Effect of End Diaphragms on Free Vibration Characteristics of Horizontally Curved Twin I-girder Bridges

Hokkaido University　Fellow member　○ Toshiro Hayashikawa
Hokkaido University　Ngo Le Tran Trong
Hakodate College　Member　Hideyuki Hirasawa

1. INTRODUCTION

During the last decades horizontally curved bridges have become an important component in modern highway systems as a viable option at complicated interchanges or river crossings where geometric restrictions and constraints of limited site space make extremely complicated to adopt standard straight superstructures. Curved alignments offer, in addition, the benefits of aesthetically pleasing, as well as economically competitive construction costs with regard to straight bridges. Besides, the advancement in fabrication and erection technology and the availability of digital computers to carry out the complex mathematical computations of the structural analysis and design of such girders are also primary reasons contributing to the development of the horizontally curved bridges.

Among some superstructures utilized in horizontally curved bridges, the multi-girder steel structures are commonly used because of the simplicity of their fabrication and construction, speed of erection as well as the low cost for maintenance. However, because of their small torsional stiffness, they can be vulnerable to vibrate when their spans become longer. Moreover, the behaviors of these horizontally curved bridges are much more sophisticated than those of straight bridges. Due to the geometric complexities, curved bridges are subjected to not only flexural stresses but also to very significant torsional stresses[1)], And while in straight bridges, diaphragms and bracings are needed for erection stability and during placement of the deck; they are very important load-carrying elements in horizontally curved bridges.

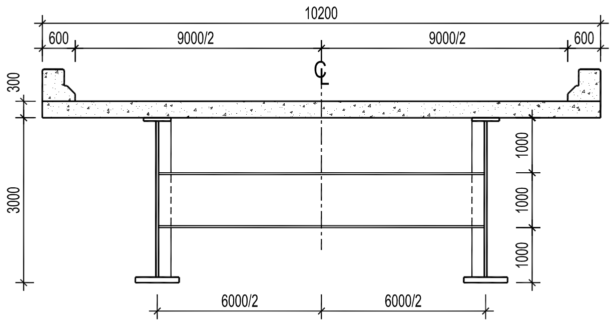
By these reasons, it is vital to improve the understanding about the dynamic behavior of these horizontally curved bridges and effect of some structural members on this behavior. In this study, the free vibration characteristics of horizontally curved steel I-girder bridge are studied by general-purpose finite element analysis MSC-Nastran software. Five different kinds of end diaphragm combining with four different types of end stiffening system are studied in details. To take into account the effect of curvature, two different radii of bridge are considered in each combination above.

2. GEOMETRY OF THE STUDIED BRIDGE

The bridge considered in this study is a simple horizontally curved steel twin I-girder one whose span, which is the length of the centerline between two main girders, is fixed as 50m. Two different radii of curvature measured from the origin of the circular arc to the centerline of the bridge deck are analyzed equal to 200m, and infinity (straight bridge). Thus, the lengths of the two main girders vary in accordance with the change of bridge's curvature; whereas, the total mass of the bridge remains unchanged. The two main I-girders are 3m deep and spaced transversely at 6m. These structural members are tied together by a reinforced concrete slab and transverse steel members. The reinforced concrete slab, which acts compositely with the steel main girders,

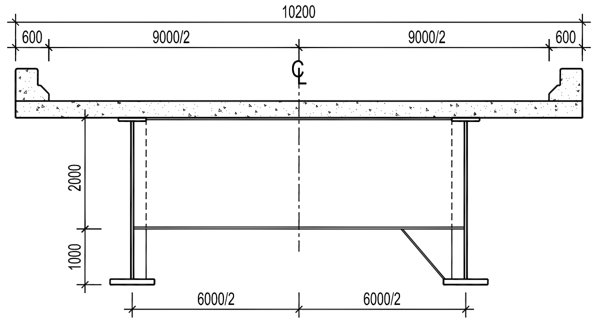
Tab1e 1 Basic geometric properties of studied bridges

