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Influence of span ratio on seismic response of steel I-girder curved bridge deck

M.M. Rahman
Bangladesh Water Development Board, Bhola, Bangladesh

M.N. Haque
East West University, Dhaka 1212, Bangladesh

ABSTRACT: Horizontally curved bridges are becoming the common form of highway interchanges and urban expressways. Curved bridges are seismically more vulnerable as compared to the straight bridges because of their geometric configuration and demands detail seismic analysis in the design stage. Along with the other important parameters, variation of adjacent span lengths may also have influence on seismic responses of the curved bridges as it is often required to alter in a highway bridge depending on the ground conditions. However, very little information is available in the literature about the seismic behavior of curved bridge with different span ratios. This study investigates the effect of adjacent span ratio on seismic behavior of curved steel I-girder bridge. A comprehensive analysis is performed for steel I-girder curved bridges of subtended angle of 0º, 30º, 60º degrees with span ratios (short to long span) of 0.4, 0.6, 0.8, 1.0. Three-dimensional finite element model of the bridge is developed and elastic time history analysis is performed. It is observed that the effect of adjacent span ratios on seismic responses of curved bridge differs significantly from that of a straight bridge. With the variation of adjacent span ratio both the modal and seismic responses of the curved and straight bridges alter and show a definite trend in the results.

1 INTRODUCTION

Application of horizontally curved bridges can be frequently seen in complex highway intersections and river crossing to meet raising traffic volume in urban highway. These bridges are used to construct large and complex highway interchanges in a densely populated area to avoid traffic congestion. However, curved I-girder bridges have low torsional stiffness, may easily vibrate under external dynamic loads such as moving vehicles, wind and seismic loads. The response and behavior of curved bridges differs than that of straight bridges.

Many researchers have already been dedicated on the seismic behavior of curved bridges. Linzell et al. (2004) focused on dynamics behavior of curved I-girder bridges and remarked that twin-I girder curved bridges have rather low torsional stiffness due to small number of main girders and simple plan configuration. Free vibration analysis of horizontally curved I-girder bridges in a numerical framework was performed by Yoon et al. (2005). Nadakuditi & Linzell(2011) parametrically studied the seismic response of horizontal curved steel I-girder bridges. Various important parameters such as radius of curvature; girder and cross frame spacings; and lateral bracing configuration was taken into consideration to find their influence on seismic responses of curved I-girder bridges. Essa et al. (2012) devoted a research work on comparative study of the seismic performance of equivalent straight and curved bridges due to transverse seismic excitation and concluded that curved bridges have higher displacement demand than the equivalent straight bridges. Serdar et al. (2017) investigated the influence of curvature radius, bridge bents skew angle, and type of column bents on the seismic response of curved bridges. Analyses revealed that increase in radius of curvature leads to increase in vibration period of the structure. As can be seen all the past studies were carried out for curved I-girder bridges having equal span length. However, it is often required to alter the adjacent span lengths in a highway bridge due to variation of the ground conditions. This variation in adjacent span lengths may also have influence on seismic responses of the curved bridges. Therefore, there is a need of an in-depth investigation to explore the seismic behavior of curved I-girder bridges with variable span length.

To this end, this study focused on the effects of span ratio variation on the seismic responses of curved I-girder bridges. Both the modal and time history analyses were performed, and the curvature was defined in terms of subtended angle. Three different values of subtended angle viz., 0°, 30°, 60° were considered and the span ratios(short to long span) were varied from 1.0 to 0.4. Later, the bridge was excited under a real ground motion and the dynamic responses such as the base shear, deck acceleration and displacement were compared among the straight and the curved bridge having different span ratios and subtended angles. The Finite Element Model (FEM) developed in the present study was validated as well by comparing modal results with past FEM and experimental data.

2 BRIDGE MODELLING

2.1 *Bridge Geometry*

A two-span two-girder continuous steel I-girder horizontally curved bridge based on an actual highway bridge was adopted in this study. The bridge had a span of 53m measured along the centerline between two adjacent girders and had two lanes together with two pedestrian lanes on both ends for walking and bicycling. Two main I-girders were 3m deep and spaced transversely at 6m. The deck slab was made of concrete 11.4 m wide and 0.31 m thick and was assumed to act compositely with the main girders. The two main girders were interconnected by end and intermediate crossbeams at a uniform spacing of 5.3 m. The geometric properties and cross section layout of the bridge are presented in Table 1 and Figure 1, respectively. The bridge piers had a solid circular cross section with a radius of 3m and height equal to 5m. The total arc lengths of the curved bridges were kept equal to the length of straight bridge, as suggested by the AASHTO Guide Specification, (2011). For the material properties, the concrete had a compressive strength of 4000 Psi, a mass density of 2402 kg/m³, a modulus of elasticity 24.86Gpa and a Poisson's ratio of 0.20. A709Gr50 steel had a mass density of 7850 kg/m³, a modulus of elasticity of 200Gpa and a Poisson's ratio of 0.30 was used.

