FREE VIBRATION CHARACTERISTICS OF HORIZONTALLY CURVED CONTINUOUS MULTI I-GIRDER BRIDGE

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ABSTRACT

Horizontally curved bridges have increased much more popularity in modern highway systems. It is constructed at complicated highway interchanges or river crossings where geometric restrictions and constraints of limited site space. Dynamic characteristics of curved bridges are complex phenomenon and are less understood. Therefore, it is vital to improve the understanding about the dynamic characteristics of these horizontally curved bridges. In this study, free vibration characteristics of horizontally curved continuous multi I-girder bridge are extensively studied by using three dimensional finite element method and field measured approach. Three spans multi I-girder express highway bridge is considered for free vibration analysis. Free vibration characteristics are studied by modeling the bridge as one, two and three spans. Results are comparing with experimental natural frequencies. Torsional frequencies are greatly influence of this type of curved bridge. Two successive torsional modes are found after first vertical mode that implies this type of bridge has low torsional stiffness. Therefore, it can be easy to vibrate under external dynamic load. Need to improve torsional stiffness of this type of bridge for better performance.

Keywords: *Horizontally curved multi I-girder bridge, finite element method, free vibration, torsional stiffness*

1. INTRODUCTION

Horizontally curved bridges have increased much more popularity in highway interchanges and river crossing because of smooth dissemination of congested traffic in urban highways. Horizontally curved girder bridges represent approximately 30% of the steel bridge market today (Zureick *et al.*, 2000 and Linzell *et al.*, 2004). Tight geometric requirements are often placed on highway structures due to right-of way restrictions in congested urban areas. Also, the modern emphasis on aesthetic considerations has motivated to increase the curved alignments uses. Despite the advantages stated above, horizontally curved girder bridges have often difficult to design simply due to the lack of information of curvature behaviour. Also due to their curvature, the behaviour of horizontally curved bridges is more complex than straight bridges. In addition, vertical shear and bending stress present in straight girder systems, curved girders must also resist torsion that occurs due to curvature. As a result the curvature of the deck reduces the stiffness (Sasmal, 2005). Therefore it is important to improve the knowledge regarding the dynamic behavior of horizontally curved bridge.

Extensive research work in the literature concerning the behaviour of horizontally curved members has been published. These investigations were primarily concerned with the analysis of curved girders. Among those some are related to free vibration characteristics of horizontally curved bridges. Maneetes and Linzell (2003) investigated the effects of cross-frame and lateral bracing of free vibration response of a single-span, non-composite, curved multi I-girder Bridge by both experimental and finite element analysis. These parametric studies provided influential parameters affecting dynamic response of the system. Another study related to finite element formulation for free vibration analysis of horizontally curved steel I-girder bridges was proposed by Yoon *et al.* (2005). This numerical formulation was extensively carried out for free vibration analyses of curved bridges considering the effects of curvature, boundary condition, modelling method, and degrees of freedom of cross-frame which provided invaluable information. Sasmal (2005) studied the free vibration characteristics of curved bridges by considering the grillage model. But it has been found that the grillage model is not capable of reflecting the dynamic characteristics accurately. Barth and Wu (2007) present a finite element approach procedure using ABAQUS to analyze the natural frequencies characteristics and proposed a frequency equation of I-girder bridges. Most of these papers used simple elements, discussed narrow range of parameter and not enough number of spans to have a clear look on dynamic characteristics of curved bridges.

In this paper, free vibration characteristics of horizontally curved continuous multi I-girder bridges are extensively studied by using three dimensional finite element method and field measured approach. Three spans multi I-girder express highway bridge is considered for free vibration analysis. Free vibration characteristics are studied by modelling the bridge as one, two and three spans using ANSYS code. An experiment is conducted on the same bridge. Results are comparing with experimental natural frequencies.