Span length [m]	50
Deck width x thickness [m]	10.2 x 0.3
Dimensions of main girders [mm]	WEB 3000x24 Upper FLG 500x30 Lower FLG 800x50
Dimensions of intermediate cross-beams [mm]	WEB 2000x16 FLG 300x25



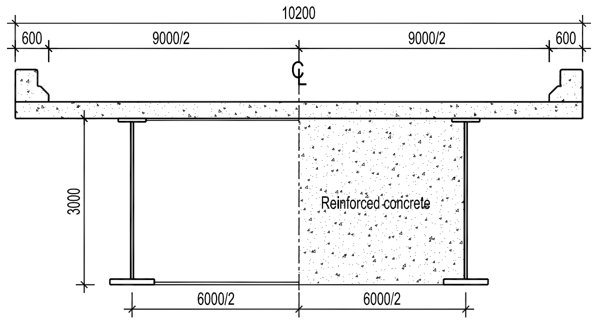
a) Intermediate cross-beam　**b)** ED1 end diaphragm

Fig. 1 Cross section of studied bridge



a) Half of ED2　**b)** Half of ED3

Fig. 2 ED2 and ED3 end diaphragms



a) Half of ED4　**b)** Half of ED5

Fig. 3 ED4 and ED5 end diaphragms

is 10.2m wide and 0.3m thick. The transverse members are radial cross-beams which are spaced equally along the span. The cross section layout and the basic geometric properties of the studied bridges are presented in **Figure 1** and **Table 1**, respectively.

To study about the effect of end diaphragms on free vibration characteristics of the bridge, five different types of end diaphragm are analyzed. These diaphragm types are shown in **Figures 1-3** and named consecutively with their stiffness. The **Figure 1** shows the first end crossbeam type – **ED1** – and typical intermediate crossbeam. These end diaphragms are exactly the same the intermediate diaphragms whose depth are 1m and connected into the middle of main girder webs. **ED2** and **ED3** end diaphragm types are presented in the **Figure 2**. These two types are 2m deep plate girders and the concrete slab is placed compositely on their top flange. The difference of these two types is the stiffening knees that only appear in the **ED3** type. The **Figure 3** depicts the two last end diaphragms **ED4** and **ED5**. They are the same in depth which is equal to that of the main girders. However, they are different in shape and material; unlike all other end diaphragm types used in this study, the **ED5** end diaphragms are concrete solid cross-section whose width is 20cm.

3. FINITE ELEMENT MODELING

Figure 4 shows a three-dimensional (3-D) view of a typical finite element model of the studied bridge. Many very detailed FEM models consisting of approximately 80,000 degrees-of-freedom (DOF) each are generated to ensure the convergence of results although a coarser mesh could be satisfactory. Two types of finite element are adopted to idealize members of these bridge superstructures; quadrilateral shell elements with 4 nodes are for all steel members and six-sided solid elements with 8 nodes are for concrete deck slab. All elements are defined based on the 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 the tangential direction shown in **Table 2**. Lumped mass method is used for mass formulation; and the numerical approach for solving natural frequencies and associated mode shapes is Lanczos method.

4. NUMERICAL RESULTS

The usual first step in performing a dynamic analysis is determining the natural frequencies and mode shapes of the structure with damping neglected.

