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An Evaluation on the Effect of Cross-Frame Spacing Limit on Buckling Strength of Horizontally Curved Multi-Girder Systems under Uniform Bending

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Abstract

This study provides an evaluation on the effect of existing cross-frame spacing limit on buckling strength of horizontally curved girder systems. Since current design specifications only consider individual buckling between cross-frames for multi-girder systems, this study utilizes global lateral torsional vertical buckling strength of such girder systems. Elastic eigen value analysis was conducted using the finite element program, ABAQUS. Models with varying degrees of curvature, flange width-to-thickness ratio of 12, 10 and 8 and span length-to-depth ratio of 16, 20 and 24 were generated and their respective maximum cross-frame spacing was computed. These models were then subjected to uniform bending in order to obtain the buckling strength and different buckling modes from the analysis. Finally, critical buckling capacity ratio ($M_{curved}/M_{straight}$) was used to establish the effect of the existing cross-frame spacing limit on the buckling strength of horizontally curved multi-girder systems. Using comparative analysis, the results showed that the existing cross-frame spacing limit gave conservative critical buckling capacity ratio for models with high degree of curvature. However, for models that yielded the maximum cross-frame spacing equal to 0.25L and low degree of curvature, the critical capacity ratio decreased significantly. A suggestion was developed based on the results of the finite element analysis to provide a better guide on the design of cross-frame spacing limit.

Keywords: Buckling, Cross-Frame, Curved Girder System, Lateral Torsional Buckling, Spacing Limit

1. Introduction

In recent years, site restrictions and aesthetic advantages play a major role in determining the kind of bridge structure to build. Horizontally curved bridges don't only give satisfaction on both requirements it also offer economic benefits. The most commonly used member for horizontally curved bridges is steel I-girders. Unlike box girders, I-girders provide minimal torsional resistance and can only be considered stable if they are connected with other girders using cross-frames or diaphragms[1]. In straight bridges, cross-frames and diaphragms are considered as secondary load carrying components, while in curved bridges, they act as primary load carrying components[2]. Another important structural role of cross-frame in curved bridges is the reduction of warping stress and bending stress[3]. Furthermore, the increase on the number of cross-frames can improve the overall stiffness of the girder system. However, designers must also take into consideration the increase in its economic cost[4].

Studies involving buckling strength of single horizontally curved I-girders are common while studies on the buckling strength of multi-girder systems are limited[5]. Likewise, research on cross-frame spacing of horizontally curved bridges is limited to bending and warping stresses[6]. This study aims to evaluate the effect of exist-

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ing cross-frame spacing limit on the buckling capacity of curved bridges. Additionally, this research provides further understanding on the global lateral torsional buckling capacity and individual lateral torsional buckling capacity of curved multi-girder systems. Finite element analysis is used in obtaining the values of buckling capacities and determining the various buckling modes of the curved girder systems. Comparative analysis was performed in interpreting the results of the finite element program. Finally, a suggested limitation is proposed based on the results of the elastic analysis.

2. Background and Previous Studies

Constant development on the cross-frame spacing limit for horizontally curved I-girder bridges is currently being made. For previous design specification, a spacing limit of 7.6m was suggested or a rational analysis could be performed. It was Yoo and Littrell[7] who developed an equation for computing the maximum cross-frame spacing. The equation considered span length, curvature and the number of cross-frames. Davidson[8] made an improvement on the previous equation of Yoo and Littrell7 taking into account more parameters which include girder depth, number of girders, flange width and girder spacing. The following equation by Davidson[8] for the maximum cross-frame spacing of horizontally curved I-girder was based on warping-bending stress ratio of 0.25:

$$S_{max} = \mathbf{L}\left[-\ln\left(\frac{Rb_f}{2000L^2}\right)\right]^{-1.52} \quad (1)$$

Where, L (m) = total span length between vertical supports; R (m) = radius of curvature; b_f (mm) = width of the flange.

3. Finite Element Modeling

Evaluation on the lateral torsional buckling capacity of curved multi-girder systems were carried out using finite element analysis program, ABAQUS[9]. Shell element (S4R) was used for flanges and webs, while truss element (T3D2) was used for cross-frames. Element size aspect ratio was kept to unity for an accurate distribution of loadings. All loading conditions and boundary conditions were transformed into cylindrical coordinate system[10]. Models were simply supported and were subjected under pure bending. Elastic eigen value analysis was used to attain the buckling capacity and buckling modes of the models.

