DYNAMIC ANALYSIS OF COMPOSITE MULTI I-GIRDERS BRIDGE USING FINITE ELEMENT METHOD

Huda J. Qassim* and Dr. Anis A. Mohamad-Ali**

* Ph.D. Student, Dept. of Civil Engineering, Basrah University/ Researcher, Dept. of Petroleum Engineering, Al-Ayen University.
** Professor, Dept. of Civil Engineering, Basrah University.

huda.j891@gmail.com

ABSTRACT

Three dimensional finite element models are developed to deal with the bridge-vehicle interaction problem of simply supported composite multi I-girders bridge. The bridge is modeled by using ANSYS 15.0 program with solid and shell elements to represent concrete and steel members, respectively. AASHTO HL-93 truck is idealized as 3D non-linear model consisting of five lumped masses connected by rigid beams and supported by spring-dampers. The separation between the tires and road surface and surface roughness condition are simulated by Gap and actuator elements, respectively. The road surface roughness profiles are generated from power spectral density (PSD) and cross spectral functions. The models used are capable to take all bridge and vehicle responses into consideration with no limitations on the complexity of the models. The dynamic responses of the multi I-girder bridge are investigated under conditions of various loading positions, roughness classes, vehicle speeds, and bump height. The dynamic behaviors are presented in terms of Dynamic Amplification Factors (DAF). The results show the girder that itself supporting the moving vehicle has lower value of DAF because of higher static responses. A 45 km/hr vehicle speed provides higher DAF value. The bump heights have significant effect on DAFs for bridge with short span.

KEY WORDS: Composite I-girder Bridge; FEM; ANSYS; Road Surface Roughness; Interaction system; Dynamic Amplification Factors.

1. Introduction

The dynamic behavior of the bridge under the effect of moving vehicles have been long recognized as one of important problem encountered in the design and rating of bridges. Though of significant role, the interaction between the bridge deck surface and the vehicle wheels is hardly taken into consideration in practice designs because of its complexity.
Therefore to account for such a dynamic effect, it is required that the static response be increased by a single dynamic allowance factor (DAF), also called as the impact factor. Many bridge design codes have adopted the same formula for various dynamic responses that is assumed as a function of a single parameter, such as the span length or fundamental frequency of vibration. This design approach is surely an oversimplification but misrepresentation of many complex phenomena, as the bridge dynamic behavior (1).

However, impact factor depends on many parameters that include the dynamic properties of the vehicle and bridge, the roughness of the bridge deck surface, velocity of the moving vehicle, etc. Therefore, it has been supposed that impact factor values which are calculated by using the current codes significantly underestimate the bridge dynamic response in many cases (1,2,3). Generally, most of the previous researchers have failed to produce formula of impact factor that is both rational and simple enough to effectively estimate the dynamic response, because all of these formulas were proposed decades ago by using simple analytical approaches. Now, dramatic changes have occurred with the traffic volume and the configurations and weights of trucks, so that, there exists a necessary need to update formulas that reflect the current situations. Later, many researchers studied the bridge-vehicle interaction by using the experimental tests or sophisticated numerical models to modify the impact factor formula. A series of studies dealing with bridge-vehicle interaction by using the numerical methods were reported by Yang et al. (4,5,6). In which, the dynamic analysis was carried out by using simple numerical models to reduce computational cost and time. Also, the dynamic response of multi I-girders bridges with different span lengths was investigated by Huang et. al (4), grillage beam model was used to idealize the bridge while, the moving vehicle was modeled as a HS20-44 truck vehicle model with 12 degrees of freedom. Many useful results for modifying the method of bridge design were concluded. A similar study was presented by Wang et al (8), to examine the behavior of Multi-girders bridge. A 3D model was adopted by Kim et. al (9), to represent the bridge-vehicle interaction, where beam and plate elements were used in the modeling.

