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EFFECT OF CROSS-FRAME SPACING ON THE MODAL PROPERTIES OF CURVED BRIDGES

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ABSTRACT

Parametric studies have been conducted to investigate the effect of variation in the number of cross-frames on the free vibration response of curved steel bridges such as natural frequencies and mode shapes. The numerical simulations were performed using the general-purpose finite element software package ABAQUS and validity of the results verified comparing them with experimental results of other researchers.According to the results, when cross-frame spacingisselected in a certain range, the number of cross-frames, especially in low modes, has negligible effect on the free vibration frequencies of a curved bridge. Nevertheless, in the higher modes, this effect is considerable.

INTRODUCTION

The need to have a smooth traffic flow, restrictions that exist on the use of straight routes, economic and environmental considerations and an emphasis on aesthetics have all led to the increased use of curved bridges (Ziemian, 2010). The geometry of a curved bridge structure has made its design and construction a bit difficult. In this system, the girders, as the main superstructure elements, have a large tendency for deformation and out-of-plane rotation. This aspect of the structure’s'behavior becomes particularly important during the construction phase, due to the lack of a hardened concrete deck and non-composite behavior of the system. Therefore, to prevent large deformations and to provide stability for the structure, the first option for the bridge engineer would be to increase the number of cross-frames in the design. Straight girders that are braced by sufficient lateral bracings only undergo vertical deflection under gravity loads. On this basis, in straight bridges, the main function of the cross-frame is to prevent the premature lateral-torsional buckling of the beams before they reach the maximum anticipated bending strength; therefore, these cross-frames are deemed as the secondary load-carrying members. In curved bridges, because of the structures’ geometry, the gravity loading causes an out-of-plane rotation of the girder sections in addition to the vertical deflection. In this way, the cross-frames not only limit the extent of the lateral-torsional deformations but also play an important role in distributing and transferring the applied load between the girders, which in this case, they are recognized as the primary members (Davidson et al., 1996; Maneetes and Linzell, 2003; Linzell et al., 2004).

The tendency of the bridge designers to reduce the number of cross-frames in order to cut down the construction time and cost, and also the solving of structural fatigue problems on one hand and the importance of having sufficient lateral braces to provide stability for curved girder on the other hand, have made it necessary to conduct more exact researchon the performance of cross-frames. In 1978, Nishida et al. investigated the lateral-torsional buckling of curved beams (Nishida et al., 1978). Then in 1996, Yoo et al. explored the difference in the lateral-torsional buckling of curved girders relative to straight girders (Yoo et al., 1996). The effects of the cross-frame spacing, span length, depth and number of girders and the distance between them, and the effects of flange width and curvature on the ratio of warping-to-bending stress were investigated by Davidson et al (Davidson, Keller and Yoo, 1996).In 2003, Maneetes and Linzellstudied the effect of the cross-frames on the dynamic response and the free vibration of a curved bridge (made of horizontally curved steel I-Girders) during construction. In this research, the effects of parameter such as bridge geometry, cross section dimensions, and the cross-frames spacing and their manner of placement have been investigated (Maneetes and Linzell, 2003). In 2012, Sharafbayani and Linzell demonstrated that by using skewed cross-frames, the unbraced lengths of the girders can be optimized and thus the excessive cross-frames can be eliminated (Sharafbayani and Linzell, 2012). These researchers also extended their proposed method to multi-span bridges and showed that the vertical and lateral deflections can be adequately controlled and the number of cross-frames can be reduced by applying the mentioned approach (Sharafbayani and Linzell, 2014).