Single span multi-girder systems were modeled having two, three and four girders spaced 2.75m apart from center and which were interconnected by cross-frames. The girders were 1.52m deep, with varying flange width-to-thickness ratio, λ_f. The X-type cross-frame was used for the diaphragm configuration having an area of 2,419 mm^2. The cross section and isometric view of the finite element model is shown in Figure 1 and Figure 2 respectively. Moreover, shown in Figure 3(a)-(d) are the buckled modes observed in the finite element analysis performed.

Steel material was modeled as simplified elastic material with modulus of elasticity of 21 GPa, a shear modulus of 8.07 GPa and Poisson's ratio of 0.3.

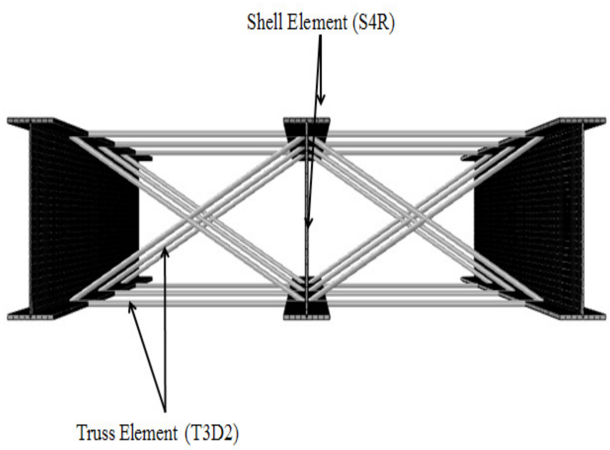


Figure 1. Cross section of finite element model.

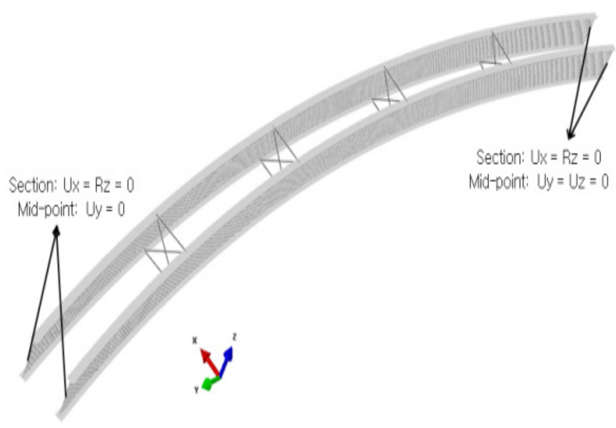
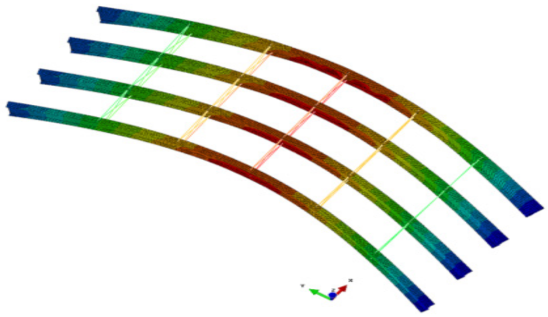
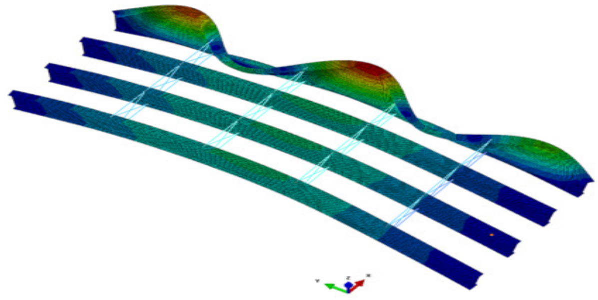


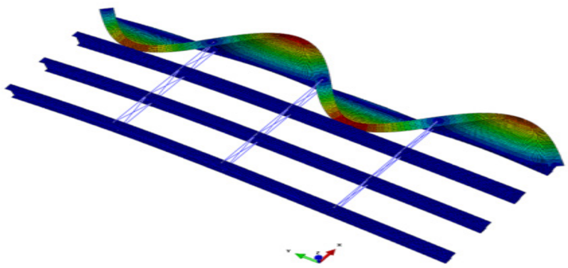
Figure 2. Isometric view of finite element model.



