DYNAMIC BEHAVIOR OF HORIZONTALLY CURVED TWIN I-GIRDER BRIDGES UNDER MOVING VEHICLES

Md. Robiul AWALL
Candidate for the Degree of Doctor of Philosophy
Supervisor: Prof. Toshiro HAYASHIKAWA
Division of Built Environment

Introduction

In modern days, the use of horizontally curved steel bridge has increased dramatically due to complex highway interchanges and river crossing to meet growing traffic capacity demands in urban highways. Horizontally curved steel twin I-girder bridges are one of the most preferred choice for short and medium span highway bridges [1] for satisfying these demands. This rationalized structural system possesses numerous merits such as simplicities for design, fabrication and construction, as well as high economical performance, owing to the reduced number of girders and secondary members. Due to the horizontal curvature, the bridge and its component members are subjected to coupled torsion and bending. For that reason the behavior of horizontally curved bridges are more complex and its analysis is difficult than straight bridge. In particular, curved twin I-girder bridges have rather low torsional stiffness [2], because of not only the small number of their main girders but also the minimized crossbeams, lateral and sway bracing structures. This type of bridge may easily vibrate under external dynamic loads like eccentric moving vehicles, wind loads, etc. [3], especially when its span becomes longer. Such unexpected excessive vibrations may cause fatigue damage to the bridge members and also the degradation of the serviceability.

For that reasons, the present study develops a fully computerized approach that uses improve three dimensional (3-D) finite element (FE) models to parametrically study the bridge-vehicle interaction of horizontally curved twin I-girder bridges, which have been considered super-elevation, inertia force and deck frictions in all direction as well as advanced contact technology. After that this study is extend to investigate the effects of bottom bracings on torsional dynamic characteristics of curved twin I-girder bridges. Lastly this research extends on human response to traffic-induced vibration of curved twin I-girder bridges to get the better serviceability performance of these bridges.

Numerical models

In this study, ANSYS program was chosen to develop 3-D FE models of studied bridges and vehicle. Many researchers and engineers prefer this module because of its parametric language and numerous element types, especially an advanced contact technology, which is useful for the vehicle-bridge interaction analysis. Details of models of bridges, vehicle and road roughness are given below.

Bridge model

In this study, horizontally curved steel twin I-girder bridge is adopted for discussion. It is simply supported at one end with roller bearings and at the other end with hinged ones. The span-length of the studied bridge is 50 m long. Two main I-girders of the studied bridge are spaced transversely at 6.0 m apart transversely. The main girders are interconnected by end- and intermediate-crossbeams at a uniform spacing of 5.0 m. The deck slab is made of concrete of 10.5 m width and 0.3 m thickness. Also 3% super-elevation is considered throughout the configuration of the bridge model. Several radii of curvatures defined as the distances from the origin of the bridge circular arc to the central line of the deck are investigated to take into account the effects of the curvature. To investigate the effectiveness of bottom bracing systems on the vehicle-induced vibration problem, the original model without bracings and five different types of bottom bracing models are considered for analyses and discussion. Geometric properties and cross-section layout of the studied bridge are shown in Table 1 and Fig. 1, respectively.

In this study, the original model is the one without any additional bottom bracings, which is referred as M0 model throughout the paper. The original model and five different types of devised bottom bracing models are shown in Fig. 2. Model M1 is the V-shaped diagonal bottom bracing system using I-section members of 0.5 m depth. In detail, dimensions of the newly added I-shaped steel members are WEB500x16 and FLG300x25. Model M2, M3 and M4 are the X-shaped bottom bracings using T-section steel members of the same dimension as model M1, while braced bays are different for each model. In these X-shaped models one T-section steel member is allocated at the lower part, while the other inverted T-section steel member is allocated just at the upper part of the first member and the touching portion of the two members are rigidly jointed. Therefore this type of bracing system is much stiffer than the M1 model. Model M5 is the bottom plate bracing system, which has 20.0 mm thick steel plates in the plane of bottom flanges along with the full height intermediate diaphragms. There are totally four end-bays braced by bottom plates, two of which are equally located at each end of this model.

Detailed FE models of the studied bridges including different types of bottom bracings are developed by using ANSYS code as shown in Fig. 2. Hexagonal 8-node SOLID45 elements are used for the 3-D modeling of the concrete deck. This element has large deflection and large strain capability and the element is defined by...
eight nodes having three degree of freedom at each node. All steel members are modeled by considering quadrilateral 4-node SHELL63 elements. This element has bending, membrane, stress stiffening and large deflection capabilities, which has six degree of freedom at each node. All the elements and boundary conditions are defined based on cylindrical coordinate system, whose origin is the centre of bridge’s curvature.

