Effect of Curvature on the Dynamic Response of Composite Steel I-Girder Bridges

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Abstract. Elaborated three-dimensional finite element models are generated to study the effect of the radius of curvature on the free vibration and dynamic response of the composite steel I-girder bridges. The bridge is modelled by using ANSYS 15.0 program with solid and shell elements to represent concrete and steel members, respectively. AASHTO LRFD HL-93 truck is idealized as 3D model consisting of five lumped masses connected by rigid beams and supported by spring-dampers. The profiles of road surface roughness are generated by MATLAB developed program depend on the power spectral density (PSD). The models used are capable to take all bridge and vehicle characteristics into consideration. The dynamic responses of the horizontally curved bridge are investigated under conditions of various vehicular loading positions. The dynamic behaviour is presented in terms of Impact Factors (IM). The results show that the bridge natural frequencies are significantly affected by the radius of curvature. The relationship between the IM and the radius of curvature is governed by the position of vehicle on transverse sections of the bridge. AASHTO LRFD specification tends to underestimate the values of IM.

Keywords. Curvature, Dynamic Response, Composite Steel, I-Girder Bridges.

1. Introduction
A significant portion of bridge structures, construction found in many cities, are horizontally curved. These bridges are usually used in large intersections to facilitate traffic, in addition to improving the sense of aesthetics. This type of structures, however, has inherently created new design problems for engineers [1]. The horizontally curvature bridge and its members are subjected to coupled torsion and bending. So that, it shows more complexity than straight bridge. Generally, the static response usually increases by a single impact factor (IM) taking the dynamic effect into consideration in the bridge design. Many codes have adopted the same concept for varied bridge dynamic responses which assumed that the impact factor as a function of a single parameter such as the span length or fundamental frequency of structure. This results in bridge designs that may satisfy strength requirements but may have undesirable dynamic responses, such as large deflection and increased in the stresses, which affect the long-term bridge performance. Dynamic stresses that are developed under the action of heavy trucks running across a bridge deck may exceed those predicted by incrementing static stresses by the IMs specified in bridge design codes [2]. So that, this design approach is surely an oversimplification but misrepresentation of many complex phenomena, as the bridge dynamic behaviour [3]. Relatively, few studies have been conducted on the investigation of the dynamic behaviour of horizontally curved bridges. Tan and Shore (1968) [4], analysed a simple supported span curved bridge under the action of moving force, where the torsional effect was studied.
in both of free vibration and the forced vibration. A free vibration response of continuous horizontally curved multiple-box girder bridges was studied by Samaan et. al. (2007) [5], it was noted that the first bridge frequency decreased with increase of the bridge curvature. Fangping and Jianting (2012) [6] investigated the influence of curvature on the dynamic displacement of horizontally curved box girder bridges under the action of pre-stressed tendons. Their study indicated that the mid-span vertical displacement value significantly related to the horizontal radius of curvature. A parametric study was conducted by Najafabadi et. al. (2017) [7] evaluating the effects of speed of moving vehicle and the arc length to radius of curvature ratio (L/R) on the value of the impact factor (IF). Xiaodong et. al. (2017) [8] introduced a study to estimate the dynamic behaviour of a four span horizontally curved box girder by using a 3D finite element model, it concluded that the loading position had a great effect on the bridge dynamic responses. In spite of these studies, no single formula of impact factor was predicted. For these reasons, this paper aims at studying the free vibration and dynamic response of bridge-vehicle interaction system where 3D finite element models of horizontally curved composite steel I-girder bridges and AASHTO HL-93 truck are developed by using ANSYS 15.0 program.

2. Finite element model
Commercially available ANSYS (APDL) program is adopted to develop a three dimensional FE models to study the problem of bridges-vehicle interaction system. This program is capable of carrying out the free vibration, static, and dynamic analyses.