AIMS AND SCOPES

The interactions between girders and cross-frames under live loads resulting from moving vehicles produce considerable forces in the cross-frames, especially in bridges with skewed piers, can lead to fatigue-induced failure. The distribution of forces resulting from live loads in the cross-frames will be proportional to the rigidity of their members. Therefore, the cross-frames must be designedaccording to the required stability and strength criteria. Unfortunately, by using conventional cross-frames and not designing them for the existing conditions, the problem of fatigue is exacerbated at the locations of cross-frames. The common sizes of cross-frames that are often used are usually larger than the sizes required for stability (Wang, 2002). On the other hand, the modal properties, depends not only on the magnitude but also on the manner by which the mass and stiffness of the system are changed. In particular, the American Association of State Highway and Transportation Official (AASHTO, 2012) specifies that cross-frames shall be designed to ensure:

1) Transfer of lateral wind loads from the bottom of the girder to the deck and from the deck to the bearings,
2) Stability of the bottom flange for all loads when it is in compression,
3) Stability of the top flange in compression prior to curing of the deck,
4) Consideration of any flange lateral bending effects, and
5) Distribution of vertical dead and live loads applied to the structure.

Because no guidelines are provided for the design of these cross-frames under dynamic or earthquake conditions, this study investigates the cross-frame spacing effects on the modal properties such as natural frequencies and mode shapes of simple-span non-composite horizontally curved steel I girder bridges. The numerical simulations were performed using the general-purpose finite element software ABAQUS and validity of the results verified comparing them with experimental results of other researchers.

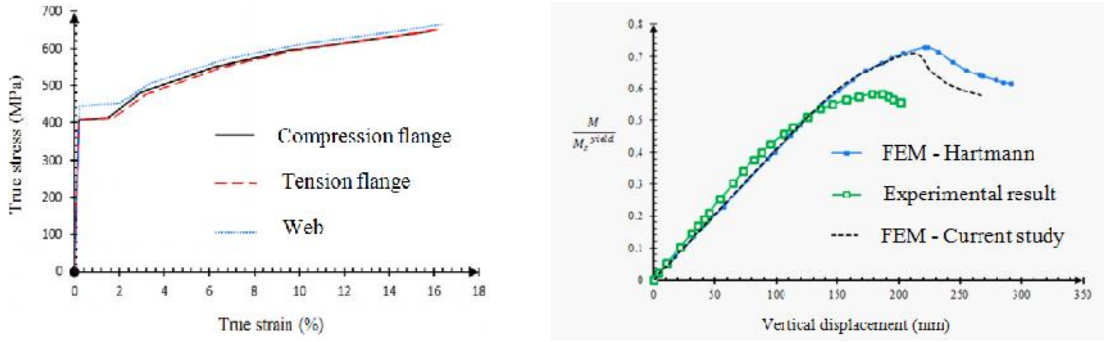
NUMERICAL MODELING AND VALIDATING

In ABAQUS software there is a variety of elements to modeling different components of structure. If existing stresses, along the thickness, are negligible and one dimension (thickness) of component is significantly smaller than other dimensions, shell elements can used for modeling such structural component. As shown in Table 1, in ABAQUS/Standard, shell elements according to the behavioral formulation categorized in three group of: (1) general-purpose, (2) thin shell elements, and (3) thick shell elements. In the general-purpose shells, finite membrane strain and large rotations are considered. These elements include the effects of transverse shear deformation and thickness change. However, in the thin and thick shell elements, only the large rotations are considered and it is assumed that strains are small and thickness of the element remains constant during the analysis. In the thick shell elements effects of transverse shear flexibility is important. However, in the thin shell elements, transverse shear flexibility is negligible and the Kirchhoff constraint, which assumes that the shell normal planes remain orthogonal, must be satisfied accurately (Hibbett et al., 2012).

Table 1.Types of shell elements in ABAQUS/Standard

General-purpose	Thin	Thick
S4,S4R,S3/S3R,SAX1,SAX2 ,SAX2T,SC6R,SC8R	STRI3,STRI65,S4R5 ,S8R5,S9R5,SAXA	S8R,S8RT