**Vehicle model**

In this study, AASHTO LRFD [4] design truck HS20-44 and design lane load are considered. The 3-D FE model of HS20-44 design truck is shown in Fig. 3. The model consists of five lumped masses with rotary inertias; representing the tractor, semi-trailer and three wheel/axle sets. Masses are connected by rigid beams and supported by spring-dampers. The upper spring-dampers represent the suspensions of the vehicle and the lower ones are for tires. Suspension force consists of the linear elastic spring and damping forces. Gap elements are incorporated into the lower spring-damper elements to imitate the separation between tires and road surface. These gap elements are interconnected with actuators elements to simulate the effects of road roughness. The vehicle is assumed to move at a constant speed on a circumferential path along the curved bridge deck. It can be seen that the vehicle model is capable to take into account the effects of pitching, rolling, and bouncing motions of the vehicle as well as the effect of road surface irregularities under tires.

**Road roughness model**

Roadway surface profiles used in the dynamic response analysis are simulated by periodically modulated random processes that can be described by Power Spectral Density (PSD) functions proposed by Dodds et al. [5], Honda et al. [6] as in Eq. (1).

\[
S(n) = S(n_0) \left(\frac{n}{n_0}\right)^{-\omega}
\]

(1)

Where, \(S(n)\) = PSD (m²/cycle/m); \(n\) = wave number (cycle/m); \(n_0\) = discontinuity frequency = \(1/(2\pi)\) (cycle/m). \(S(n_0)\) = roughness coefficient (m²/cycle/m). According to the values recommended by Motor Industry Research Association [5]; \(S(n_0) = 5\times10^5, 20\times10^6, 80\times10^6\) and \(320\times10^6\) for very good, good, average and poor road surfaces, respectively are considered in this study. The value of \(\omega\) is varied from 1.36 to 2.28 depended on the road class.

Most vehicles travel over two wheel tracks, thus subjected to two simultaneous road surface profiles including bouncing, pitching, and rolling effects of its body. Correlated road surface profiles are generated from PSD and cross spectral density functions by assuming the road surface as homogeneous and isotropic random process proposed by Dodds et al. [5] Sayers [7] as in Eq. (2).

<table>
<thead>
<tr>
<th>Table 1 Geometric properties of studied bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span length [m]</td>
</tr>
<tr>
<td>Deck width × thickness [m]</td>
</tr>
<tr>
<td>Dimensions of main girders [mm]</td>
</tr>
<tr>
<td>Dimensions of intermediate cross-beams [mm]</td>
</tr>
<tr>
<td>Dimensions of end cross-beams [mm]</td>
</tr>
<tr>
<td>WEB 3000 × 24</td>
</tr>
<tr>
<td>Upper FLG 500 × 30</td>
</tr>
<tr>
<td>Lower FLG 500 × 50</td>
</tr>
<tr>
<td>WEB 1000 × 16</td>
</tr>
<tr>
<td>FLG 300 × 25</td>
</tr>
</tbody>
</table>

Fig. 1 Cross-section of studied bridge (mm)

Fig. 2 Original model and bottom bracing models

Fig. 3 Finite element model of HS20-44 design truck
Where, $S_i(n) = \text{cross spectral density function}$; $x = \text{longitudinal distance}$; $N = \text{number of sinusoidal components}$; $n_i = \text{spatial frequency}$; $\Delta n_i = \text{bandwidth}$; $\phi_i, \theta_i = \text{First and second random phase angle respectively}$. By using these equations, several road roughness profiles are generated for very good, good, average and poor road surface conditions. Typical good road roughness profile is shown in Fig. 4.

**Contact model**

To couple the motion of the vehicle and bridge structure, contact technology is employed in this study. ANSYS node-to-surface contact pair consisting of a target surface mapped on the surface of deck element and contact elements connected with actuator elements are adopted. This is the most widely used contact elements in ANSYS. This contact technique allows contact nodes to slide on the target surfaces with or without friction. Isotropic coulomb friction is considered to the analysis. Lagrange multipliers and kinetic constraint equations between these systems are utilized by using augmented Lagrangian method; which is an iterative series of penalty updates to find the Lagrange multipliers. This method is selected over others such as pure penalty, pure Lagrangian multiplier methods because it usually leads to better conditioning and is less sensitive to the magnitude of the contact stiffness coefficient while introduces no additional equations to the discrete system. Correlated road surface roughness is input as stroke (length) of the actuator elements to simulate the unevenness of road surface.