Many others studies were carried out to help for better understandings of the dynamic behavior of bridge under moving vehicle. In spite of these studies, no single formula of dynamic amplification was predicted. For these reasons, this paper aims to study the bridge-vehicle interaction where 3D finite element model of composite multi I-girder bridges and AASHTO HL-93 truck are developed by using ANSYS 15.0 program. This bridge type is one of the most popular bridges a round world, in which the deck is made to be a composite with the steel girders through shear connectors to attach the components to each other.

2. Dynamic Amplification Factors (Impact Factor)

The dynamic responses of a bridge usually are calculated indirectly by increasing the static responses such as, forces, stresses, and displacements by an impact factor (8). The impact factor is defined as the maximum dynamic response to the static response ratio minus one.
Where, $R_{dyn}$ is bridge dynamic response and $R_{sta}$ is bridge static response value.

The impact factor (IM) in AASHTO specifications \(^{(10)}\) is presented as,

$$IM = \frac{15.24}{L+38.1}$$

Where, $L$ is the loaded bridge span (m). Traditionally, impact factor is not greater than 0.3 in AASHTO Standard code. Recently, the significant effect of the uneven joints on vehicle has been recognized in the AASHTO LRFD code \(^{(11)}\) that specifies an impact factor of 0.75 for joint design.

3. Numerical Models

Commercially available ANSYS program, Parametric Design Language (APDL) is used to develop 3D finite element models to study the interaction bridges-vehicle problem. This program is capable of carrying out both static and dynamic analyses.

3.1 ANSYS Modeling of Bridge

Most types of composite multi-girders bridges consisted of four structural elements that including: slab, girder, crossbeam, and lateral bracing. These elements are made from two main materials: concrete and steel. In general, for the FE modeling of bridge by using ANSYS program, Solid element are used for representing of the concrete members and Shell element for modeling of steel components, as in most of previous studies. In present paper, hexagonal 8 nodes SOLID185 Element and quadrilateral 4 nodes SHELL181 Element are used to model the concrete and steel structural members, respectively. Fig. (1) illustrates all details of the element geometry and node location of the used elements.
To achieve a full composite action in the composite bridge type, concrete and steel components share the same nodes at the surface of contact.

The Wildcat Creek Bridge\textsuperscript{(13)}, which locates in Indiana, USA is chosen to study the dynamic behavior of composite I-girders bridge under the moving vehicle. The bridge which consists of three spans 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 Fig. (2). Steel diaphragms of type (C15x33.9) which are located at every 12ft (3.657m), are connected to the steel girders.

Concrete deck has a mass density of 2350 kg/m$^3$, modulus of elasticity equals to 24.9 GPa and Poisson ratio 0.2. While, all the steel members have 7697 kg/m$^3$ as a mass density, modulus of elasticity of 200 GPa, and Poisson ratio 0.3. Support conditions are specified to be constrained in translation X-, Y-, Z-directions at one end, while the vertical and lateral displacements are completely constrained at the other end. A typical FE bridge deck model is shown in Fig. (3)
3.2 ANSYS Modeling of Vehicle

In this study, 3D FE model was developed by using ANSYS program to model of AASHTO HL-93 truck as shown in Fig. (4). In which, the HL-93 truck is identified into five lumped masses (three wheel axle, tractor and semi-trailer). All of these lumped masses are connected by rigid beam and supported by spring-damper. Properties of the masses, springs stiffness, and damper coefficients that were suggested in Wang and Huang report\(^{(14)}\), are used in this model.

All the lumped masses in the FE model of the vehicle was modeled 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 Fig. (5).

The upper and lower spring-dampers in the vehicle model are used to represent the suspension of vehicle body and tires, respectively. COMBIN40 suspension element is used for identification of the spring-damper element in the FE model. COMBIN40 element has two nodes, which consists of a spring-slider and damper in parallel, which coupled to a gap element. A mass may be
associated with one or both nodal points, as shown in Fig. (5). The rigid beam that is used to connect the lumped masses in vehicle model is modeled by Beam4 element in the current FE model.

