Dynamic behavior and distortion-induced stress in curved multi I-girder bridge under moving vehicles

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Introduction

The curved multi girder bridges are serving as a vital role in transportation system. The dynamic responses of such structure are of significance in design that considerably affected by the actual realization of the bridge-vehicle characteristics while vehicle running over the bridge (Kim et al., 2005). In addition, the coupled bending and torsion induced by curvature and low torsional stiffness of I-girder effect the structural response (Linzell et al., 2004) and significantly increases the dynamic deflection (Mermertasm et al., 1998). Huang et al. (1994) evaluated impact factors for curved multi-girder bridge and found curvature increases both torsion and bi-moment significantly. A 3-D numerical approach presented by Kwasniewski et al. (2006) using LS-DYNA and disregarding the bridge and approach road roughness. Barefoot et al. (2000) and Martin et al. (2000) studied the dynamics of bridge-vehicle-interaction (BVI) using simple moving load and ANSYS program that ignored the roughness for bridge. Again Ngo-Tran et al. (2009) investigated the dynamic response of simply supported twin I-girder bridge considering the roughness, but ignored the centrifugal force and deck friction. All aforementioned investigation significantly improved BVI problem with some limitation itself and a little work on curved multi girder bridge using 3-D BVI analysis and spaced vehicle and bridge model found in literature.

Fatigue is major forms of structural damage imposed by out-plane distortion or distortion-stress that ultimately leads failure of bridge components or a whole structure failure. In multi-girder bridges, diaphragms rotation caused by differential deflection of girders enforce out-plane distortion of unstiffened web-gap as well as distortion-stress, which considered as a major source of fatigue problems (Keating, 1994; Jajich and Schultz, 2003; Connor and Fisher, 2006). Several researches (Zha and Roddis, 2007, Fisher, 1979, Hassel et al.; 2013) have performed to measure and identifying the factors that influence the distortion-stresses. Lenwari et al. (2012) and Berglund and Schultz (2006) clarified differential deflection as cardinal reason that affected by span length, girder spacing and stiffness, slab thickness and skew angle. Several investigations (Jajich and Schultz, 2003, Fisher, 1990 and Li and Schultz, 2005) based on linear elasticity proposed analytical relation describing distortion-stress is proportional to differential deflection. Such experimental or statically based works focused only conventional bridge that ignored the vehicle eccentricity or curvature. None of those considered the BVI and effect of a moving vehicle on distortion-stress in curved multi-girder bridge under moving vehicle.

The purpose of this study to develop and propose a 3-D BVI system to predict the dynamic behavior and distortion-stress in curved multi I-girder bridge. For this purpose, a versatile and computationally efficient BVI model developed using spaced bridge and vehicle structure modeled by ANSYS code. The vehicle modeled as a three-axle mass-spring-damper system. The analysis considered the approach road, inertia force, centrifugal force, deck friction, contact technology and vehicle model includes the effect of pitching, rolling, bouncing and separation between tires and bridge surface.

Finite Element Modeling

The Kita-go multi girder bridge has three spans about 50 m each and a radius of 1000 m. It consists of five I-girders of 2.8 m depth, spaced by 2.1 m and tied together with ten equally spaced diaphragms. The basic geometric properties are shown in Table 1 and Fig. 1. A 3-D FE model of the bridge shown in Fig. 1c developed using solid45 and shell63 elements for concrete and steel, respectively. Concrete has mass density, $\rho=2500$ kg/m$^3$, $E=28.57$ GPa and $v=0.20$ were used for deck section and for all steel members, $\rho=7850$ kg/m$^3$, $E=210$ GPa and $v=0.30$ were used. Fig. 2 and Fig. 3 indicate the location for distortion stress for 45° skew bridge.

A 3-D model for HS20-44 truck as shown in Fig. 5a is developed using ANSYS code that consists of five lump-masses as shown in Fig 5b. All masses and rigid beams are modeled by MASS21 and BEAM4 elements, respectively and suspension of vehicle body and tires are modeled by COMBIN40. Separation between tire and road has integrated by gap element at the lower spring and an actuator modeled by LINK11 has connected with gap element to simulate road surface roughness. The tire stiffness and spring suspension values are shown in Table 2 (Wang et al.1992). Fig. 4 indicates the transverse position of vehicles on the bridge.