**Free vibration analysis**

Free vibration analysis results are investigated for different radii of curvatures and different types of bottom bracing models, being compared with that of the original model. First vertical and first torsional natural frequencies of different studied bridge models are presented in Fig. 5. It can be seen from these results that torsional vibration frequencies increase and vertical vibration frequencies decrease with decreasing radius of curvature. Also frequencies are increasing compared with the original model by providing bottom bracing systems. Among those vibration modes, torsional mode frequencies are increasing considerably by providing bottom bracings. That means additional bracings increase the structural rigidity including the torsional stiffness of the studied bridge, though increasing rate depends on bottom bracing patterns. Among all studied bottom bracing models, frequencies of M2 and M5 models are increasing more significantly compared with the original model. The first vertical and first torsional modes are related to the first and second mode shapes, respectively, while the first combined torsional-
horizontal mode shape is obtained in the third mode. On the other hand, the first torsional mode of model M5 is obtained at 7th mode. Between the vertical and torsional modes of this model, the first combined torsional-horizontal mode and some local vibration modes of the plates are observed. Such local vibrations of bottom plates are undesirable for dynamic responses due to moving loads or aerodynamic forces, because fatigue damages and sometimes brittle fracture of the bridge members are concerned. Also in M1 model, pure local vibration modes in bracings and local vibrations combined with global vibrations are observed after the first torsional mode.

To illustrate the effect of different bottom bracing models with various radii of curvatures on the performance of the system, the frequency ratios \( f_{T1}/f_{V1} \) of these models are depicted in Fig. 6. According to Road Bridge Wind Resistance Design Manual [8], frequency ratio should be larger than 2 for aerodynamic performance. The original bridge has very low torsional stiffness and is vulnerable to eccentric dynamic loads, thus should be enhanced reasonably. It can be seen from the figure that frequency ratios of all studied models are increasing compared with the original model for all studied radii of curvatures. That is, torsional stiffness is increasing by providing different bottom bracing systems. In particular, the M5 model gives higher frequency ratios (3.0-3.6) for all studied radii of curvatures, which means box effect greatly increases the torsional stiffness of the structure, whereas this model produces local vibrations of the plates as mentioned above. M2 model gives about 2.5-2.6 frequency ratios, which are larger than those of the M1 model (2.3-2.4) for all studied curvatures. Therefore, the M2 model that does not produce any local vibration should be the most suitable one to increase the torsional stiffness of the studied bridge.

### Forced vibration analysis

In the forced vibration analyses, one percent of Rayleigh damping is assumed for the first and second modes. The Newmarks’ \( \beta \) and Newton-Raphson procedures are adopted to solve the problem. Forced vibration is investigated for different radii of curvatures and different bottom bracing configurations of the studied bridges with 3% super-elevation.

Vertical displacements of different types of studied models of both girders are shown in Fig. 7. Note that the displacements of the outside girder are larger than those of the inside one and curvatures have great influence on vertical displacements, that is, the smaller radius of curvature the larger is the vertical displacement. This is because torsional effect becomes larger with decreasing radius of curvature, and the original bridge model subjected to outside lane loading has no load transmitting bracings. By providing bottom bracing configurations displacements of the inside girder are increasing and those of the outside girder are decreasing. That means bottom bracings can transmit loads from the outside girder to the inside one, while load transmitting rates are different for different types of bottom bracing.
configurations. By providing bottom bracings, the decreasing percentages of outside girder displacements are 31.4%, 33.6%, 29.0%, 22.2% and 34.6%, while the increasing percentages of the inside girder are 28.0%, 29.1%, 25.9%, 19.3% and 29.3% for models M1, M2, M3, M4 and M5, respectively. Among these five types of bottom bracing configurations, both M2 and M5 models have high load transmitting rates and their outside girder displacements are small.

Maximum bottom flange stresses at mid span of different models of different radii of curvatures are shown in Fig. 8. The maximum stress of outside girder is larger than the inside girder. Also, in small radius bridge, the maximum stress variation of outside and inside girders is large, while it is decreasing with increasing bridge radius. This is because torsional vibrations increase with decreasing radius of curvature and lack of load transmitting bracings. Note that if bottom bracing system is provided the outside girder stresses decreased and the inside girder stresses increased. This is because the stresses are transferring from the outside girder to the inside one through bottom bracings. That means bottom bracings act as load transmitting members, while stress transmitting rates are different depending on the bottom bracing configurations. Also maximum stress variations of the outside and inside girders are greatly enhanced by providing bottom bracings for all radii of curvatures. Among the five types of bottom bracing configurations, load transmitting rates from the outside to inside girder are high in M1 and M2 models.