In this study, elements ‘S4R’ and ‘B31’ are used to model the girder components and the cross-frames, respectively. The selection of the mesh sizes are based on the mesh sensitivity analysis. In the midsection of girders, between the middle cross frames, where flexural failure occurs, 50x50 mm size meshes and in the other regions, 150x150 mm meshes were applied. To verify the credibility of the modeling, the bending test Sample B1 was selected from the 7 samples tested by Hartmann in (Hartmann, 2005).All the geometrical and material properties, distribution of residual stresses, and the support and loading conditions of the mentioned experiment are available in the cited reference. The material properties of the test Sample B1 have been shown in Fig. 1a. After precisely modeling the test of B1, the geometrical and material nonlinear analyses was performed by applying the "Modified Riks Method" (Hibbett et al., 2012). In Fig. 1b, the B1 mid-span moment from the applied loads normalized with respect to the strong-axis yield moment, (M_x^{yield}), and then plotted versus the vertical deflection of the midpoint of Sample B1. According to the test report, the total moment that can be resisted by Sample B1 (including the sum of moments resulting from the self-weight effects and point loading) is equal to 4539.2 kN.m, which is very close to the maximum bending capacity predicted by the finite element simulation, with a maximum difference of 4%.



a) b)

Figure 1.a) B1 material properties b) Comparing the B1 test mid-span moments and finite element predictions

DETAILS AND GEOMETRIC PROPERTIES OF MODELS

In order to investigate the research objectives, 21 curved bridge systems have been considered. All the models have been constructed of 4 curved girders (G1 through G4), laterally spaced at 3.417 m from each other, with the arc length of the outer girder (G1) being 27.3 m. A view of the models and support conditions has been presented in Fig. 2.According to Table 2, three groups (A, B, C) have been considered, which for investigating the effect of changing the number of cross-frames (N) in each group on the changes in the modal properties of a curved bridge, other models (with N=4 to N=10) have been created. The cross-frame spacing and the average radius of curvature at the central axis of deck have been designated as L_b and R_{avg}, respectively. The cross-frames have a radial arrangement and they divide the central subtended angle to equal portions. The K-type cross-frames have been selected and after design, their horizontal and diagonal members are selected as L150×150×12 and L120×120×12 angle profiles, respectively. The left and the right side bearings have been considered as fixed type and expansion type, respectively; and to eliminate the thermal stresses, the expansion type bearing has been allowed to expand along the Y direction. To investigate the respective effects of curvature and section height on the natural frequencies and mode shapes, the average radiuses of 30 and 70 m and web heights of 1.0 and 1.20 m are considered.According to the AASHTO guidelines, in horizontally curved steel I-Girder bridges, the cross-frame spacing must satisfy the $L_b \le R/10 \le 9\text{m}$ constraint. Notethat the constraint $L_b \le R/10$ has been presented empirically by McManus (Jung, 2006). With regards to the abovementioned limit, the models have been selected in such a way that a fair range of plausible circumstances can be covered ($0.035 \le L_b/R \le 0.26$).

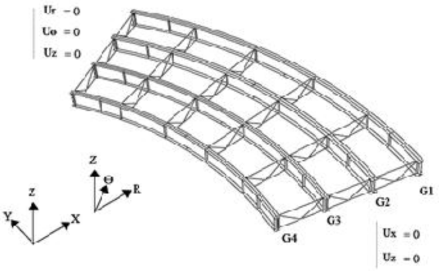


Figure2. Support conditions in the finite element model with six cross-frames (N=6)

Table 2. Specifications of models used in parametric studies

Group	Number of Cross-frames (N)	L_b(m)	R_{avg} (m)	$\frac{L_b}{R}$	Flanges (mm)				Web (mm)	
					G1,G2		G3,G4		G1,G2	G3,G4
					Top	Bottom	Top	Bottom		
A	4	8.94	30	0.2546	450x25	500x40	350x15	400x25	1200x20	1200x10
	5	6.70		0.1910						
	6	5.36		0.1528						
	7	4.47		0.1273						
	8	3.83		0.1091						
	9	3.35		0.0955						
	10	2.98		0.0849						
B	4	8.94	70	0.1190	450x25	450x35	350x15	350x25	1000x20	1000x10
	5	6.70		0.0893						
	6	5.36		0.0714						
	7	4.47		0.0595						
	8	3.83		0.0510						
	9	3.35		0.0446						
	10	2.98		0.0397						
C	4	8.94	70	0.1190	600x40	600x40	500x30	500x30	1000x20	1000x10
	5	6.70		0.0893						
	6	5.36		0.0714						
	7	4.47		0.0595						
	8	3.83		0.0510						
	9	3.35		0.0446						
	10	2.98		0.0397						