2.1. FE modeling of bridge
Slab, girder, crossbeam, and lateral bracing are considered as the main component of the composite steel I-girders bridges. These elements are usually made from two materials: concrete and steel. The Wildcat Creek Bridge is selected to study. It is located in Indiana, USA [9]. The bridge consists of three spans each of which has a 15˚ skew angle, which is ignored in this analysis. A middle span, with 60ft (18.288m) long and 27ft 10in (8.484m) wide, is selected. The concrete deck comprises of five steel girders of type (W30x124) spaced at 5ft 7in (1.702m). The deck slab is 7in (0.178m) thick, act integrally with the supporting girders by means of shear connectors welded to the top flange of the steel section and embedded in the slab. More details of the bridge deck are shown in figure 1. Steel diaphragms of type (C15x33.9) which are located at every 12ft (3.657m), are connected to the steel girders. Four models are made with different radius of curvature (R = 200, 100, 50, and 35 m).

![Figure 1. Geometry of Wildcat Creek bridge [9].](image)

In ANSYS model [10], hexagonal 8-nodes SOLID185 element and quadrilateral 4-nodes SHELL181 element are used for representing the concrete members and steel components, respectively as shown in figure 2. Concrete and steel members share the same nodes to achieve a full composite action between the bridge components. Concrete deck has a mass density of 2350 kg/m³, modulus of elasticity equals to 24.9 GPa and Poisson ratio 0.2. While, all the steel members have 7697 kg/m³ as a mass density, modulus of elasticity of 200 GPa, and Poisson ratio 0.3. The boundary conditions at the end of the main girders are hinged and roller supports. The roller support is modelled by releasing the horizontal movement at tangential direction. However, the hinged support is constrained from any horizontal movement. All supports were constrained in vertical direction, but they are allowed to rotate around support line.
2.2. FE modeling of vehicle

The HL-93 truck, standard AASHTO LRFD truck [11], is adopted in this study as a moving vehicle. A 3D mass-spring-damper model is developed by using ANSYS program to model of truck as shown in figure 3.

Five lumped masses, that were modelled by using ANSYS MASS21 element which is a point element having up to six degrees of freedom including: translations in the x, y, and z axis and rotations about the x, y, and z directions as shown in figure 4.a, are used to identify the three wheel axle, tractor and semi-trailer of the HL-93 truck. All of these lumped masses are connected by rigid beam and supported by spring-damper. The upper and lower spring-dampers in the vehicle model are used to represent the suspension of vehicle body and tires, respectively. COMBIN40 element is used for identification of the spring-damper element in the ANSYS model. COMBIN40 element, figure 4.b, has two nodes, which consists of a spring-slider and damper in parallel, which coupled to a gap element. The rigid beam that is used to connect of the lumped masses in vehicle model is modelled by Beam4 element in the current FE model. Properties of the masses, springs stiffness, and damper coefficients that were suggested in Wang and Huang report [12].
2.3. Road roughness model

The roughness of bridge deck surface is an important factor which affects the dynamic behaviour of bridge-vehicle interaction system. In the current study, the road roughness profile effect is taken into consideration, where the road profile is generated by using developed MATLAB program. A widely acceptable Power Spectral Density PSD function, which was introduced by Dodds and Robson [13] is used in this study. It assumed that the road roughness profile is homogeneous and isotropic two dimensional Gaussian random processes, equation (1).

\[
S(\varnothing) = S(\varnothing_o) \left( \frac{\varnothing}{\varnothing_o} \right)^{-w_1} \quad \text{for} \quad \varnothing \leq \varnothing_o \\
S(\varnothing) = S(\varnothing_o) \left( \frac{\varnothing}{\varnothing_o} \right)^{-w_2} \quad \text{for} \quad \varnothing > \varnothing_o
\]

(1)

Where; \( S(\varnothing) \) is Power spectral density PSD \((m^2/cycle/m)\), \( S(\varnothing_o) \) is Roughness coefficient \((m^3/cycle)\), \( \varnothing \) is Wave number \((cycle/m)\), \( \varnothing_o \) is discontinuity frequency = \(1/2\pi \) \((cycles/m)\), and \( w_1, w_2 \) is roughness exponents.