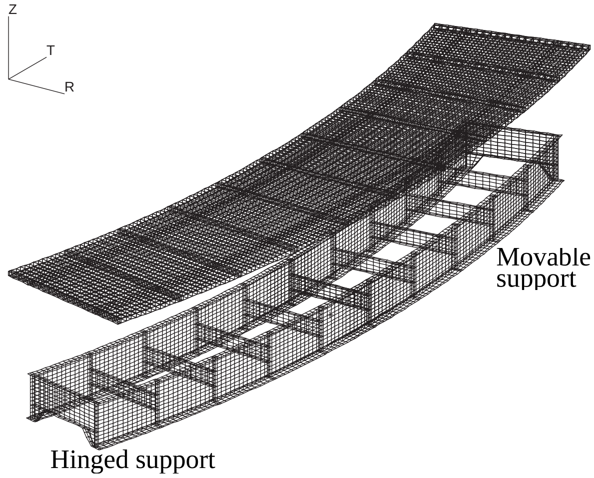


Fig. 4 Typical 3-D view of finite element model

Table 2 Boundary conditions

Type	u_1	u_2	u_3	θ_1	θ_2	θ_3
Hinged	*Fix*	*Fix*	*Fix*	*Free*	*Free*	*Free*
Movable	*Fix*	*Free*	*Fix*	*Free*	*Free*	*Free*

u_1, u_2, u_3 are translations in the R, θ, Z directions.
θ_1, θ_2, θ_3 are rotations about the R, θ, Z directions.

These results characterize the basic dynamic behavior of the structure and are an indication of how the structure will respond to dynamic loading. However, amongst many natural frequencies and associated mode shapes, only some of the first ones are usually interested because of their influences in dynamic response of the structure. In this study, only the first five modes are usually taken into account. These mode shapes represent the behaviour of whole system vibration, not local vibration of some members.

4.1 Original models

The original models in this study are the models without any additional end stiffening system such as lateral bracings, intermediate plate diaphragms. A typical FE model of original models is presented in **Figure 4** and their numerical results are shown in **Table 3**. For the ease of considering, more intuitive results are plotted in **Figure 5** in two different categories: the series of mode's order and those of mode shape type.

From the results, it is obvious that these different types of the end diaphragm cause changing not only in the natural frequencies but also in the associated mode shapes of the studied models. Except the natural frequencies of the first modes is nearly unchanged; those of the remaining modes increases with the increase of end diaphragm stiffness. The higher of the

Table 3 Numerical results of model with different types of end diaphragm

Bridge's radius	End dia. type	Mode 1		Mode 2		Mode 3		Mode 4		Mode 5		Mode 6	
		f (Hz)	type	f (Hz)	type	f (Hz)	type	f (Hz)	type	f (Hz)	type	f (Hz)	type
R ∞	ED1	2.5718	V1	2.6057	T1	3.6643	TH1	5.7882	TH2	8.5424	V2	9.2533	T2
	ED2	2.5718	V1	2.9508	T1	4.5988	TH1	7.8665	TH2	8.5446	V2	9.4728	T2
	ED3	2.5744	V1	3.1063	T1	6.3510	TH1	8.5647	V2	9.2352	T2		
	ED4	2.5734	V1	3.1291	T1	6.6842	TH1	8.5890	V2	9.3266	T2		
	ED5	2.5728	V1	3.1679	T1	6.9753	TH1	8.5578	V2	9.4280	T2		
R200	ED1	2.1737	V1	2.7729	TH1	3.8740	T1	5.7732	TH2	7.9569	V2	9.6785	T2
	ED2	2.2097	V1	3.2039	T1	4.5209	TH1	7.5221	TH2	8.1186	V2	9.7606	T2
	ED3	2.2285	V1	3.4441	T1	6.2248	TH1	8.0508	V2	9.6696	T2		
	ED4	2.2313	V1	3.4676	T1	6.5214	TH1	8.0774	V2	9.7326	T2		
	ED5	2.2389	V1	3.5002	T1	6.7708	TH1	8.1570	V2	9.7872	T2		