![Figure 5: Details of ANSYS Element Geometry](image)

3.3 Road Roughness Modeling

The dynamic responses of bridge due to the moving vehicle are significantly affected by the condition of road roughness. The exerted force by the vehicle is larger than that in static case due to the presence of suspension and damping systems in the vehicle. 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 (15) is used in this study. It assumed that the road roughness profile is homogeneous and isotropic two dimensional Gaussian random processes.

\[
S(\varphi) = S(\varphi_0) \left( \frac{\varphi}{\varphi_0} \right)^{-w_1} \quad \text{for} \quad \varphi \leq \varphi_0
\]
\[
S(\varphi) = S(\varphi_0) \left( \frac{\varphi}{\varphi_0} \right)^{-w_2} \quad \text{for} \quad \varphi > \varphi_0
\]

Where, \( S(\varphi) \) is Power spectral density PSD (m²/cycle/m). 
\( S(\varphi_0) \) is Roughness coefficient (m³/cycle).
\( \varphi \) is Wave number (cycle/m).
\( \varphi_0 \) is discontinuity frequency = 1/2\( \pi \) (cycler/m).
\( w_1, w_2 \) is roughness exponent.

The International Organization for Standardization (ISO 8608, 2016) (16) has defined a road roughness classification from very good to poor based on the values of roughness coefficient \( S(\varphi_0) \). In this study, the roughness coefficient values are taken as \((5*10^{-6}, 20*10^{-6}, 80*10^{-6}, 320*10^{-6})\) m²/cycle/m, for very good, good, average and poor road surface, respectively. The
roughness exponent value depends on road type, $w = 2.0$ is used in current analysis for the modeling simplicity. Road surface profile is produced by generating random numbers; which were passed through the MATLAB 1st order recursive filter to obtain the required road surface profile based on the corresponding PSD function.

$$r(x) = \sum_{k=1}^{N} \sqrt{2S(\phi_k)\Delta\phi} \cos(2\pi\phi_k x + \theta_k)$$

Where, $N$ is number of sinusoidal components

$\phi_k$ is the spatial frequency associated with $i^{th}$ component.

$\Delta\phi_k$ is Bandwidth of the $i^{th}$ component vary (0.011 - 3.281) cycle/m.

$\theta_k$ is a random phase angle uniformly distributed (0 - 2$\pi$) for 1st profile.

$X$ is longitudinal distance (m).

The generated road profile corresponding to ISO classes: very good, good, average, and poor, shown in Fig. (6), 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. To simulate the road roughness, the generated road profile is input as stoke of the actuator element (LINK11) in the current ANSYS FE model.

![Figure (6): Typical Road Surface Roughness Profile](image-url)
3.4 ANSYS Modeling of Bridge-Vehicle-Interaction

The vehicle-bridge interaction system consists of two separate components: bridge and vehicle, which affect each other by contact force. This contact force varies with time and position for the time-domain dynamic analysis. The equilibrium between the tires and the bridge deck can be achieved by the contact element at the points where the wheel of vehicle stands. For the interaction system analysis, the nonlinearity is attributed not only to geometric and material nonlinearities, but also, the contact analysis adds to the nonlinearity of the analysis when the exact position of contact components is unknown.

In ANSYS program, five different contact models are available: node to node, node to surface, surface to surface, line to line, and line to surface. In this study, interaction surface condition is modeled by node to surface contact model using CONTA175 and TARGE170 elements.

4. Numerical Results

4.1 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 type of loading. However, a model analysis is usually the first step in performing of 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 behavior under dynamic load. Free vibration analysis results are investigated by using ANSYS, where mass matrix is formulated by using Lumped Mass Method; the natural frequencies and the associated mode shape is solved by using Block Lanczos Method.