The International Organization for Standardization (ISO 8608, 2016) [14] has defined a road roughness classification from very good to poor based on the values of roughness coefficient \( S(\varnothing_o) \). In this study, the roughness coefficient values is taken as \((20*10^{-6}) m^2/cycle/m\), for good road surface. The road profile is generated by using a random numbers having normal (Gaussian) distribution with zero mean and specified variance value. The value of variance affect by the roughness coefficient in equation (2).

\[
(x) = \sum_{k=1}^{N} \sqrt{2S(\varnothing_k)} \Delta \varnothing, \cos(2\pi \varnothing_k X + \theta_k)
\]

(2)

Where; \( N \) is number of sinusoidal components, \( \varnothing_k \) is the spatial frequency associated with \( i^{th} \) component, \( \Delta \varnothing_k \) is Bandwidth of the \( i^{th} \) component vary \((0.011 - 3.281) \) cycle/m, \( \theta_k \) is a random phase angle uniformly distributed \((0 \text{ to } 2\pi)\) for \( i^{th} \) profile, and \( X \) is longitudinal distance \((m)\).

The generated road profile corresponding to ISO classes shown in figure 5, where the \( x \)-axis represents the length of the approach road and bridge deck, and the \( y \)-axis illustrate the vertical distance between the road surface tips from zero surface level. The road roughness is input as stroke of the actuator element (LINK11) in the current ANSYS FE model.

2.4. FE modeling of bridge-vehicle-interaction

ANSYS node-to-surface contact technology is adopted to couple the motion of the vehicle and bridge deck using CONTA175 and TARGE170 elements, where the two system components affect each other by contact force. This contact force varies with time and position for the time-domain dynamic analysis. In contact system, a target surface mapped on the bridge deck elements while the contact elements connected with actuator elements. Contact nodes slides on the target surfaces with or without friction, where isotropic coulomb friction is adopted. Lagrange multipliers and kinetic constraint equations are applied depend on augmented Lagrangian method. This method is selected because it often leads to better conditioning and is less sensitive to the contact stiffness coefficient magnitude and no further equations are introduced to the discrete system.
3. Numerical results

3.1. Free vibration analysis

The free vibration analysis is one of the most important steps in the process of any dynamic analysis, although it does not relate to any types of loading. The model analysis is usually the first step in performing dynamic analysis problem, where the natural frequencies and mode shapes of the structure are determined. These characteristics give an indication of how the structures will behave under dynamic load. Natural frequencies are the frequencies at which the structure tends to vibrate naturally under the effect of external disturbance. Each natural frequency is associated with a specific mode shape, which depend on the structural and material properties, and boundary conditions of the structure. Free vibration analysis results are investigated by using ANSYS, where mass matrix is formulated by using Lumped mass method; and the natural frequencies and associated mode shape is solved by using Block Lanczos method. Five natural frequencies of composite steel I-girders bridge with varies radius of curvatures (R = 200, 100, 50, and 35 m) are obtained. All the mode shapes of curved bridge are coupled of bending and torsion vibrations, where the first and fourth mode shapes are bending (B), while the torsional mode associated with second and fifth mode. Torsional-horizontal (TH) are related to third mode, the first mode shapes for the bridges with (R = 200, 35m) are shown in figure 6.

![Figure 6](image_url)

**Figure 6.** The bending mode shape for bridge with radius of curvature: a. 200m b. 35m.

It is easy to recognize from figure 7, that the change of radius of curvature has significant influences on the natural frequencies of the composite steel I-girder bridge. It can be observed that the boundary conditions, the actual length of centreline, the spacing of girder, the number of diaphragms, the geometric and material properties of concrete deck are unchanged. This means that the natural frequencies under effect of bridge curvatures only. However, the frequencies that are corresponding to bending and torsional-horizontal mode shapes tend to decrease, and those which are related to torsional mode increase with the decrease of radius of curvatures. An increasing bridge curvature means that the inside girders length should be reducing in opposite of the length of outsider girders which tend to increase. In total, this leads to a lower bending stiffness and a larger torsional stiffness of the bridge. Generally, the ratios between the second to first mode shapes (T/B) are small for all bridge models regraded of the radius of curvature, which ranged from 1.31 to 1.94, so that the torsional and vertical modes are easily obtained simultaneously under any external disturbance due to small torsional stiffness.
3.2. Dynamic response