Table 1 Geometric property of Kita-go bridge (mm)

<table>
<thead>
<tr>
<th>Component</th>
<th>Span length</th>
<th>Deck width + thickness</th>
<th>Web of main girder</th>
<th>Flange of main girder</th>
<th>Slab thickness</th>
<th>Web of intermediate diaphragm</th>
<th>Flange of intermediate diaphragm</th>
<th>Vertical Stiffener of main girder</th>
<th>Horizontal Stiffener of main girder</th>
<th>Vertical Stiffener of Intermediate Diaphragm</th>
<th>Horizontal Stiffener of Intermediate Diaphragm</th>
<th>Vertical Stiffener of End Diaphragm</th>
<th>Horizontal Stiffener of End Diaphragm</th>
<th>Flange and Web of Lateral Bracing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front axle (kN/cm)</td>
<td>Drive axle (kN/cm)</td>
<td>Semi-trailer axle (kN/cm)</td>
<td></td>
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<tr>
<td>Ties</td>
<td>8.75</td>
<td>35.02</td>
<td>65.33</td>
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<tr>
<td>Springs</td>
<td>2.43</td>
<td>19.03</td>
<td>16.69</td>
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Table 2 Suspension and stiffness coefficients of HS20-44
To include vehicle bouncing, pitching and rolling effect, two different roughness profiles for both tracks as shown in Fig. 6 are derived from PSD and cross-spectral density functions (Dodds et al. 1973; Honda et al. 1982; Awall, 2012) assuming road surface as a homogenous and isotropic random process. This analysis considered node-to-contact algorithm to model the BVI using CONTA174 and TARGE170 elements. An isotropic coulomb friction of value 0.18 assumed in all cases (Samman et al. 2007). The Augmented Lagrangian method used to perform the contact analysis. Newmark’s $\beta$ and Newton-Raphson method used to calculate the structural response.

**Result and Discussion**

Fig. 7 shows the dynamic response of the bridge under transverse loading position as shown in Fig. 4. It found the supporting girder has lower value of DAF for higher static response. Vehicle eccentricity increases the transverse vibration as well as DAF value for the remotest unloaded girder. Loading L3 cause bending dominant vibration and less variation in DAF. Torsional vibration increase DAF for outside girders. Bearing force for outside girder is higher for curvature and exterior girder has 60-70% more value than that of center girder. Fig. 8 indicates DAF for loading L6 and it found under very good and good roughness DAF value is lower, but average and poor roughness DAFs are extremely higher than AASHTO-LRFD specification (17.3%). In addition, lower and upper speed limit gives highest DAF and lowest for 75 km/hr. It found DAF of remote girder (G1) are 2-3 are times more than loaded girder (G5). Both uplift and positive forces are lower for good and very good roughness condition and extreme higher in average and poor conditions that are about 50% more than good roughness conditions as shown in Fig. 9. So, frequent surface treatment or revised DAF are needed to ensure better serviceability.

Fig. 10 shows bump effect on DAF for loading L6 which has a little influence on DAF at lower and upper speed and negligible for rest of speed. At mid-span, the dynamic deflection remains unchangeable because of dissipation of bump disturbance energy when vehicle reach at mid-span. Fig. 11 indicates bump has small effect on uplift force at lower speed and rest of speed effect is minor because of steady state of vehicle at mid-span. For loaded girder, both bump height and vehicle speed increase the bearing force up to speed 60 km/hr after which increasing of speed causes lowering the bearing force because of low energy dynamic responses and vehicle rolling or pitching over the bumpy surface. It found 8 cm bump increases bearing force up to 55%. Fig. 12 shows high curvature and vehicle eccentricity increases DAF up to 42% for all girders under outside loading (L6). For R > 600 m, curvature effect is insignificant. Inside girder DAFs are increasing and outside girder decreasing with an increase of radius while the vehicle moves from inside to outside direction.
Differential deflection for outside loading (L5) decreases and increase for inside loading (L1) both for curvature and skew angle as shown in Fig. 13a and Fig. 13b, respectively, but magnitude for outside loading is higher than inside one. Torsional rotation of bridge for curvature and vehicle eccentricity causes higher value. In contrary, tight geometry and the least eccentric inside vehicle and vehicle eccentricity causes higher value. In contrary, according to curvature and skew effect for outside loading is more than that of 1000 m bridge. Curvature effect found significant up to radius 400 m after which insignificant. Fig. 13a indicates a non-skew 100 m curved bridge has differential deflection (4.00 and 1.10 mm) twice times more than that of 1000 m bridge (1.10 and 0.5 mm). Increasing skew angle causes the diaphragm closing to support at obtuse corner and shortening the diagonal which resulting load transfer through deck and decreasing the differential deflection. It found, skew effect is intensely higher at bridge end (Diaphragm 1) compared to mid-span (Diaphragm 4). From Fig. 13a and Fig. 13b, it is about 30-35% for mid-span location and 125-300% for end location for skew angle changes from 0° to 45°. Although, differential deflection for outside vehicle decreases with skew angle. Fig. 13a indicates higher value for 30° and 45°. At lower angle, point T subject to higher deflection than S. However, for 30° or more, deflection trend reverse and point from P to S undergoes higher deflection than T.