For the bridge under study, the bending vibration of bridge deck associate with the first and forth mode in 6.89 Hz and 10.04 Hz, respectively. From comparison of the FE model results with the experimental results, it was found that there was a good agreement, where the first and second vertical frequencies were measured to be 6.85Hz and 9.25Hz, respectively\(^{(13)}\). The second mode is found to be a torsional mode with natural frequency equal to 8.17Hz. Fig. (6) illustrates mode shape corresponding to the first five modes of composite I-girder bridge.

| Mode | 1   | 2   | 3   | 4   | 5   |
|------|-----|-----|-----|-----|-----|
| Frequency | 6.891 | 8.173 | 9.412 | 10.041 | 13.536 |
4.2 Parametric Study

Many parameters are taken into consideration in this study, such as, surface irregularities, deck friction, damping, inertia force, surface to node contact, 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.

4.2.1 Effect of Vehicle Position

To study the effect of load position on the dynamic response of the straight bridge, a total of three loading cases are considered as shown in Fig. (7). In which, the vehicle in loadings (P1 and P2) directly stand on the girder one (G1) and two (G2), respectively. For loading case (P3), the running vehicle is symmetric with respect to center line (girder three G3). In each case, one vehicle travel along the moving path under good roughness condition with speed of 45 km/hr that was selected to give maximum dynamic effect.
From Fig. (8), it can be noted that the values of DAF are significantly related to their static response. The larger DAF value is achieved at the smallest static response. So that, the girder directly below the vehicle wheel suffers smaller DAF value than that of other girders. While, the remoter girder from the moving vehicle have the larger DAF value compared to closer one.

4.2.2 Effect of Vehicle Speed

This section focuses on the effect of moving vehicle speed on the bridge dynamic response. Two lane positions (P₁ and P₃) are selected for this purpose, vehicle speed ranged from (30 to 120 km/hr) with interval 15 km/hr and good roughness condition. Dynamic amplification factors of all girders at lane position (P₁) with varies speeds are shown in Fig. (9).

It can be observed that the DAFs for all girders achieve its maximum values at 45km/hr and 105 km/hr, but the lowest values occur at 75 km/hr and 90 km/hr. The dynamic response is dominated by the first mode which corresponds to bending mode. And, the dynamic response
reaches the largest value in frequency domain when the vehicle speed approaches 45 km/hr, and this is reason why the largest values of DAF are occur at these speed. For all speeds, the DAF values of girder one (G1) that directly locate under the vehicle wheel, are lower than that of other girders due to the highest static responses at this girder.

The same trend is noted for the bridge behavior under the moving vehicle along the path of load position (P3). The maximum DAFs achieve at (45 and 105 km/hr), while the lowest values at (75 and 90 km/hr) as shown in Fig. (10). Nearly, all girders have close values of DAF at each speed.

4.2.3 Effect of Road Surface Roughness
To have full understanding of the effect of surface condition on the dynamic response of composite I-girder bridge, a total of four roughness classification, namely very good, good, average, and poor are considered in this section. The vehicle run along two rout (P₁ and P₃) with 45 km/hr as speed.

For loading case (P₁), a linear correlation between DAF and roughness condition as shown in Fig. (11). Worsen condition of road means higher DAF value. So that, under very good roughness condition, very small values of DAF can be produced with little variation for all girders, these values increase rapidly and reach to extreme values at poor road roughness condition. These large differences of DAF values between these roughness models can be explained for the contribution of the vehicle roll mode on poor roughness road in combination with low torsional stiffness of the multi I-girder bridge.

![Figure (11): Influence of Roughness Condition on Impact Factors (Loading Case P₁).](image)

The same relation between the DAF values and roughness condition are noted as illustrated in Fig. (12). The values of DAF increase distinctly when changing the road roughness condition from very good toward the worsen state. The DAF values of all girders uniformly alter because of centric loading condition that produces bending dominant vibration under the effect of moving vehicle, compared with the eccentric loading case (P₁) that are causing torsional vibration and then, larger difference of DAF values between the girders specially in case of poor road condition.

