Improving Natural Vibration Characteristics of Horizontally Curved Two-girder Steel Bridges by Using Bottom Bracings

Hokkaido University　Student member　○ Md. Robiul Awall
Hokkaido University　Fellow member　Toshiro Hayashikawa
Hokkaido University　Regular member　Takashi Matsumoto
Hokkaido University　Regular member　Xingwen He

1. INTRODUCTION

Horizontally curved bridges are commonly used in highway interchanges in large urban areas. Two-girder steel bridges are one of the most popular bridge types for short and medium span highway bridges in Japan[1]. Advantages of such a simplified structural system of horizontally curved two-girder steel bridges possess numerous beneficial merits such as design, fabrication, and the low cost for maintenance and construction[2]. However, wider girder spacing and more simplified structural system of the two-girder bridge than the conventional multi-girder bridge can give rise to change of dynamic characteristics of the bridges[3]. Also due to their curvature, the behavior 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. However, because of its small torsional stiffness and its sectional aerodynamic characteristics, curved two-girder steel bridge can easily vibrate due to external dynamic load like wind, moving vehicle etc., when its spans become longer[4]. As a result, these unexpected vibrations could cause severe fatigue damages in the bridge member.

In straight bridges, diaphragms and lateral bracing are needed for erection stability and during placement of the deck; whereas, they are important in load-carrying and torsional resistance elements in horizontally curved bridges, both during construction and while in-service. Dynamic loads not only occur while the bridge is in-service, but also during construction where they can result from equipment impact loads, accidental vibration loads. These loadings can lead to locked-in stresses and changes in the geometry of the bridge prior to it being placed into service that could alter its behavior from what is expected[5]. Moreover, alignment problems that may result from costly construction delays could be minimized. Therefore it is vital importance to improve the knowledge regarding to dynamic behavior of horizontally curved bridge.

Very little documentation has been made available on the studies of free vibration characteristics of horizontally curved bridges. Maneetes and Linzell[5] 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[6]. This numerical formulation was extensively carried out for free vibration analyses of curved bridges considering the effects of curvature, boundary condition, modeling method, and degrees of freedom of cross-frame which provided invaluable information. Most of these papers used simple elements or not enough number of curvatures to have a clear look on dynamic response of curved bridges.

In this study, a series of horizontally curved steel twin I-girder composite bridges with varying of radius are investigated in detail by using three-dimensional finite element method of ANSYS code. Five different types of bottom bracing and curvatures are studied to clarify its effects on free vibration characteristic of horizontally curved bridges. These investigations are not only to enhance the understanding about free vibration characteristics but also to find out the methods improving these characteristics of the bridge.

Table 1 Geometric properties of studied bridge

Span length [m]	50
Deck width × thickness [m]	10.5 × 0.3
Dimensions of main girders [mm]	WEB 3000 × 24 Upper FLG 500 × 30 Lower FLG 500 × 50
Dimensions of intermediate cross-beams [mm]	WEB 1000 × 16 FLG 300 × 25
Dimensions of end cross-beams [mm]	WEB 3000 × 16 FLG 300 × 25

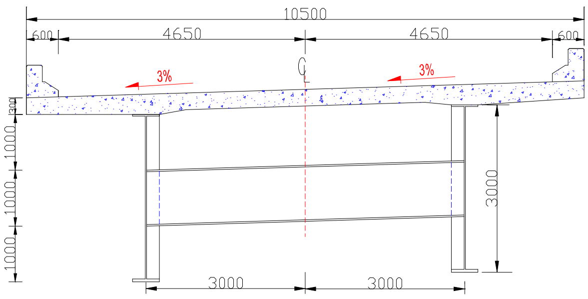


Fig. 1 Cross-section of studied bridge (mm)