Hinged supports bearing forces of both girders of the original model are shown in Fig. 9a. Note that the static and dynamic bearing forces of the outside girder are larger than those of the inside girder due to outside lane loading. The important fact is that the negative bearing force occurred in the inside girder hinged support. Negative bearing forces depend on curvature, that is, smaller bridge radius of curvature leads to larger negative bearing force due to the torsional effect. Such large amount of negative bearing force can lift up the girder, which is unsafe for the structure. Maximum negative bearing forces at the hinged support of the left girder for different types of models are shown in Fig. 9b. This figure shows negative bearing forces are reduced much compared to the original model by providing bottom bracings for all studied curvatures. Reducing rate varies depending on the model type and the radii of curvatures. For 100 m radius bridges, negative reaction force is larger and its reduction rates of M2 model (49.5% reduction) and M5 model (50.7% reduction) are higher than others. Therefore M2 and M5 models’ performance for negative force reduction is better.

**Human response to vibration**

The perceptible vibration of curved twin I-girder bridges under traffic loads is an important design consideration, because this bridge have rather low torsional stiffness that produce excessive vibrations. The human body, however, is primarily sensitive to dynamic effects such as acceleration and change of acceleration. Although not related to issues of safety, this may have the
psychological effect of impairing public confidence in the structure and, therefore, demands consideration at the design stage.

Smith [9] presents the work of Irwin, who suggested a base curve for acceptable human response to the vibration of a bridge shown in Fig. 10. In this study, Irwin's curve for vertical component of bridge motion in stormy wind conditions was selected as a base curve for the human-perceptible to vibration. Vertical component of acceleration at a point on the footway are calculated to determine the corresponding root-mean-square (r.m.s.) acceleration, while the frequency is obtained by Discrete Fourier Transform. These accelerations with corresponding frequency are then compared with the base curve; lie only if the calculated values below the respective base curve are the criterion met.

An important factor affecting the dynamic response of bridge-vehicle interaction system is road surface roughness. Four roughness classes, namely very good, good, average and poor with 30 km/h vehicle speed are analyzed to clarify its effect on perceptible vibration. Three different bump heights are investigated for parametric study namely $h = 2$ cm, 4 cm, and 6 cm. Another model without bump is also considered to clarify the effect of bumps. The perceptible vibration level for good road roughness under 30 km/h and different bump heights are shown in Fig. 12. From this figure it can be seen that acceleration values are increasing with increasing bump heights, while the vibration frequency is little affected. At this almost constant frequency, it is true to say that the perception of vibration is only related to the bump height. The perception of vibration is dominated with combined effect of vehicle and first vertical mode of the bridge vibration. If the bump height at expansion joint in appropriate level, the maintenance of bridge deck is necessary to keep the good road roughness condition for the better serviceability performance of the studied bridge.

To analyze the effect of bump heights on perceptible vibration, three different bump heights are investigated for parametric study namely $h = 2$ cm, 4 cm, and 6 cm. Another model without bump is also considered to clarify the effect of bumps. The perceptible vibration level for good road roughness under 30 km/h and different bump heights are shown in Fig. 12. From this figure it can be seen that acceleration values are increasing with increasing bump heights, while the vibration frequency is little affected. At this almost constant frequency, it is true to say that the perception of vibration is only related to the bump height. Therefore, frequently maintenance of bridge deck is necessary to reduce the bump height at expansion joint in appropriate level.

By providing bottom bracings, responses are reduced form the original model as shown in Fig. 13; that is torsional stiffness increase significantly after providing bottom bracings. For good roughness conditions, M2 and M5 models acceleration are lie below the base curve and for average roughness conditions M2 model acceleration is lie below the base curve. That is among all models, M2 model exhibit better dynamic performance and remarkably reduced dynamic vibration.

Conclusions

This study investigated bottom bracing effects on dynamic characteristics and human response to traffic-induced vibration of horizontally curved twin I-girder bridges using developed 3-D FE interaction analyses by ANSYS. Based on the numerical results, the following conclusions are summarized.

- The curvature has a significant effect on natural frequencies. The natural frequencies of vertical modes increase for small radius bridges and torsional modes frequencies can be enhanced significantly by providing stiffer bottom bracing systems. The changing rates depend on bracing patterns; therefore, appropriate bottom bracing design is necessary to effectively improve the torsional stiffness.
- Bottom bracings can greatly contribute to transfer loads from one girder to the other smoothly, thus to reduce the excessive displacements and stress variations of outside and inside girders.
- Negative bearing forces occur in hinged support of the inside girder and become larger with increasing curvature and it reduced remarkably by providing bottom bracings. Therefore, bridge designer should pay attention to this phenomenon and consider suitable bracings to minimize such undesirable condition.
- As the road roughness and bump height increases, dynamic acceleration also increases. Therefore frequently maintenance of bridge deck is necessary to ensure the good roughness and reduced the bump height for the better serviceability performance.
- Providing bottom bracing, are also advantages in reducing the perceptible vibrations due to increasing the torsional stiffness. Based on the numerical results, M2 model is the suitable one to increase the torsional stiffness of curved twin I-girder bridges.

References