2. GEOMETRY OF THE STUDIED BRIDGE

The real bridge considered in this study is Kita-go multi I-girder continuous expressed highway bridge situated in Sapporo, Japan. It consists of three spans; each span is 50 m length. Five main I-girders are 2.8 m deep and spaced transversely at 2.1 m. The deck slab is made of pressurised concrete of 11 m wide and 0.2 m thick, and is assumed to act compositely with main girders. The main girders are interconnected by end-span diaphragms as well as intermediate diaphragms at uniform spacing of 5.0 m. The radius of curvature of the studied bridge is 1000 m. The basic geometric properties and cross-section layout of Kita-go Bridge are presented in Table 1 and Fig.1, respectively.

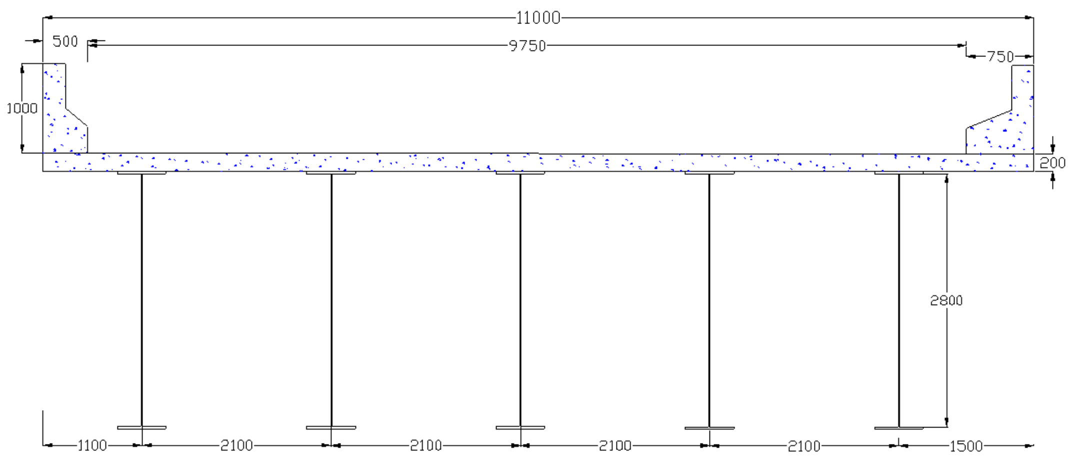

Figure 1: Cross-section of studied bridge (mm)

Table 1: Geometric properties of Kita-go Bridge

Span length [m]	50	
Deck width × thickness [m]	11 × 0.2	
Dimensions of main girders [mm]	WEB 2800 × 10	
	FLG1: 540 × 25	FLG2: 350 × 16
	FLG3&4: 370 × 14	FLG5: 510 × 25
Vertical stiffener of main girder [mm]	145 × 12	
Horizontal stiffener of main girder [mm]	115 × 11	
Dimensions of intermediate cross-beams [mm]	WEB 200 × 8	
	FLG 100 × 8	
Vertical stiffener of intermediate cross-beams [mm]	145 × 12	
Dimensions of end cross-beams [mm]	WEB 2400 × 9	
	FLG 250 × 10	
Vertical stiffener of end cross-beams [mm]	145 × 22	
Dimensions of lateral bracing [mm]	WEB 150 × 10	
	FLG 150 × 12	