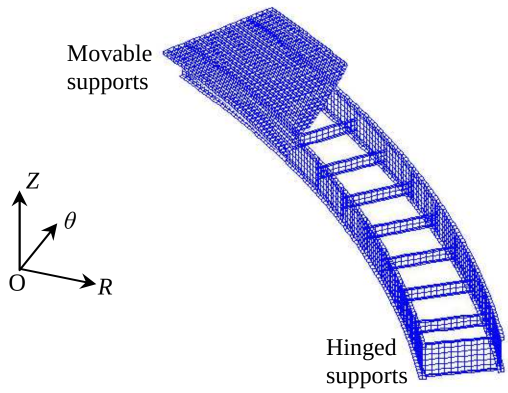


Fig. 2 Detailed FE model of studied bridge (R=100m)

2. GEOMETRY OF STUDIED BRIDGE

The bridge chosen in this study is simply supported horizontally curved twin I-girder bridge, whose length is 50m measured the centerline between two main girders. Two main I-girders are 3m deep and spaced transversely at 6m. The deck slab is made of prestressed concrete of 10.5m wide and 0.3m thick, and is assumed to act compositely with main girder. The main girders are interconnected by end-span diaphragms as well as intermediate diaphragms at uniform spacing of 5.0 m. 3% super-elevation is considered throughout the configuration. Original studied bridge geometric properties and cross-section layout are presented in **Table 1** and **Fig.1**, respectively. The same cross sectional properties but five different radii of curvatures are considered equal to 100m, 200m, 400m, 800m, and infinity (straight configuration) for free vibration analysis.

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-node solid elements are used to model the concrete deck and quadrilateral 4-node shell elements are used for all steel members. All elements are defined based on cylindrical coordinate system whose origin is center of bridge's curvature. The boundary conditions at the end of the main girders, which are also based on the cylindrical coordinate, are hinged and movable-supported in tangential direction. **Figure 2** shows a three-dimensional (3-D) view of a typical finite element model of the 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.

4.1 Original models

Original models in this study are the models without any additional intermediate plate diaphragms or bottom bracings which are describe in section 2 and typical finite element model is shown in **Fig.2**. Typical first vertical mode (f_{V1}) and first torsional mode (f_{T1}) of original model of 200m radii of curvature and 3% super-elevation are shown in **Fig.3**. In these bridges, regardless of curvature, the first vertical mode is always related to the first mode and the first torsional mode is the second one. Unlike in straight bridge, whose mode shapes are easily classified, both the first and second modes of vibration in these curved systems are coupling modes of flexure and torsion due to the effect of curvature. The smaller of the radius of curvature, the larger of the coupling effect can be seen. In the vertical related modes, the magnitude of the outside main girder's vibration is always larger than that of the inside one and vice versa in the torsional related modes.

From the calculated results, it is easy to realize that the curvature has a significant effect on the natural frequencies and mode shapes of the studied bridges. The results clearly shows that the frequency of vertical modes decreases and torsional modes tends to increases with the decrease of bridge's radius as plotted in **Fig.4**. Decreasing of bridge's radius means shortening the length of the inside main girder and lengthening that of the outside one; in connection with the primary difference in vibration between torsional and vertical modes, the changes of frequencies with radius can be understood. This figure also shows the frequency ratio, which is the ratio between the first torsional mode and first vertical mode frequencies, changes inversely with the radius of bridges. Because the frequency ratio of almost all studied models is small, the torsional and vertical vibration of these bridges could occur coincidently by external loads. Therefore, it is practical to increase these values by improving torsional stiffness of the studied bridges and that is developed in the next section.

4.2 Models with bottom bracing

When a bridge is subjected to aerodynamic forces or an eccentrically running vehicle, it is usually vibrates both vertically and torsionally. These unexpected vibrations cause fatigue damage in bridge members especially at connections

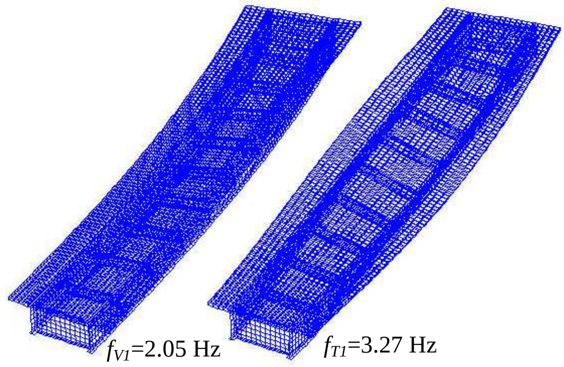


Fig. 3 Mode shapes of original model (R = 200m)