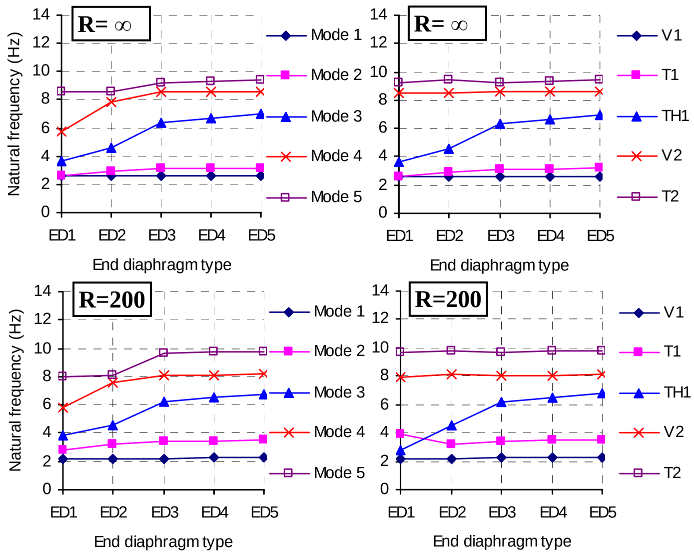


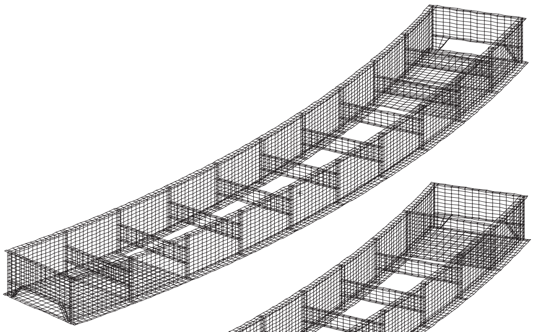
Fig. 5 Natural frequency in 2 different categories

stiffness of end diaphragm, the better of the natural frequencies are gained. However the rates of changing are not the same in every mode; those of the third and fourth modes have considerable increases; whereas those of the second ones change only a little. Another remarkable point is that the natural frequencies of all modes in models with **ED3**, **ED4**, and **ED5** are nearly the same.

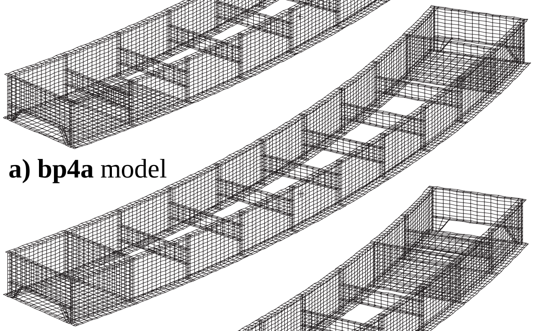
Because the second torsional modes (**T2**) do not appear in the first five modes of the models with **ED1**, **ED2** end diaphragms; the sixth modes are taken to complete the graphs of natural frequencies in the series mode shape type shown in **Figure 5**. The graphs interestingly reveal that only the **TH1** modes which are coupling modes of lateral and torsional vibration are greatly influenced by the stiffness of end diaphragm types. This is attributed to the characteristics of these coupling mode shapes; they change from larger portion of lateral vibration in **ED1** models to larger one of torsional vibration in **ED5** models. This phenomenon is caused by the differences in distortional stiffness of these end diaphragm types; the lower of distortional stiffness the stronger of lateral vibration happens in the coupling mode shapes. And in the curved system (R=200m), the low distortional stiffness of **ED1** model causes the happening of **TH1** prior to the first torsional mode (**T1**) that usually is the second mode in the original models. This mode transposition makes an abnormal high frequency of **T1** mode in **ED1** model. In addition, also because of the low distortional rigidity of the **ED1** and **ED2**, there are undesired **TH2**s (the second lateral-torsional modes) appearing in the first five modes and making a shift of **V2** (the second vertical mode) and **T2** modes to the fifth and sixth ones, respectively.