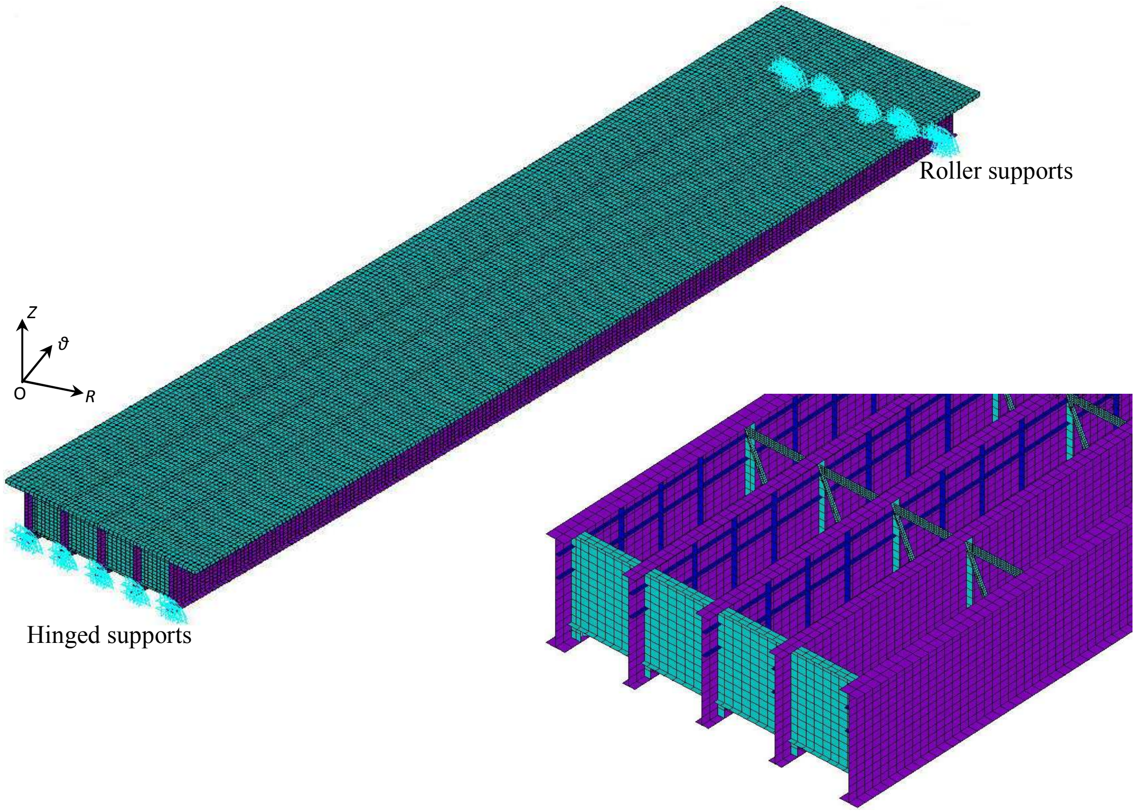

Figure 2: Finite element model of Kita-go Bridge

3. FINITE ELEMENT MODELING

Detailed finite element model of studied bridges is developed by using ANSYS code to analyze the free vibration analysis. Hexagonal 8-noded solid45 elements are used to model the concrete deck and quadrilateral 4-noded shell63 elements are used for all steel members. All elements are defined based on cylindrical coordinate system whose origin is centre of bridge's curvature. The boundary conditions at the end of the main girders, which are also based on the cylindrical coordinate system, are hinged and roller-supported in tangential direction. All supports are restrained in vertical direction but allow rotating along support line. Figure 2 shows a three-dimensional (3-D) view of a typical finite element model of the single span original studied bridge. Lumped mass method is used for mass matrix formulation; and the numerical approach for solving natural frequencies and associated mode shape is Block Lanczos method.

4. ANALYTICAL RESULTS

Although free vibration analysis does not relate to any types of loading, it is one of the most important steps in any dynamic analysis process. It is the usual first step in performing a dynamic analysis to determining the natural frequencies and mode shapes of the structure with damping neglected. These results characterize the basic dynamic behavior of the structure and are an indication of how the structure will respond to dynamic load (MSC. Software Corporation, 2004). To conduct the natural vibration analysis is to determine the vibration characteristics (natural frequencies and mode shapes) of a structure while it being designed. Natural frequencies of a structure are the frequencies at which the structure naturally tends to vibrate if it is subjected to a disturbance. Each mode shape is associated with a specific natural frequency. Natural frequencies and mode shapes are functions of the structural properties and boundary conditions.

Free vibration analysis results are investigated by modelling the bridge as one, two and three spans. The original bridge have 2% super-elevation, but the effect of super-elevation on natural frequencies are negligible because of large radius of curvature *(r* = 1000 m) (Awall *et al.*, 2012). Therefore in this study, super-elevation is not considered in the model.