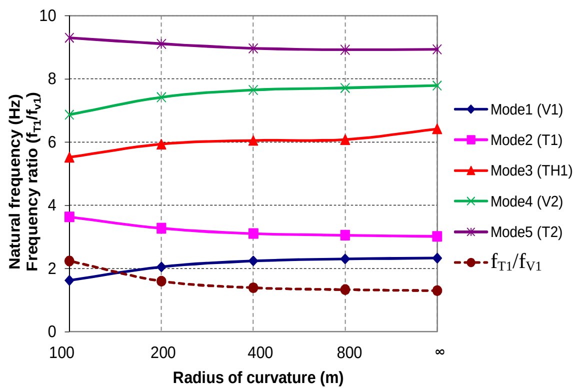


Fig. 4 Natural frequency/frequency ratio with different radii of curvature

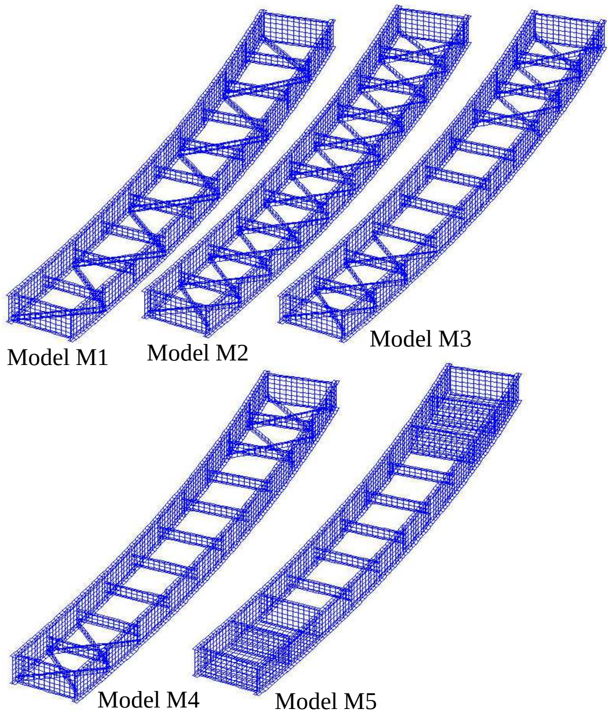


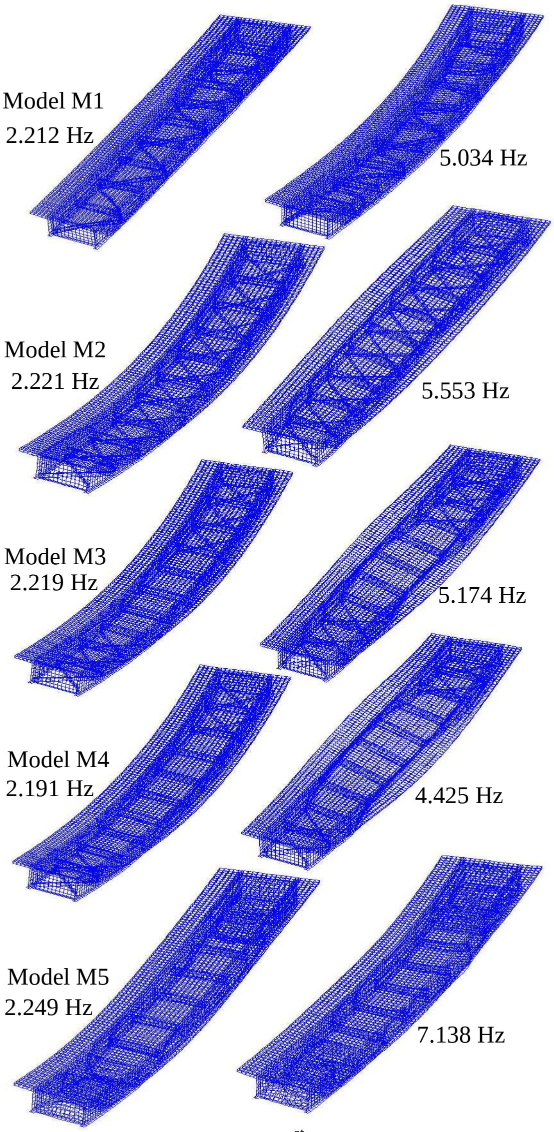
Fig. 5 Typical models (R = 200m) with different bottom bracing configurations

