Susceptibility of the Critical Structural Components of Railway Bridges to the Changes in Train Speed

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Abstract
Modern trains with different axle configurations, speeds and loads are used in railway networks. As a result, one of the most important questions of the mangers involved in bridge managements systems (BMS) is how these changes affect the structural behavior of the critical components of the railway bridges. Although researchers have conducted, many investigations on the dynamic effects of the moving loads on bridges, the influence of the changes in the speed of the train on the demand by capacity ratios of the different critical components of the bridge have not yet been properly studied. This study is important, because different components with different capacities and roles for carrying loads in the structure may be affected differently. To investigate the above phenomenon in this research, a structural model of a simply supported bridge is developed. It will be verified that the dynamic behavior of this bridge is similar to a group of railway bridges in Australia. Demand by capacity ratios of the critical components of the bridge, when it is subjected to a train load with different speeds will be calculated. The results show that the effect of increase or decrease of speed should not be underestimated. The outcome is very significant as it is contrary to what is currently expected, i.e. by reducing the speed of the train, the demand by capacity ratio of components may increase and make the bridge unsafe for carrying live load.

Keywords: Train Speeds, Axles Spacing, Criticality, Bridge Management System

1. Introduction

In every bridge management system, one of the most important aims is to determine whether the bridge is safe and serviceable to live load. Constantly assessing the condition of bridges and rating them is one of the significant tasks of managers and engineers. The structural behavior of a bridge and its ultimate capacity are mainly dependant on the condition of its critical components [1, 2]. The critical components are those whose any failure can cause the failure of a portion or the collapse of the whole structure [3, 4]. Depending on the type of loads applied to the structure including live load, earthquake, wind, collision, or flood, the criticality of components will change [5, 6].

Live load is of great interest, as the aim of building a bridge is to carry live load with the acceptable level of safety. Live load changes over time, as new types of trains with different loads and speeds are used in railway systems. Sound dynamic analyses are required to determine the effect of changes in load and speed on the demand by capacity ratio of the critical components of the bridge.

Many researchers have studied the dynamic behaviour of bridges to live load [7-10]. Chan et.al [11, 12] investigated the bridge responses to twisting and pitching modes. Xia et.al [13] developed formulations for a three dimensional model of a suspension bridge. Kim [14] conducted experimental studies to investigate the influence of track structure including rail, sleeper, ballast on the railway bridge. Lee et.al [15] evaluated the dynamic response of a monorail bridge by establishing a procedure, including analytical, experimental and field test. The focus of the all above studies was on some particular modes or only on some specific response. The effects of the increase of the speed of the train considering the ultimate capacity of the critical components of the bridge have not been investigated.

The resonant vibration of railway bridges was investigated by Xia et.al [16]. The outcome of their research identifies the natural frequencies of the train motion, the axle spacings of the train, the span length and the stiffness of the bridge in lateral and vertical directions, as the main parameters for resonant vibration of railway bridges. The studies of Liu et.al [17] identified the speed of the train, the bridge damping ratio, the vehicle by bridge mass ratio, and the vehicle by bridge natural frequency ratio as the factors which have a significant impact on the dynamic behaviour of the bridge.

Therefore, it can be concluded that the focus of the past research was on evaluating the dynamic response of the bridge when it is subjected to train loads. The effect on internal forces such as moment, axial, shear or the combination of them induced by train loads, with respect to the capacity of different components have not been taken into consideration. In other words, the susceptibility of the different critical structural components of the bridge to the changing speed of the train has not been taken into account.

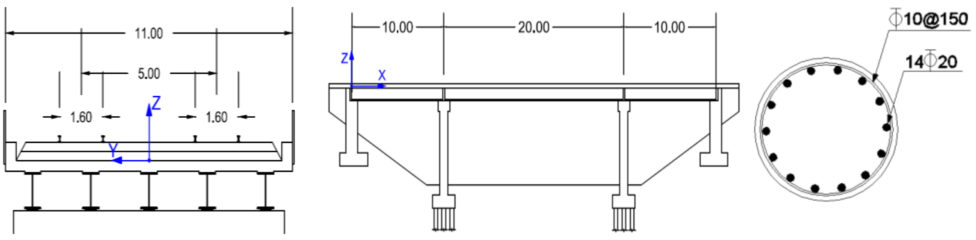
This research will focus on evaluating the sensitivity of the critical components of a bridge to the changes in train speed through calculating the demand/capacity ratio. Demands means the internal stresses generated in components due to live and dead load. The capacities of the different components are the combined strength capacities for carrying internal axial, and shear forces and moments, and these capacities will be calculated, based on structural member, e.g. beams, and columns.

The unique, important outcome of this research will be its anticipated influence on the decisions made by engineers and managers on the safety of the railway bridges when they carry new train loads with different speed and axles' configurations.