Fig. (13) shows the correlation between the velocity and the road roughness condition for the first, third and fifth girder (G₁, G₃, and G₅) under the effect of loading case (P₁). It can be
indicated that the DAF has been always minimum at vehicle speed of 75 km/hr for all girders under any case of road roughness because of the low frequency dynamic response and contribution of torsional mode.

![Graph showing Influence of Roughness Condition on Impact Factors (Loading Case P3).]

Figure (12): Influence of Roughness Condition on Impact Factors (Loading Case P3).

For other speeds, it can be seen that the DAF values fluctuate with change of vehicle speed, it tends to achieve the maximum values at (45 and 105 km/hr) for very good and good roughness conditions. The highest DAF is found for 120 km/hr vehicle velocity for average and poor surface condition. This can be attributed that the moving vehicle with high speed along poorly road surface condition cause highly hammering effect when the vehicle tires get into contact again with the road surface after bouncing and then unfavorable response of bridge can be obtained due to the impact. For all speeds, Girder one (G1) still have the lowest DAF under different roughness condition because of highest static response.
4.2.4 Effect of Bumps at Expansion Joint

Bridge approach span are normally considered as a slab located on the soil embankment to connect the bridge deck to adjust roadway, and hence to provide a smooth translation between them. Commonly, the approach slab loses its contact and support from soil due to the settlement of embankment soil, for this, the approach slab will deform in a concave manner and a faulting is formed between the approach slab and bridge deck at expansion joint. So that, complaints about the riding comfort involve a suddenly bumps when the vehicle entering or leaving bridge. The
vehicle suffers an initial disturbance before entering the bridge due to bumping at joint and causes highly dynamic response because of extra impact load on bridge deck. Previous field observations indicate that the faulting at joint expansion between the bridge deck and approach slab can be as large as 1.5 in (3.8 cm). To analysis the effect of bump height on bridge dynamic response, different height are investigated (2 and 4 cm) in addition to a case of bump height equals to 6 cm, to have full understanding on faulting effect. The shape and length of the joint are ignored; all of these bumps are superimposed into the road roughness profile at expansion joint. Fig. (14) illustrates the relation between the bump height and DAF value for composite I-girders bridge deck at girders (G₁, G₃, and G₅) under the effect of moving vehicle along loading position (P₁) with good roughness surface condition at various vehicle speeds.

It can be noted that, the bump height significantly influenced the DAF at lower speed, where the DAF increase sharply and attained the maximum values at 30 km/hr and then this effect decrease quickly with increasing of vehicle velocities. This high effect of bump on DAF values can be attributed to the short span of studied bridge and therefore, there is no more time to dissipate the initial disturbance of vehicle. The speed of 75 km/hr still has the minimum DAF value because of low frequency dynamic response as mentioned in previous sections.

However, it is obvious that the change of bump height has a negligible effect DAF values at high vehicle speed, but clear unevenness in these values at low speed with alteration of bump height.
5. Conclusions

The bridge-vehicle interaction dynamic of composite multi I-girder bridge is studied using ANSYS program. There are no limitations on the complexity of presented models, so, many important parameters, such as bouncing, rolling, pitching separating between tires and road surface effects of; as well as road surface roughness conditions are taken into consideration. From calculated results in terms of DAF, it can be concluded:

1. By taken different loading cases, it can be said that the larger static response is, the smaller dynamic amplification factor can be obtained. Therefore, the DAF value of remotest girder relative to vehicle position must be considered as reasonable value in the bridge design.

2. The dynamic amplification factor fluctuates with the vehicle velocity. It seems to achieve the maximum DAF value at the speeds of (45 and 105 km/hr) for all surface roughness conditions.

3. The dynamic amplification factor is greatly affected by road surface conditions. The higher DAF values will be at the worse the road surface. In the cases of average and poor surfaces, the AASHTO LRFD specification seems to underestimate the values of DAF.

4. Bump height influences the values of DAF at the lower speed limit only; these values are much higher than that estimated by AASHTO LRFD.

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