DISCUSSION OF RESULTS

After preparing and analyzing the models, the results obtained from the finite element analysis are presented in this section. Figs 3a, b, c show the free vibration frequencies magnitudes versus the mode numbers of bridges for different number of cross-frames. In order to better illustrate the bridge behavior, the analysis results of a model with four cross-frames have been shown in Fig. 4. According to Fig. 4, by increasing the mode number, the free vibration behavior of bridge is changed from a global behavior to a local behavior.

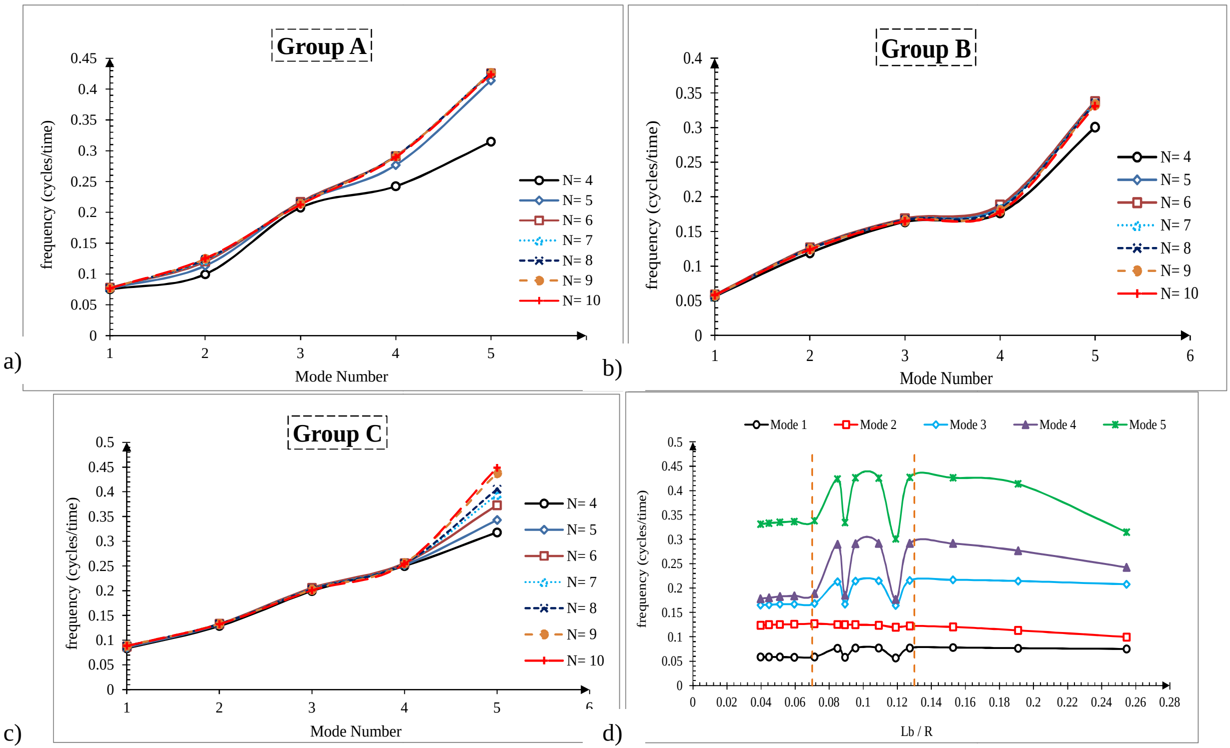
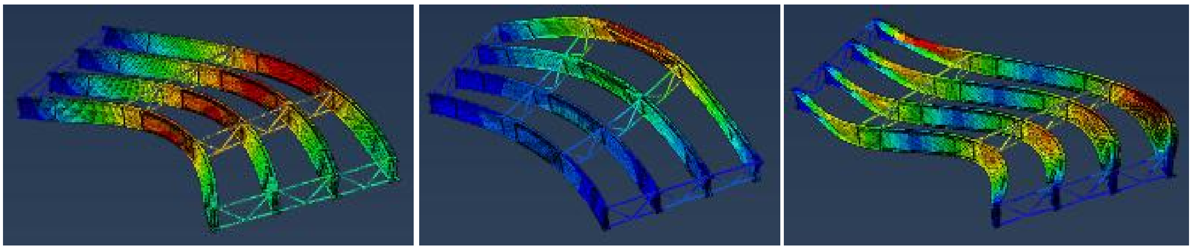
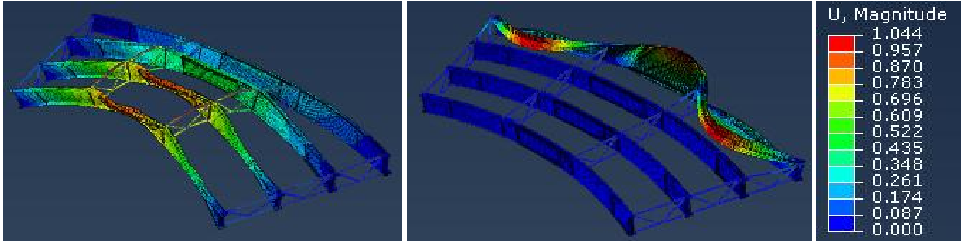