4.2 Models with different types of end stiffening systems

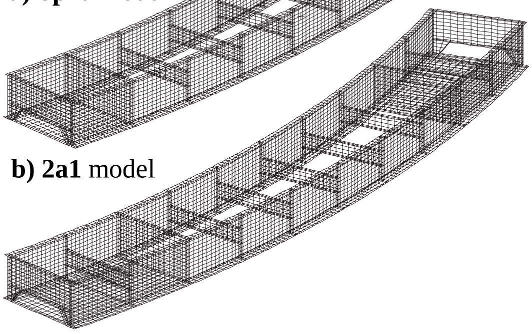
In this part of study, the above five different types of end diaphragm are combined with three various end stiffening systems typically shown in **Figure 6**. **Figure 6a** presents the first end stiffening system - **bp4a** model - which uses only lateral bracings which are 20mm steel plates in the plane of bottom flanges



a) bp4a model



b) 2a1 model



c) 4a1 model

Fig. 6 Typical models with different end stiffening system

(bottom-plate); there are totally four exterior-most bays braced by bottom-plates in this model. The two remaining models are composed of the bottom-plates and intermediate diaphragms whose height is equal to that of the main girders. In **2a1** model which is shown in **Figure 6b**, only two bottom-plates and two intermediate diaphragms are used symmetrically in both bridge ends. The **4a1** model which is presented in **Figure 6c** is similar to **2a1** model. However the number of bays braced by bottom-plates is four. In fact, the **4a1** model is a combination of **bp4a** model with two intermediate diaphragms. In the last two models, the intermediate diaphragms replace the original cross-beams located at the far-most interior sides of the bottom-plates. These diaphragms with end diaphragms, main girders, bottom-plates, and concrete slab all together form two close boxes at both ends which greatly increase the rigidity of the system. All of these models are considered as one of the efficient methods to enhance the torsional stiffness of horizontally curved bridges [2)].

The numerical results show that, like in original models, except the natural frequency of the first modes is nearly unchanged; that of the remaining modes increases with the increase of end diaphragm stiffness. Because of these similar tendencies, the graphs of natural frequencies in series of mode's order are not presented here. Only the graphs showing the natural frequencies in series of mode shape type are plotted in **Figures 7-9** for both straight and curved models.

In general, it can be observed from these graphs that all natural frequency of vertical-related modes (**V1**, **V2**) is nearly unchanged in straight models or increases a little in horizontally curved models with the different types of end diaphragm. Only that of torsion-related modes (**T1**, **T2**, **and TH1**) is influenced by the different stiffness of end diaphragms. This is well correlation with the fact that the transverse members have no effect

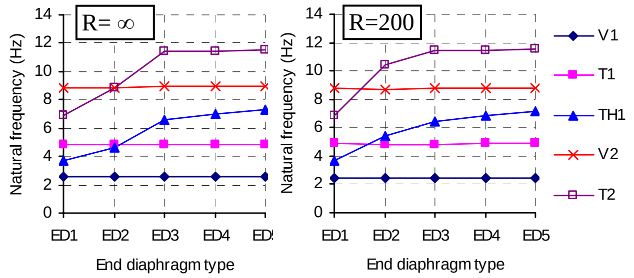


Fig. 7 Natural frequency of **bp4a** models

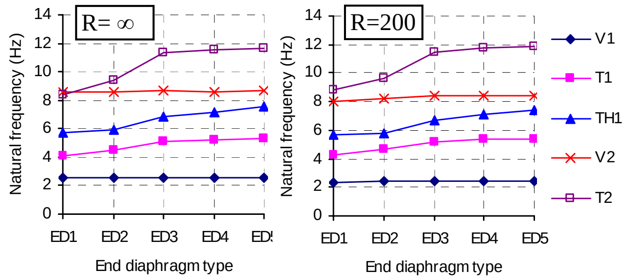


Fig. 8 Natural frequency of **2a1** models

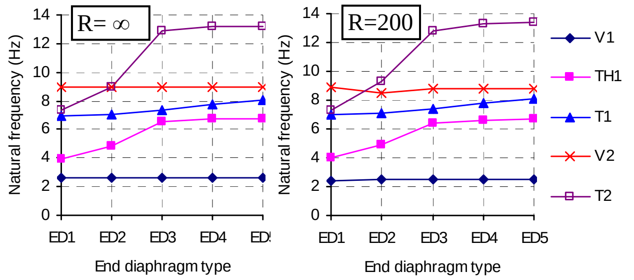


Fig. 9 Natural frequency of **4a1** models

on the vertical vibration of straight systems and slightly effect on that of curved system [2)].