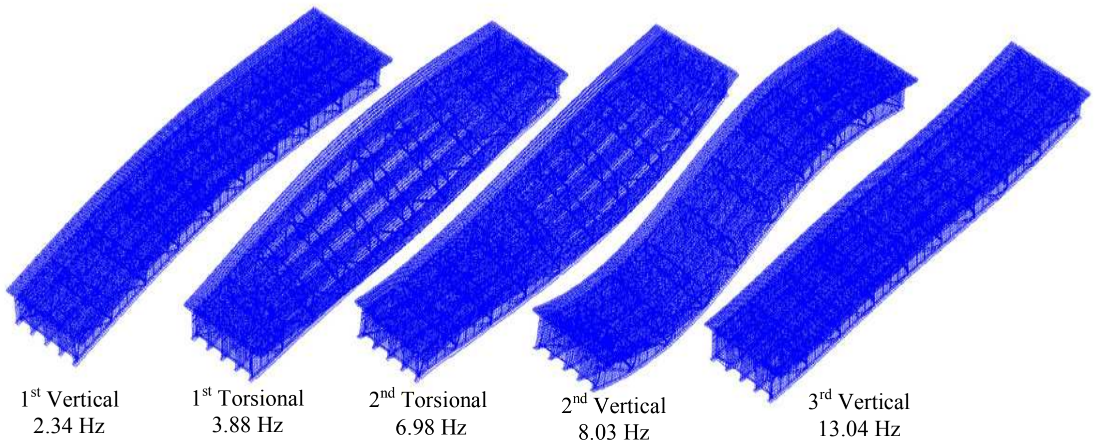

Figure 3: Natural frequencies and mode shapes of one span Kita-go bridge

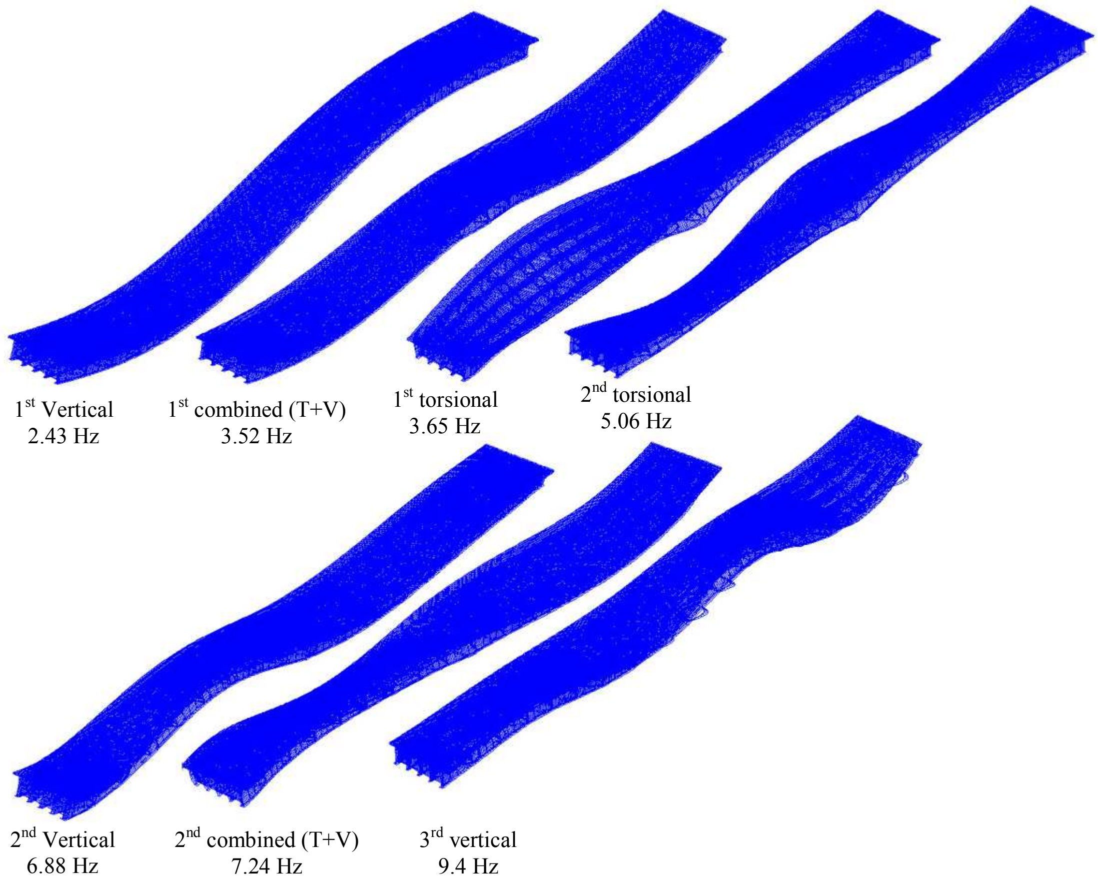

Figure 4: Natural frequencies and mode shapes of two-spans Kita-go bridge

Natural frequencies and mode shapes of Kita-go Bridge with considering one span, two spans and three spans are shown in Fig. 3, Fig. 4 and Fig. 5 respectively. For considering one span, first vertical mode is obtained in 2.34 Hz. After that two successive torsional modes are found in 3.88 Hz and 6.98 Hz. Second vertical mode is obtained in 8.03 Hz shown in Fig.3. For considering two spans bridge shown in Fig. 4, first vertical mode is obtained in 2.43 Hz and first and second torsional modes (3.65 Hz and 5.06 Hz) are shifted in third and fourth modes, and in second mode first combined torsional-vertical mode is obtained in 3.52 Hz. Second vertical mode is found in 6.88 Hz. Also for considering three spans bridge, first vertical mode (2.43 Hz) is always first mode