According to Fig. 14, both inside and outside loading increase the distortion-stress with an increase of curvature. In addition, curvature effect on mid-span location is higher, whereas the bridge end location is highly affected by skew angle. It found, a bridge has curvature less than 400 m subjected to higher distortion-stress, which is 2-8 times for 100 m curved bridge in comparison with 1000 m bridge because of high distortion of web at low curvature. For radius more than 400 m, curvature effect is minor. For example, Fig. 15a and Fig. 16a indicates maximum distortion stress at point A for 100 m bridge is 45 MPa and 75MPa, whereas for 1000 m curved bridge these values are ~20 MPa and 20 MPa. Again, differential deflection for outside loading is 6-10 times more deflection than inside one. However, the stress conditions are similar and for location E, inside loading causes higher stress (45-75 MPa) compared with
outside loading (30-48 MPa) shows the distortion-stress and differential deflection is not proportional. In addition, location T has the lowest value of differential deflection; Fig. 14a shows it subjected to higher stress value compared to other locations, because of torsion or web twisting and the high rigid connectivity. The distortion-stress increase for skew angle but no specific relation found except for obtuse corners T. Fig. 14 indicates, the skew effect for highly curved (100 m) bridge is about 30-50% having highest value 45 MPa and 75 MPa at location E for skew angle 30°. For end location T, stress values changes notably from -5 MPa to 55 MPa for 0° to 45° for 100 m bridge, where for 1000 m radius bridge these values are -15MPa and 30 MPa, respectively.

It found both uplift and positive force decrease with an increase of radius of curvature and curvature effect is substantial up to radius 400 m as shown in Fig. 15. Both skew angle and curvature causes uplift force twice (-70 to -140 kN) times more than that of non-skew 1000 m curved bridge as shown in Fig. 15a. Fig. 15b shows positive bearing force on both ends of girder G5 decrease with radius, but increase for 2nd end at skew angle 30° and 45° because of load concentration at 2nd end of girder G5 for formation of high acute angle. It found curvature increases bearing force 45% from 165 to 240 kN which further increased by 35% from 240 to 310 kN for skew angle changes from 0° to 45°.

Neither theoretical nor AASHTO specify any method to calculate distortion-stress except some analytical method proposed by Jajich and Schultz ($\sigma_{vex} = 2EI_s/g*\Delta/s$) and Fisher ($\sigma_{vex} = 3EI_s/g \Delta L$). Fig. 16 indicates the distortion-stress in non-skew curved bridge for inside and outside vehicle position based on FE and analytical method proposed by Jaich. It found under outside loading, the FE result significantly lower than Jajich and Schultz value, because this formula counted the differential deflection only and ignored the vehicle eccentricity or curvature that increased the differential deflection by torsional rotation without increasing corresponding stress. Again, for inside vehicle, the FE results show higher value and for $R > 400$ m, the FE result close to analytical value. However, at radius 100 m, the FE result is significantly higher than Jajich value because of least differential deflection for inside vehicle. Hence, Jajich formula gives the lowest value of distortion-stress; On the other hand, the FE result shows higher value because of tighter geometry and rigid connectivity, small rotation of web gives higher stress value. It found a large variation in FE result and Jajich & Schultz formula. The difference in model geometry and boundary conditions are another factors influencing these results. Therefore, it needs to revise the analysis under the same model and boundary condition to calibrate these formulas for curved bridge.

**Conclusions**

- Transverse vehicle position must be considered since vehicle supporting girder has lower value of DAF and vehicle eccentricity increase DAF, torsional vibration and also bearing force up to 60-70%.
- Lower and upper speed limit causes higher DAF value and lowest for 75-90 km/hr. The worse in roughness condition increase DAF (40-70 %) more than AASHTO (17.3%). Both uplift (-65 to -100 kN) and +ve bearing force (210 kN to 330 kN) increase more than 50%. For better performance, frequent surface treatment or effect of worse roughness must be considered and speed should be limited to 75-90 km/hr.
- Highly curve and vehicle eccentricity increase DAF up to 42% and causes excessive torsional vibration.
- Bump has little influence on DAF and uplift bearing force. Downward bearing forces tremendously increase for bump up to vehicle speed 60 km/hr. For design of bearings and girder web, the bump effects need to be considered.
- Distortion-stress found not proportional to differential deflection as defined by Fisher, Jajich and Schultz that need to revise for curved or for vehicle eccentricity. Curvature increase distortion-stress 2-8 times and skew angle must need to be considered in design stage.
- Both curvature and skew angle doubling the uplift bearing force with maximum -140 kN. Curvature increase 45% and skew angle increasing 35% at obtuse corner. Therefore, additional cares need to be paid for curvature and skew angle.