2.2 *Bridge Modeling*

The curved bridges with different subtended angles of 0°, 30°, 60° and span ratios of 1.0, 0.8, 0.6, 0.4 (short to long span) were considered. In case of span ratio, the base span was kept constant at 53m and other span was varied. To determine the dynamic responses of the bridge, 3-D finite element (FE) model was developed in CSiBridge. In FE modeling, the bridge deck was modeled using thin shell elements and the girders are modeled using linear beam elements and divided into 20 segments per span. At the first abutment, roller support was placed. At the second abutment and the bent, hinged support was provided. Further detailed information regarding the geometric properties and the material properties of the bridge can be found in Rahman et al. (2017).

2.3 *Model Validation*

To demonstrate the validity of the bridge model, the following comparisons are made. Validation is performed by comparing with FEM results presented by Kim et al. (2004) and field test data cited in Kim et al. (2004). The measured natural frequencies of an actual two span twin I-girder bridge are given in Kim (2004).

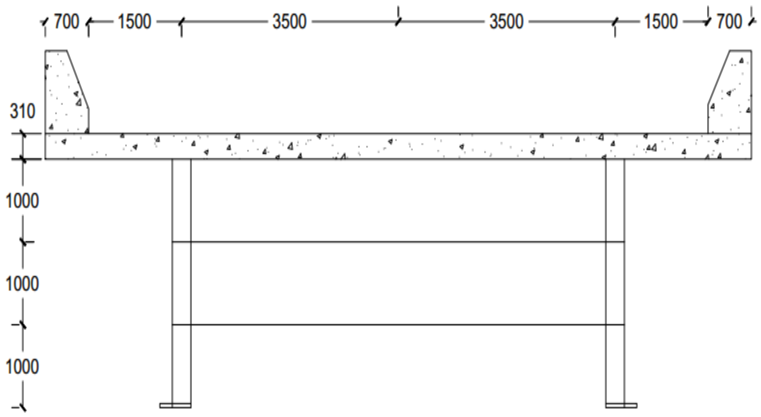


Figure 1. Cross-section of the bridge deck (mm).

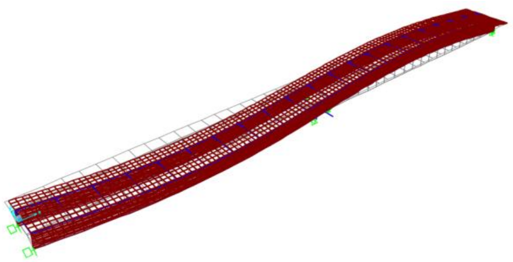
Table 1. Geometric properties of the bridge deck section.

Parameters	Value
Span length (m)	53
Deck width X thickness (m)	11.4X0.31
Dimension of the main girders (mm)	WEB 3000X23 Upper FLG 960X44 Lower FLG 970X40
Dimension of intermediate cross-beam (mm)	WEB 1000X16 FLG 300X25
Dimension of end cross-beam (mm)	WEB 3000X16 FLG 300X25

Where the cross-section, span number, boundary conditions and other properties are same to the bridge adopted in this section. Therefore, the bridge used in the reference was modeled with using ANSYS and natural-vibration analysis was performed to compare it with field test data. As can be noted the experimental frequencies agrees well with the present FE analyses. Also, mode shapes obtained from our analysis are similar to those obtained by Kim (2004). Therefore, it can be concluded that the FE modeling technique using CSi-Bridge for the present bridge is validated.

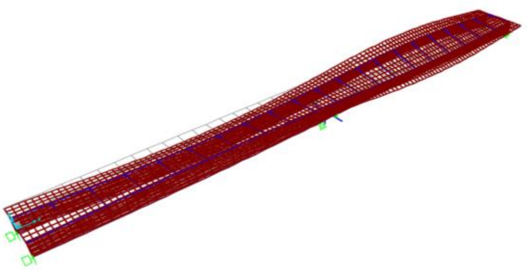
3 RESULTS AND DISCUSSION

The modal frequencies of the first three modes of the curved I-girder bridges for various span ratios are summarized in Table 2. As can be seen the natural frequencies shows a linear relationships with the curvature and span ratios of the bridge. For all the span ratios, the natural frequencies reduce with the increase in curvature (subtended angle). Similar conclusion was drawn by Serdar et al. (2017). However, the natural frequencies increase with the decrease in span ratios. One of the reasons for such kind of behavior could be due to reduction of total mass of the bridge with the decrease in span ratios. The mass of the bridge deck decreases with the decrease in span ratio, yet the same cross sectional dimension of the bridge was used as a result the bridge becomes stiffer and the natural frequencies decreases.