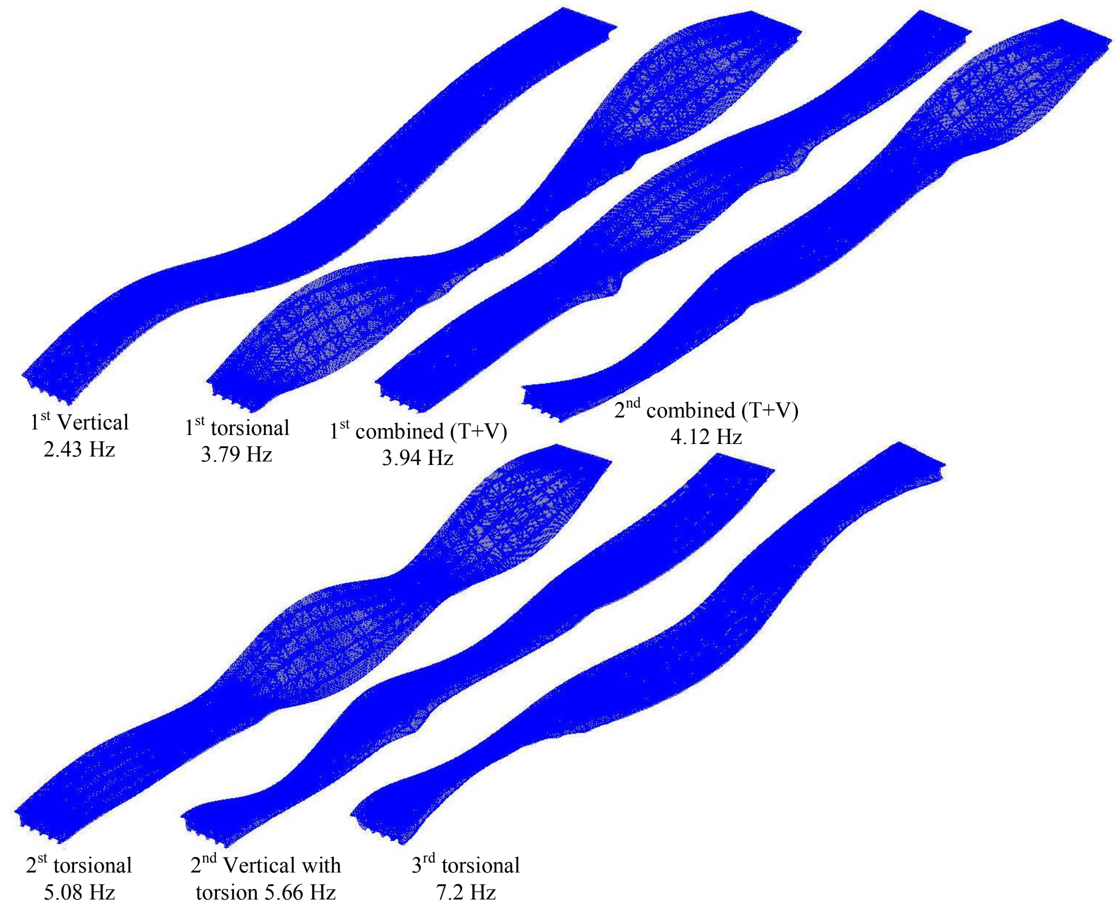

Figure 5: Natural frequencies and mode shapes of three-spans Kita-go bridge

shown in Fig. 5: First pure torsional mode is obtained in 3.79 Hz. After that first and second combined torsional-vertical modes are obtained in 3.94 Hz and 4.12 Hz. Second torsional mode is obtained in 5.08 Hz and second vertical mode that is couple with torsion is found in 5.66 Hz. From the free vibration analysis result it is observed that torsional vibration is increasing with number of curved spans. That is, if the number of curved span is more the torsional vibration is more dominated.

5. EXPERIMENTAL RESULTS

Free vibration experimental test have been done in original three spans Kita-go bridge site. Six accelerometers are placed in the bridge girders G2, G3 and G4 as shown in Fig. 6. From those, accelerometers 1, 2 and 3 are placed in the mid-point of mid-span and accelerometers 4, 5 and 6 are placed in the mid-point of the first span. In the mid-point of mid span, 25^T free-fall mass truck is used for excitation of bridge. Then the free vibrations are recorded in the six accelerometers.