2. Modelling

To investigate the impact of the increase of the speed of the train on the critical structural components of a railway bridge, a 3D finite element model of the bridge is created by using CSI Bridge Software. CSI Bridge is a structural and earthquake engineering software, developed by Computers and Structures, INC in USA. Figure 1 shows the geometry of the bridge under consideration. The bridge is subjected to train load with different speeds. It is first analyzed and designed for a single (intermediate) speed and then its performance is checked under other train speeds. Results for demand/capacity ratios of different components were recorded. AASHTO LRFD 2007 [18] , ACI 318-05/IBC2003 [19] and AISC360-05/IBC2006 [20] have been used for the bridge design.

Two bents and two abutments support the whole deck, and three columns transfer the loads of each bent (Figures 1 and 4). Circular columns C1 and C2 with 700 mm diameter are considered as shown in Figures 1-c and 4. L100×100×10 are utilized for diaphragms. The space between diaphragms is 5 meters. The composite deck with I steel girders e.g. P1, P2 and P3 shown in Figure 4, are used. The height of the I section is 1170 mm, the thickness of flange is 30 mm, the thickness of web is 16 mm. The thickness of the concrete slab is 300mm and it is modeled with shell elements. The interaction between the concrete slab and I section of the deck has been taken into consideration. The two side spans are 10 m long and the middle span is 20 m. All spans are simply supported structures.



a) Deck b) Spans c) Column Section

Fig. 1 The geometry of the structure, and the cross section of the columns

At bent supports, translations in all directions are fixed and all the three rotations about their local axes are free. At the abutments supports, translation in vertical direction and rotation about longitudinal axis are fixed and all other degrees of freedom are free. Figure 2 shows the train load applied to the bridge. This load moves across the bridge in opposite directions with the same speed, and entering the bridge at the same time. For different speeds, linear dynamic structural analysis is conducted. In order to capture dynamic effects, time history (direct integration) load case has been selected instead of static moving load case.

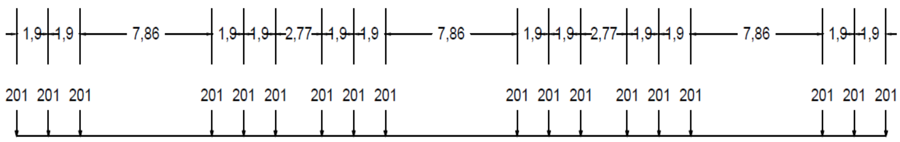


Fig. 2 Moving Load (Forces are in KN and Distances are in Meter).

The Dead Loads applied to this bridge are, the weight of the structural components calculated by CSI Bridge Software. The magnitude of the Superimposed Dead Load on the deck, due to weight of ballast, rail, sleepers, and non-structural components etc calculated to be 10 KN/m2 and applied to the bridge.

In order to validate the dynamic behavior of the model, the Natural Frequencies of the real bridges with different span lengths investigated by Chan et.al [(8)] and shown in Table 1, have been used. Similar to the model developed in this research, these bridges are simply supported bridges and their decks are composite concrete slab with steel girders. As can be observed, the span lengths of the bridges mentioned in Table 1 are between 11.28m to 13.72m and the span length of the middle span of the model developed in this research is 20m.

Table 1. Summary of Natural Frequencies for Composite Concrete Slab and Steel Girder Bridges [(8)]

Bridge	Mass (kg/m)	E (GPa)	I_x (m^4)	L (m)	f (Hz)	Lf (mHz)
Six Mile Creek (1st)	5600	200	0.0213	11.28	10.8	121.82
Six Mile Creek (1st)	5600	200	0.0256	13.72	8.0	109.76
Bremer River (1st)	7740	25	0.2279	11.43	10.3	117.73
Bremer River (2st)	7740	25	0.2897	13.72	8.1	111.132
Goodbye Creek	5600	200	0.0228	13.38	7.9	105.702
Sandy Creek	6250	200	0.0304	11.276	12.2	137.57
St. Aranadus Creek	6500	200	0.0235	11.4	10.3	117.42

In Table 1:

E: Modulus of Elasticity
I_x: Second Moment of Area
L: Span Length
f: Natural Frequency of Bridge
Lf: Span Length multiplied by Natural Frequency of Bridge

In order to validate whether the dynamic behavior of this model so that its response is similar to real bridges, it is necessary to find an equation, which estimates the relation between span length of a simply supported bridge with its dominant natural vertical frequency. Based on that, it will be possible to investigate, whether the natural frequency of this model is close to the natural frequency of the real bridges, and as a result, the dynamic behavior of this model is similar to real bridges. Figure 3 shows the relation between span length and natural frequencies of the bridges mentioned in Table 1.