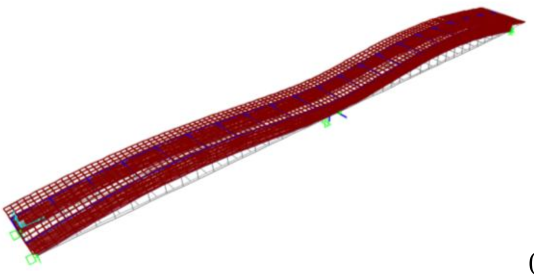
1st mode (1st bending)
Present FE analysis: 2.15 Hz
Kim et al. (2004) results: 2.26 Hz (1st Bending)
Experiment: 1.8 – 2.2 Hz (JHPC)

(a)



2nd mode (1st torsion)
Present FE analysis: 2.58 Hz
Kim et al. (2004) results: 2.55 Hz (1st Torsion)
Experiment: 2.2 – 2.8 Hz (JHPC)

(b)

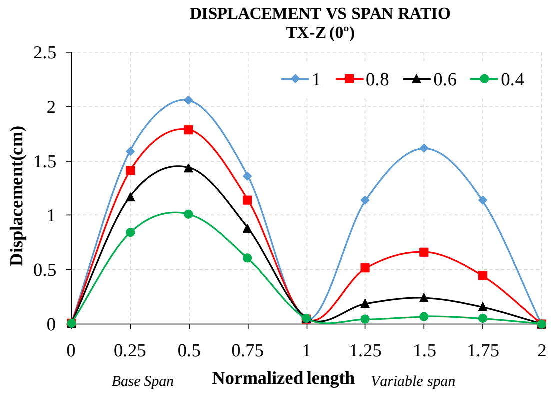


3rd mode (2nd bending & torsion)
Present FE analysis: 3.05 Hz
Kim et al. (2004) results: 3.37 Hz (2nd Bending & Torsion)
Experiment: 3.0 – 3.4 Hz (JHPC)

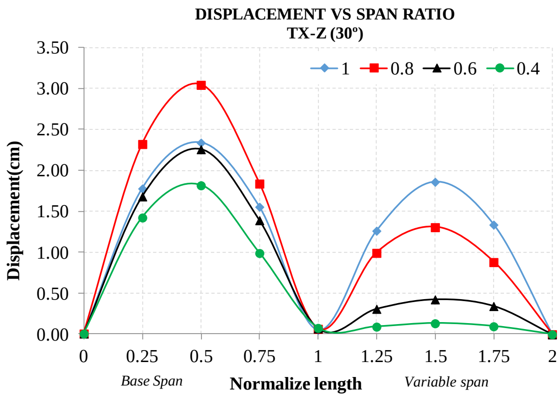
(c)

Figure 2. Comparison of present natural vibration frequencies and mode shapes with past FEM and experimental results.

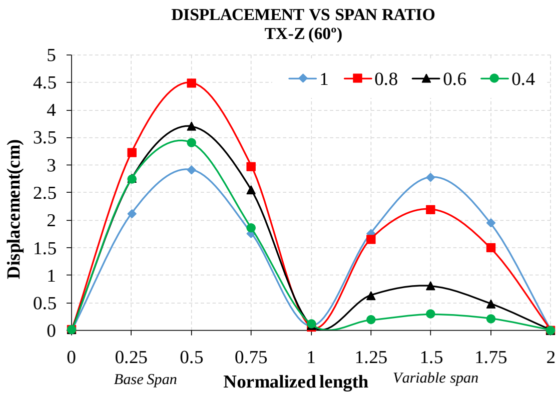
To carry out the time history analysis of the bridge, a real earthquake data namely, Tokachi-Oki earthquake (2003) occurred in Japan was utilized. The dominant frequency of the earthquake was between 2.5 to 1 Hz, which coincides with the modal frequencies of the bridges. The base shears of the bridges along the longitudinal direction are listed in Table 3. Both for the straight and curved bridges, the base shear decreases with the decrease in span ratio.