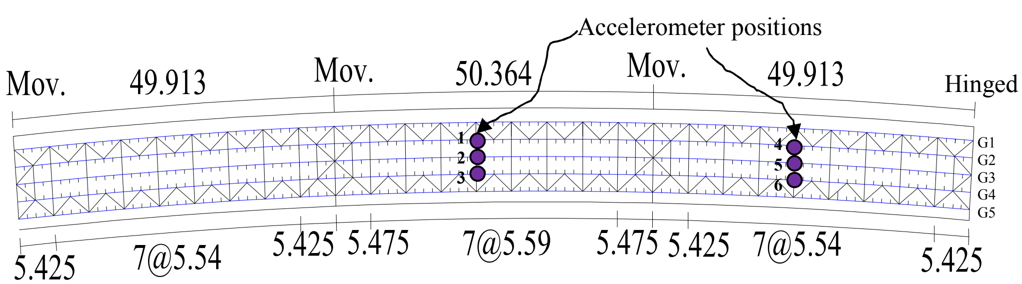

Figure 6: Accelerometer positions of three-spans Kita-go bridge

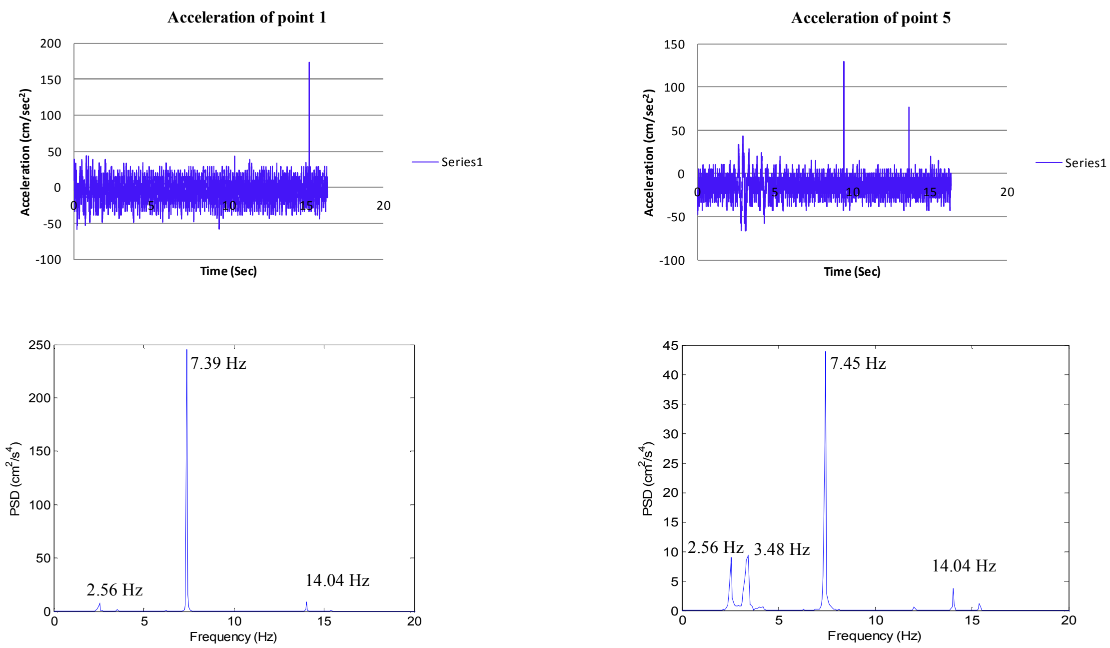

Figure 7: Time history acceleration and PSD of point 1 and 5

Table 2: Comparison results between numerical and experimental

Number of Span	1st Vertical (Hz)	1st Torsional (Hz)	2nd Torsional (Hz)	2nd Vertical (Hz)	3rd Vertical (Hz)
One span	2.34	3.88	6.98	8.03	13.04
Two spans	2.43	3.65	5.06	6.88	9.4
Three spans	2.43	3.79	5.08	5.66	
Experimental	2.50 ~ 2.56			7.14 ~ 7.45	13.55 ~ 14.10

By using the free vibration time history accelerations power spectrum density (PSD) are calculated to find out the dominant frequency. Writing some code on Matlab software PSD with dominant frequency is calculated. Figure 7 shows the time history acceleration with corresponding PSD results of accelerometer point 1 and 5. Observing the all events and all accelerometer time history results and their corresponding PSDs, first vertical frequency is obtain between 2.50~2.56 Hz and second and third vertical frequencies are between 7.14 ~ 7.45 Hz and 13.55 ~ 14.10 Hz respectively. In the experimental results, torsional frequencies are not obtained because the accelerometers are recorded only vertical accelerations. Comparison results of dominant frequencies between numerical and experimental are shown in Table 2; the results are very near and acceptable.

6. CONCLUSIONS

The present study has been investigated the free vibration characteristics of horizontally curved continuous multi-I girder bridge by using 3-D finite element method of ANSYS and experimental test in the field. The original curved bridge has three spans; results are investigated by considering the bridge model as one, two and three spans. In all cases first vertical mode is always first mode and vertical modes frequencies are good agreements with experimentally obtained frequencies. Also, the first and the second torsional modes as well as combined torsional-vertical modes are obtained between first and second vertical modes. Combined torsional-vertical modes are increasing with number of span considered in the curved bridge model. In the three spans curved bridge model torsional vibrations are mostly dominated. This implies that this type of curved bridge has low torsional stiffness and it can be easy to vibrate under external dynamic load. Therefore, needs to improve the torsional stiffness of this type of bridge for better performance. For to get the actual dynamic characteristics of curved bridge, all curved spans should be considered in the analysis.

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