Figure 3.Results obtained from finite element analysis



Mode 1: freq= 0.075 Mode 2: freq= 0.099 Mode 3: freq= 0.207



Mode 4: freq= 0.242Mode 5: freq= 0.314

Figure 4.Frequencies and mode shapes of a model in Group A (N=4)

Thus, it can be seen that, in compliance with the maximum spacing of cross-frames, $L_b \le 9\text{m}$, the number of cross-frames, especially in bridges with lower curvatures, have a little effect on the free vibration behavior of bridges in low vibrational modes. However, in thehighermodes, the effect ofcross-frame spacingonthefrequency magnitudes isconsiderable. According to Fig. 3d, it is observed that in the range $L_b/R \le 0.07$, the cross-framespacing has no effect on the frequency magnitudes and the global vibration behavior will bedominant. However, in the range $L_b/R \ge 0.13$, the cross-frame spacing effect is negligible and the local vibration behavior is dominant. Nevertheless,in the interval $0.07 \le L_b/R \le 0.13$, free vibration of the bridges, especially in higher modes, is more sensitive to the cross-frame spacing.It should be mentioned thatthe above obtained range of $L_b/R \le 0.07$, is comparable tothat recommended bythe AASHTO guidelines, $L_b/R \le 0.06$, forutilizing the approximate methods in the analysis of curved bridges.

CONCLUSIONS

This study provides valuable insight into the effect of various cross-frame spacing (L_b)on the free vibration response of the non-composite horizontally curved steel I girder bridges. The numerical simulations were performed using the general-purpose finite element software package ABAQUS.The conclusions drawn from this research include:

- In compliance with the maximum spacing of cross-frames, $L_b \le 9\text{m}$, the number of cross-frames, especially in bridges with lower curvatures, has a little effect on the free vibration behavior of bridges in low vibrational modes.
- Inthehighermodes, the effect ofcross-frame spacingonthefrequency magnitudes isconsiderable.
- In the range $L_b/R \le 0.07$, the cross-frame spacing has no effect on the frequency magnitudes and the global vibration behavior will bedominant. However, in the range $L_b/R \ge 0.13$, theeffects ofcross-frame spacing are negligible and the local vibration behavior is dominant. Nevertheless,in the interval $0.07 \le L_b/R \le 0.13$, the free vibration of the bridges, especially in higher modes, is more sensitive to the cross-frame spacing.

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