(a) For subtended angle 0°

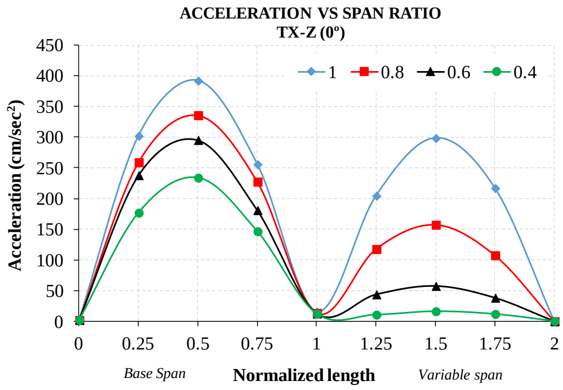


(b) For subtended angle 30°

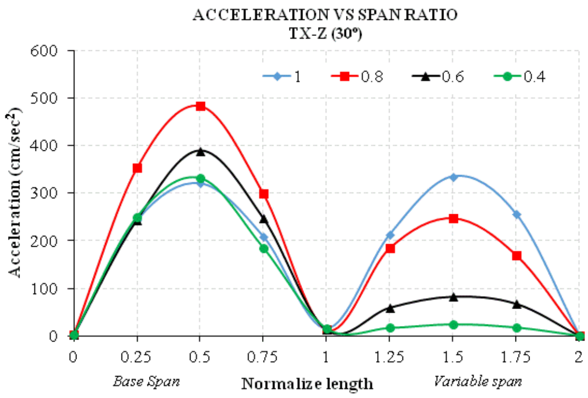


(c) For subtended angle 60°

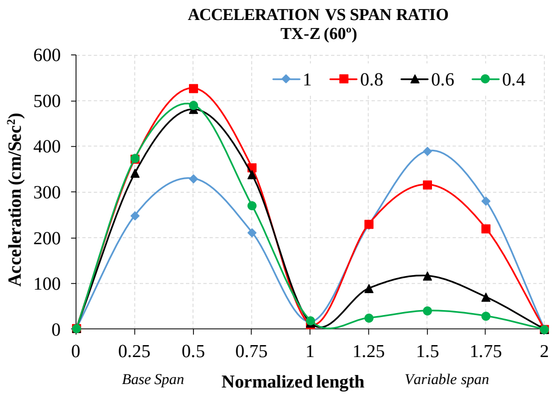
Figure 3. Variation of vertical deck displacement (longitudinal ground motion) for various span ratios.



(a) For subtended angle 0°



(b) For subtended angle 30°



(c) For subtended angle 60°

Figure 4. Variation of vertical deck acceleration (longitudinal ground motion) for various span ratios.

However, for a same value of the span ratio, the base shear mostly increases with the increase in curvature. The vertical displacement and acceleration of the bridge deck due to longitudinal excitation are plotted in Figures 3 and 4 respectively. As can be seen both the deck displacement and acceleration have similar trend in the results. For any value of span ratio, the base span experiences higher responses at the mid-span of the bridge deck. For the straight bridge, the span ratio has favorable effects. The deck response decreases with the decrease in span ratio both for the base and variable spans. On the other hand, at the base span of the curved bridge, the deck response increases with the decreases in span ratio.

Table 2. Influence of curvature and span ratio on the modal frequencies of the bridge section.

Subtended Angle	Mode (Hz)	Span Ratio 1.00	0.80	0.60	0.40
0°	1st	2.15	2.41	2.54	2.63
	2nd	2.58	2.96	3.11	3.20
	3rd	3.04	3.68	4.04	4.37
30°	1st	1.88	2.13	2.24	2.31
	2nd	2.72	3.16	3.33	3.49
	3rd	2.88	3.42	4.03	4.49
60°	1st	1.52	1.73	1.82	1.87
	2nd	2.33	2.89	3.18	3.35
	3rd	3.01	3.45	4.37	4.73

Table 3. Influence of curvature and span ratio on the base shear.

Subtended Angle	Base Shear (kN)	Span Ratio 1.00	0.80	0.60	0.40
0°	Longitudinal	2920	2392	2133	1849
	Transverse	6890	4493	3568	3101
30°	Longitudinal	2873	2594	2294	1876
	Transverse	5300	4914	4874	3400
60°	Longitudinal	3489	2921	2735	2474
	Transverse	5523	5250	4705	4582

4 CONCLUSIONS

Effects of adjacent span ratio on seismic response of straight and curved steel I-girder bridges were investigated. After analysis and discussion of the results it was found that the span ratio has significant influences on seismic responses of steel I-girder bridges. It was seen that the natural frequencies increases whereas base shear of the bridge decrease with the decrease in span ratio both for the straight and curved bridges. However, in case of displacement and acceleration different trend was observed. The base span experienced higher responses and the mid-span vertical displacement and acceleration increased with the decrease in span ratio. Therefore, designing base span (larger span) of the curved I-girder bridges with variable span length special care must be taken as it posses higher seismic responses as compared to the adjacent span. The present study was limited to analyze the deck behavior of a two span I-girder bridge. Further detailed analysis is required to investigate the effect of span ratio both on the super and sub-structures of multi-girder bridge.

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