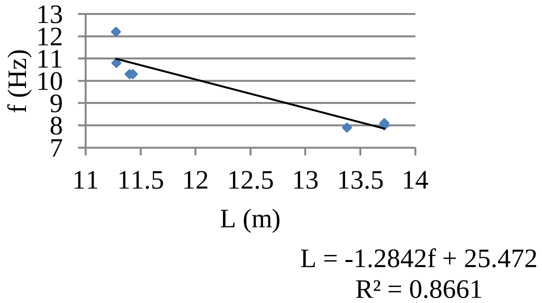


Fig. 3 The relation between Span Length and Natural Frequency of the above bridges

Based on Figure 3, the following function (Eq. 1) can be formulated, which may represent the relation between span and natural frequency of the real bridges.

$$\text{Span} = -1.2842\text{f} + 25.472 \tag{1}$$

From Eq. 1, for $\text{f} = 3.97$ Hz, which is the natural frequency of the developed model in this research, L will be almost 20m, which is the length of the middle span of this model. Therefore, it can be assumed that the section properties and the dimensions used for the components of this model are realistically selected.

3. Results

The structural analyses are conducted on this model, considering moving loads with different speeds from 20 to 300 km/hr. The results of demand/capacity ratio of the critical components including columns and girders shown in Figure 4, when a train passes over the bridge with different speeds are shown in Figure 5. Based on ACI 318-05/IBC2003 [(19)], columns have been checked for axial force and biaxial moments. In addition, they have been checked for shear in both directions. Beams members have been checked for stresses due to axial and shear forces and biaxial moments according to AISC360-05/IBC2006 [(20)].

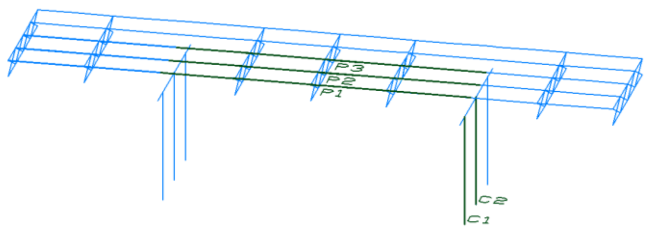


Fig. 4 Critical Component

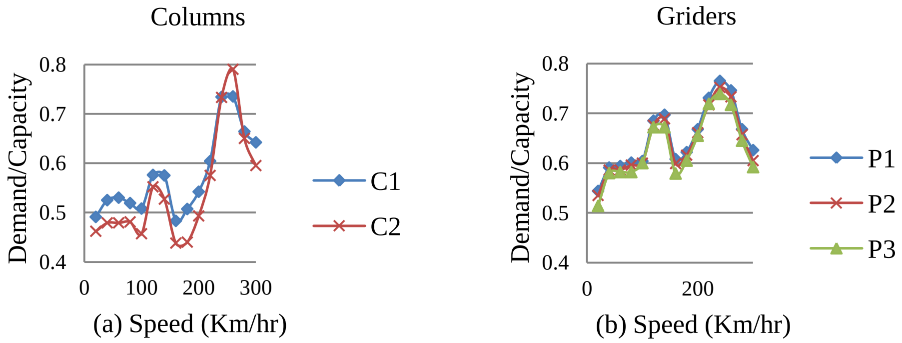


Fig. 5 Demand/Capacity ratio of the bridge structural components Vs speed of the train

As can be observed in Figure 5, distinctive peaks appeared at certain speeds in the middle span. These peaks mean larger forces will be applied on those components. It is has been identified that when the frequency of the load multiplied by an integer is equal to the natural vertical frequency of the bridge resonant responses takes place and as a result, these peaks appear. The speed of the train, the distance between axles and the natural frequency of the bridge are the parameters that influence resonance.

Figure 5 shows that, the dynamic effect of the changes in the speed of the train on vertical vibration of the bridge can have a very high impact on the internal forces and consequently demand by capacity ratio of the critical components of the bridge. It can be observed that, the increase of speed may not always increase the demand by capacity ratios. In other words, for the train with lower speed these ratios can be higher and as a result, the railway bridge can be in more critical condition.

4. Conclusion

The safety and serviceability of the railway bridges are dependent on their structural condition. Based on the condition of the critical components of the bridge and the magnitude and speed of the applied loads, the overall condition of the bridge will be evaluated. In this paper the effect of increase in speed on critical components has been investigated though performing dynamic analysis. Demand by capacity ratio of the critical components is calculated to evaluate the sensitivity of them to the increase or decrease of the train.

The results show the significant effects of the changes in the speed of the trains, on demand by capacity ratio of the critical components of the railway bridge. The outcomes depict that, when the frequency of the train load is close to the natural frequency of the bridge, resonance will take place, and as a result, the internal forces may unexpectedly increase and based on the different capacities that different components have, they may be affected to different extents. The outcome of this research is very significant as it shows that, reducing the speed of the train on the contrary to current expectations, may subject bridges to danger more than before, especially by increasing the effect of fatigue in the long run.

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