due to stress concentration and sometimes lead to brittle fracture of the bridge. An effective method to mitigate these vibrations in bridge members is changing of its natural frequencies. Generally lateral bracing can be used to transfer lateral loads both during construction and while in-service. Also, it increases the torsional resistance in curved bridges. In this section, the natural frequencies of the studied bridge are enhanced by providing several types of bottom bracings.

The effect of bottom bracings are studied through five types of bottom bracing configurations typically represented in **Fig.5**. Model M1 is the “V” shaped of subsequent two bays braced by I-section members of 0.5m depth. More details, dimensions of the new I-section steel members are WEB500×16; FLG300×25. Model M2, M3 and M4 are the “X” shaped by considering T-section steel members of same dimension, but bracing bays are different of each model. Model M5 is the bottom plate bracing with 20mm steel plates in the plane of bottom flanges along with the full height intermediate diaphragms. There are totally four exterior-most bays braced by bottom plates equally divided at both ends of this model.

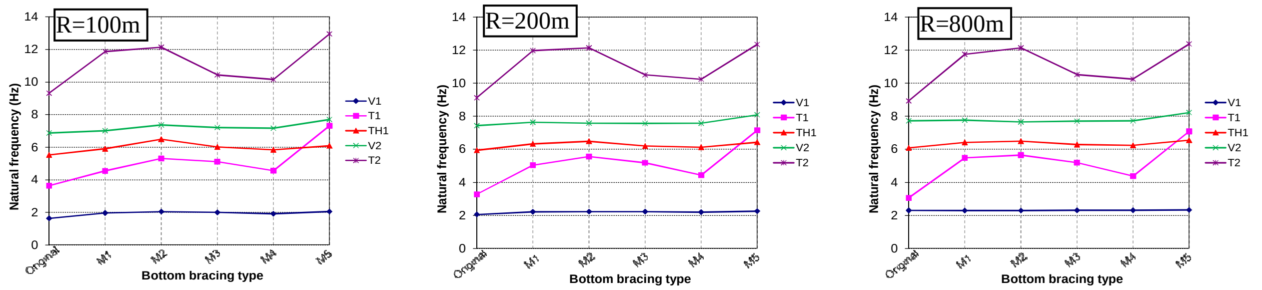
Amongst many natural frequencies and associated mode shapes, those of the first vertical and first torsional modes are usually the most important one, because of their influences in dynamic response of the structure. First vertical and first torsional mode shapes and natural frequencies of different models with bottom bracing configurations of 200m radius of curvature are shown in **Fig.6**. In these models, regardless of curvature, the first vertical mode always related to the first mode. But, for first torsional mode of model M5 is obtained at 7th mode. Between the vertical and torsional mode of this model, there are first horizontal mode and some local vibration modes of plate are observed. Also local vibration modes are observed in bottom bracing of M1 model after torsional mode and combined local vibration with bridge vibration are observed.