However, unlike in the original models whose only **TH1** mode is greatly influenced, all of torsion-related modes are significantly enhanced by the stiffer of end diaphragms except **T1** modes in models with **bp4a** end stiffening system. It is noticeable that the frequencies of **T1** modes in **2a1+ED1** and **2a1+ED2** models are smaller than those in **bp4a+ED1** and **bp4a-ED2**, respectively. However those in **2a1+ED3-5** are higher than those in **bp4a+ED3-5**. This could be attributed to the lack of intermediate diaphragms in **bp4a** models.

Considering the orders of mode shape type, it is recognized that only the models with **ED1** and **ED2** usually have irregular mode shape types' order as compared with other end diaphragm types. For example, in **bp4a+ED1** models, the order of **TH1** and **V2** are the second and fifth, respectively; whereas they are third and forth in other models, respectively. This is because of the low distortional stiffness of end diaphragms as aforementioned. Another position changing is of **T1** modes in **4a1** models. They change from the second modes in other models to the third modes in **4a1** models because of the high torsional stiffness of the systems.

Figure 10 shows the frequency ratio which is the ratio of natural frequencies between the first torsional mode and the first vertical mode ($\mathbf{f_{T1}/f_{V1}}$) of all studied models. It can be seen that all of the frequency ratios increase with the increase of end diaphragm stiffness except an abnormal value appeared in original model

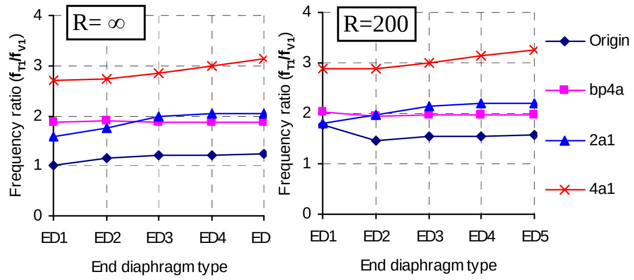


Fig. 10 Frequency ratio of studied models

with **ED1** end diaphragm and frequency ratios of **bp4a** models. In models with **ED1-2**, the frequency ratios of **bp4a** models are larger than those of **2a1** models and vice versa in models with **ED3-5**. The original models always have the lowest values of frequency ratio; and the highest ones are in models with **4a1** end stiffening system. However, the maximum differences between ED5 and ED1 always happen in **2a1** models.

5. CONCLUSIONS

In this study, five different types of end diaphragm combining with other three different end stiffening systems are studied in details by 3-D FEM. Some conclusions can be drawn from this study:

- These different types of the end diaphragm cause changing not only in the natural frequencies but also in the associated mode shape and their order of the studied models
- The natural frequency of vertical-related modes is nearly unchanged with the various types of end diaphragm. Only that of torsion-related modes increases with the stiffer end diaphragms. The rates of changing depend not only on the stiffness of end diaphragm but also on the types of end stiffening system.
- To greatly enhance the performance of the bridge and to avoid some undesired mode shapes, the employed end stiffening systems and end diaphragms should have adequate rigidity for both torsion and distortion. The 2a1 and 4a1 end stiffening systems are recommended.
- The worse performance end diaphragm type is ED1; and the best one is ED5. However, using concrete ED5 end diaphragms in steel I-girder bridges is not as simple as using steel ones. Besides, the free vibration characteristics of the models with the two ED3 and ED4 diaphragms are also quite good. Moreover, the ED3 diaphragm is better for maintenance of bearings whose service life is shorter than that of steel girders. Consequently, The ED3 end diaphragm is considered a reasonable one.

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