Many parameters are taken into consideration in this study, such as, surface irregularities, deck friction, damping, inertia force, surface to node contact, centrifugal force for curve alignment, and also approach road effect where the vehicle is moved on along a 45m approach road with the same surface roughness to get the initial condition of the vehicle when entering the bridge. Vehicle model includes the effect of pitching, rolling, bouncing and separation between tires and bridge surface. The results are in term of the impact factor, which is defined as the maximum dynamic response to the static response ratio minus one, equation (3).

\[ IM = \frac{R_{\text{dyn}} - R_{\text{sta}}}{R_{\text{sta}}} \times 100\% \]  

(3)

Where; \( R_{\text{dyn}} \) is bridge dynamic response and \( R_{\text{sta}} \) is bridge static response value.

The investigation of the curvature effect on IMs is obtained for good surface roughness condition with vehicle velocity about 45 km/hr under the action of three different loading cases (P1, P3, and P5), where the vehicle moves along the inside girder (G1) in case of first loading position (P1), whereas, the vehicle runs on the outside girder (G5) for the loading case (P5). In the loading case (P3), the vehicle runs along the longitudinal centreline, as illustrated in figure 8.

![Figure 8. Loading position cases.](image)

It is noted that the relationship between the IM and the radius of curvature significantly influenced by the position of vehicle on transverse sections of the bridge. For loading case (P5), the IM values for all bridge girders tend to decrease as the radius of curvature increase, but the decreasing rate for girder (G5) is larger than that of other girders, as shown in figure 9. Also, the minimum IM achieved at girder five (G5) and this phenomena can be attributed to the higher static response that occurred at the outer girder. The increment ratios due to decrease the radius of curvature from 200m to (100 and 50 m) are (8 and 54%) for girder (G5), and (2 and 9%) for girder (G1). At radius of curvature of 35 m, all girder has nearly a close values of IM because the increase of the vehicle load eccentricity with respect to support centreline as the bridge curvature increase, as well as the torsional effect increase too. The IM of girders (G5 and G4) under the action of loading case (P1) decrease with the increasing of radius...
of curvature, as shown in figure 10. Slightly increase in IM values are noted for the girders (G3, G4, and G5) with the degrees of the bridge curvature. In the different cases of the bridge curvature, the IM of girder (G1) remain has the lowest value due to higher static response at these girder and the variation between the IM of the girders decrease with the increasing of the radius of curvature.

Figure 9. Influence of bridge radius of curvature on impact factors (P5).

Also, the IM for the outer girder tend to decrease with the decreasing of bridge curvature in case of loading (P3), in opposite of the inner girder whereas the IMs increase, as illustrated in figure 11. Girder three have the minimum value of IM at the largest radius of curvature, but with the increasing of bridge curvature, the inner girders carry the lowest IMs that increase transversely with moving toward the outer girders, this can be attributed to increase the torsional vibration with increase of radius of curvature under loading (P3). The IM value according to AASHTO LRFD is equal to 3.3 for the case of studies bridge, which significantly underestimate the calculated IMs specially in case of bridges with small radius of curvature under eccentric loading. The IM for the girder five of bridge with 35m as radius of curvature reach a twice of that predicted by AASHTO LRFD.

Figure 10. Influence of bridge radius of curvature on impact factors (P1).

Figure 11. Influence of bridge radius of curvature on impact factors (P3).

4. Conclusion
From calculating results in terms of IM, it can be concluded that:

- The natural frequencies that are corresponding to bending and torsional-horizontal mode shapes tend to decrease, and those which are related to torsional mode increase with the decrease of radius of curvatures.
The smaller impact factor values can be obtained whereas the larger static response is occurred. Therefore, the IM value of remotest girder relative to vehicle position must be considered as reasonable value in the bridge design.

The IMs of outer girders (G4 and G5) tend to decrease with the increasing of the radius of curvature under the different lane loading. While the curvature-IMs relation of inner girders significantly affected by the vehicle location.

AASHTO LRFD specification seems to underestimate the values of IMs for the bridge with large curvature under the eccentric load.

5. References

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