The numerical results of five modes of all studied curvature of bridge models are shown in **Fig.7**. The calculated results shows the torsional modes greatly effect of bottom bracing configurations. Moreover, the bottom bracings enhance also vertical bending rigidity of the curved systems. This could be interpreted through the coupling effect in both of vertical and torsional modes in curved system. In addition, frequencies of the studied systems are influenced considerably by both of the bottom bracing types, the number and location of the braced bays. In every model vertical related mode frequencies are increases from original bridge model and increasing rate is higher in small radius of curvature bridges shown in **Fig.7a**. Combined torsional horizontal mode frequency also increases from original model of every bottom bracing configurations model. Torsional horizontal mode frequency is increasing much in M2 model than other model

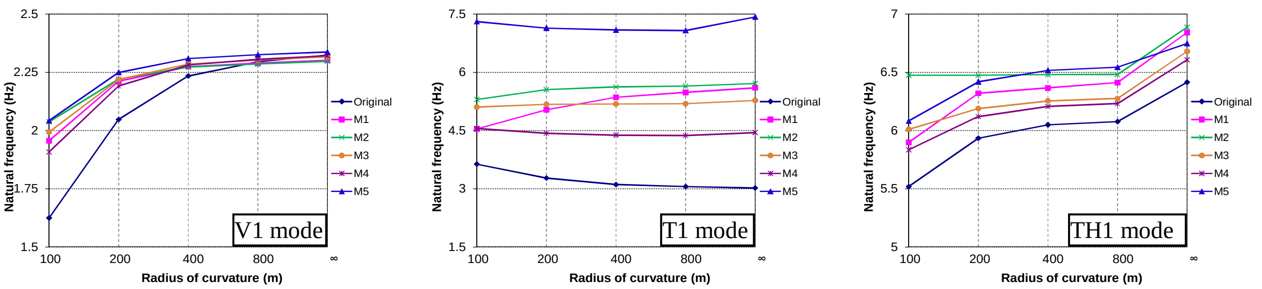


a) 1st vertical modes　**b)** 1st torsional modes

Fig. 6 Mode shapes of different model with bottom bracing configurations (R = 200m & e = 3%)



a) With different types of models



b) With different radius of curvatures

Fig. 7 Natural frequencies of different mode with different models and radius of curvatures in small radius of curvature bridge model. In torsional related modes, M5 model that is full bottom plates together with full height diaphragm of exterior bays give the higher frequency than others model in every curvature shown in **Fig.7b**. But, in this case first torsional mode occurs after combined torsional horizontal mode and some local vibration modes of bottom plates. This type of local vibrations of bottom plates are dangerous for dynamic responses due to moving loads or aerodynamic forces, causes fatigue damage in bridge members and sometimes lead to brittle fracture of the bridge. However, inspection and repair of fatigue damage is extremely difficult of this type of end bays box system especially when the fatigue damage occur at middle intermediate diaphragm.

M1 model also gives higher torsional frequency, but local vibrations are observed in the brace and combined local vibration with bridge vibration. Because in this model bracing is extremely large about 7.81m. So, there is a possibility of fatigue damage of this type of "V" shaped of subsequent two bays bracing system. Therefore, this type of bottom bracing system choosing is impractical.

However, "X" shaped model by considering T-section steel members that are M2, M3 and M4 models dose not produce any local vibrations of the bottom braced members. Because in this bottom bracing model one T-section steel member is attach the lower part and another inverted T-section steel member is attach just the upper part of the first member and the touching portion of the two members are jointed. That's why this type of bottom bracing gives much stiffer to resists the local vibrations of the components. Among these three models M2 model that all bays braced by "X" shaped T-section steel members is gives the higher frequency than others two model. Also M2 model gives the higher frequency in vertical mode, torsional mode and torsional horizontal mode of all the radius of curvature models than the M1 model shown in **Fig.7b**. In small radius curvature also M3 model which is total 6 bays equally divided on two exterior bays braced by "X" shaped T-section steel members, natural frequencies of all the modes are higher than M1 model.

To confirm the effect of different bottom bracings on the performance of the system, the frequency ratios of these models, which are the ratios between the natural frequency of the first torsional and that of the first vertical modes, are depicted in **Fig.8**. It can be seen that M5 model gives higher frequency ratio (more than 3), this means box effect greatly increases the torsional stiffness of the structure but this model produces local vibrations of the plates as mention above. Which is dangerous of dynamic vibrations due to dynamic loads, causes fatigue failure and inspection and repair are extremely difficult of this model. It can be assured the better performance of bottom bracing configurations with "X" shaped T-section steel members such as M2, M3, and M4 models. M2 model gives about 2.5 frequency ratio, which is greater than the M1 frequency ratio among the all studied radius of curvature models. For small radius of curvature M3 model frequency ratio (between 2-2.5) is higher than M1 model and gives the good performance of torsional stiffness. However, using too many bottom bracings becomes impractical when considering the cost effectiveness. Therefore, the M3 configuration should be most suitable ones to increase the torsional stiffness of the studied bridges.

