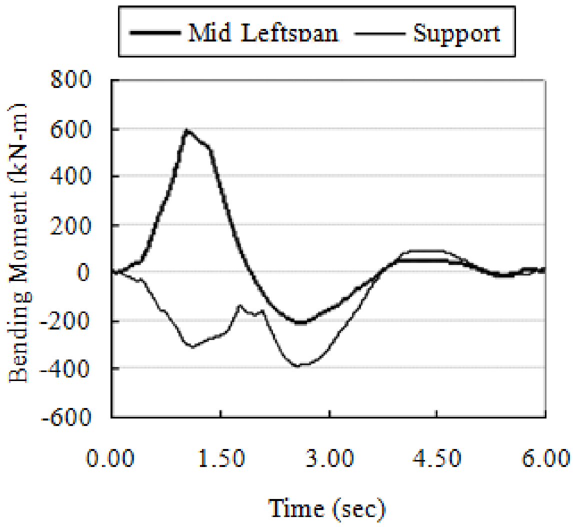

Figure 7. Bending moment for CB (5% Damped, V=50 km/hr).

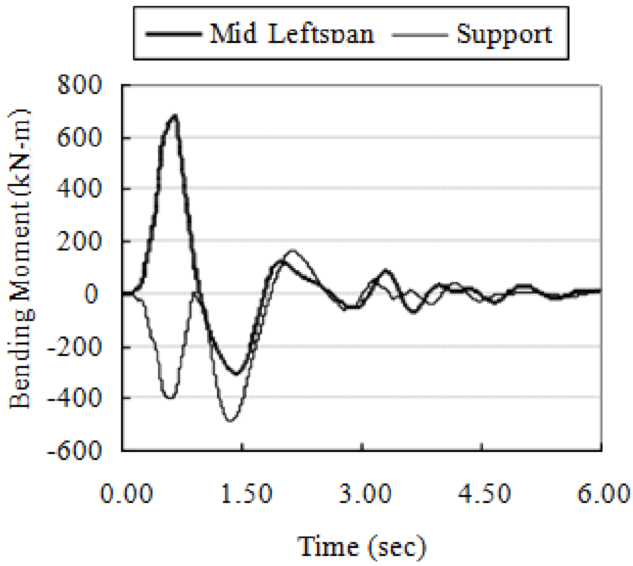

Figure 8. Bending moment for CB (5% Damped, V=100 km/hr).

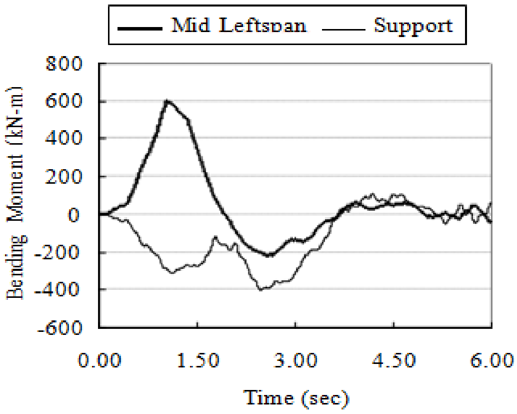

Figure 9. Bending moment for CB (Undamped, V=50 km/hr).

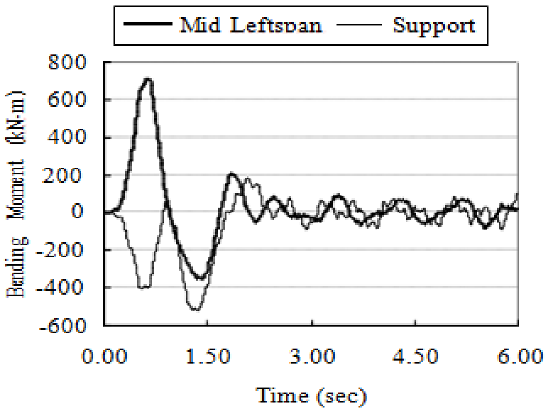

Figure 10. Bending moment for CB (Undamped, V=100 km/hr).

Analysis of multi-span ridges

In order to show the effect of the number of spans on the behavior of continuous bridges, the study is extended to include multi-span bridges. Table 4 summarizes the results (only the bending moments at the first support) for multi-span continuous bridges (of 2, 3 and 4 spans, each 30 m long). The results show that the maximum bending moments do not change significantly with the number of spans [10]. Particularly, the maximum moments for the 3-span and 4-span bridges are almost identical. Here also the maximum impact factors are shown to be very high for V=100 km/hr but are within the AASHTO specified limit for V=50 km/hr. Another significant result from the dynamic analyses is the presence of alternating (positive and negative) moments, which makes it imperative to design the sections using substantial amount of positive and negative reinforcements [11-13].

Table 4. Results for multi-span continuous bridges.

Type of bridge	Velocity km/hr	$M_{(max)}$ kN-m	Impact factor
		-520	
	Static		
		-587.18	
2Span CB	50		0.13
		-948.99	
	100		0.82
		-553.44	
	Static		
		-641.06	
3Span CB	50		0.16
		-903.7	
	100		0.63
		-555.91	
	Static		
		-641	
4Span CB	50		0.15
		-904.48	
	100		0.63

Conclusion

The main conclusions of this study are: In most of the results shown, the dynamic forces and deflections for the undammed structure are greater than the results for damped structure, followed by the static results, which is a natural conclusion. However, the effects of dynamic analysis appear to be more important for deflections and bending moments than for the shear forces.

The vehicular speed is a crucial factor in the dynamic effects on bridges. In this study, the faster vehicle (at V=100 km/hr) was almost always found more critical than the slower moving vehicle (at V=50 km/hr). A relationship with the structural properties with vehicular speed should provide a more rational conclusion.

The impact factor suggested by AASHTO was found adequate for the slower moving vehicle but sometimes largely underestimated the impact factor found from the faster vehicle. Some of the impact factors are found even greater than 1.0. Moreover, the impact factor is shown to depend on the type of bridge, vehicular speed, damping ratio and the parameter considered (i.e., moment, shear or deflection).

In addition to the impact factor, another significant feature was the oscillating nature of the deflections and forces. This may render the structural design of the bridge unsafe or inadequate if the RC sections are not sufficiently reinforced to resist both moments.

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