5. CONCLUSIONS

The present study has been investigated the effect of bottom bracing configurations on natural vibration characteristics of horizontally curved twin I-girder bridges by using 3-D finite element method of ANSYS. The results of many detailed FEM models provide sufficient evident for the followings remarkable conclusions:

1) In studied curved bridge, frequency of the first vertical mode tends to decrease; that of the first torsional mode, on contrary, tends to increase with the decrease of curvature radius. Because of these tendencies, the frequency ratio of first torsional mode and vertical mode increases as the radius of curvature decreases;
2) By using different types of bottom bracings cause changing not only in the natural frequencies but also in the associated mode shape and their order of studied models.
3) The natural frequency of vertical-related modes changing is very small with the various types of bottom bracing systems. Torsion-related modes increase much with the stiffer bottom bracing systems. The rates of changing depend not only on the stiffness of bottom bracing but also on the types and location of bottom bracing system.
4) The poor performance of bottom bracing type is M4; and the best one is M5. However, M5 model has limitation to use because of its local vibrations cause fatigue failure, inspection, repair problem and shorter service life. Besides, the free vibration characteristics of the models M2 and M3 are also quite good. Moreover, the M2 model becomes impractical when considering the cost effectiveness. Consequently, the M3 bottom bracing configuration is considered a reasonable one.

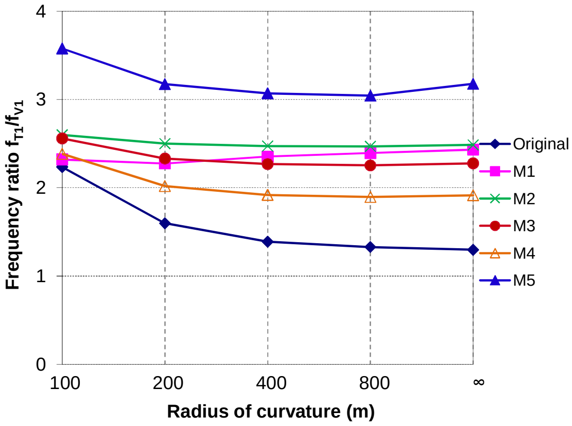


Fig.8 Frequency ratio of different types of model

REFERENCES

1) Kim, C. W., Kawatani, M. and Hwang, W. S.: Reduction of traffic-induced vibration of two-girder steel bridge seated on elastomeric bearing, *Engineering Structures*, Vol.26, pp. 2185-2195, 2004.
2) Montens, M., Vollery, J. C. and Park, J. H.: Advantages of twin I beams composite solutions for highway and railway bridges, *Steel Structure International Journal*, Vol.3(1), pp. 65-72, 2003.
3) Kim, C. W. and Kawatani, M.: End-Cross beam reinforcement against traffic-induced high-frequency vibration of steel twin-girder bridge, *Steel Structures*, Vol.3, pp. 261-270, 2003.
4) Linzell, D. G., Hall, D. and White, D.: Historical perspective on horizontally curved I girder bridge design in the United States, *Journal of Bridge Engineering*, Vol.9, No. 3, pp. 218-229, 2004.
5) Maneetes, H., Linzell, D. G.: Cross-frame and lateral bracing influence on curved steel bridge free vibration response, *Journal of Constructional Steel Research*, Vol.59, pp. 1101-1117, 2003.
6) Yoon K. Y., Kang Y. J., Choi Y. J., and Park.N. H. : Free vibration analysis of horizontally curved steel I-girder bridges, *Thin-Walled Structures*, Vol.43, pp.679-699, 2005.