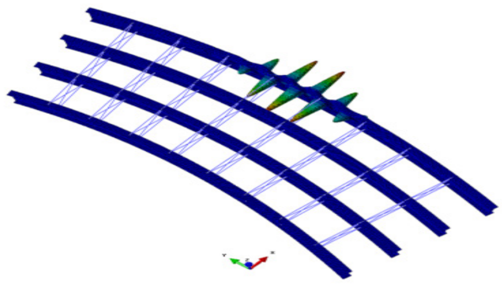
(a) Global lateral torsional buckling



(b) Individual lateral torsional buckling



(c) Individual lateral torsional buckling of exterior girderonly



(d) Web local buckling

Figure 3. Deformed shapes of finite element models.

4. Finite Element Results

The existing equation for S_{max} may vary according to span length (L), radius (R), and flange width (b_f). This study made use of these variables to account for the effect of cross-frame spacing on the buckling capacity of curved girder systems. Models generated in the study have λ_f of 8, 10 and 12, L/d between 16 and 24 and values of subtended angle (θ) of 1 to 30 degrees.

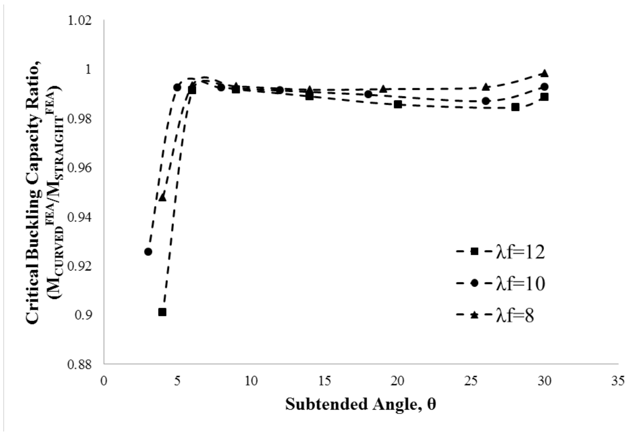
4.1 Varying Flange Width-to-Thickness Ratio, λ_f

According to AASHTO Guide Specifications for Horizontally Curved Highway Bridges11, flanges are said to be compact if λf is less than or equal to 18. For this investigation, flanges were remained to be compact in order for the elastic analysis to be carried out. The results of the finite element analysis were plotted in Figure 4 and 5. In Figure 4 (a)-(c), the critical buckling capacity ratio was graphed against the subtended angle. In Figure 5(a)-(c), the buckling capacity of the curved girder system was plotted against the maximum cross-frame spacing-to-span length ratio.

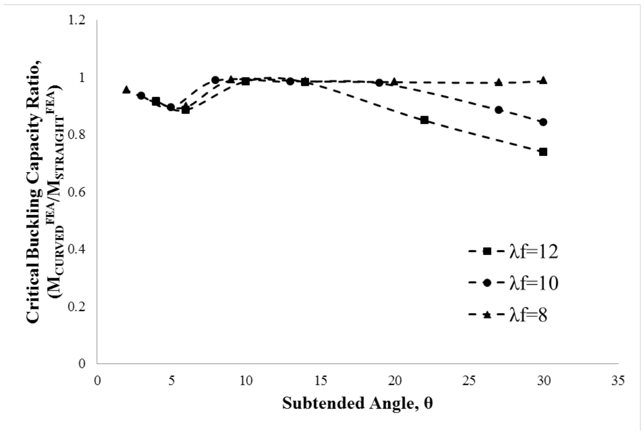
Figure 4 shows that for 2-girder systems, the existing cross-frame spacing limit provided by Davidson's Smax gave a critical buckling capacity ratio of 0.90 to 0.99, for 3-girder systems the capacity ratio ranges from 0.74 to 0.98 while for 4-girder systems the capacity ratio is between 0.62 and 0.97. Figure 5 shows that when Smax/L is equal or greater than 0.25 the buckling strength decreases significantly. In addition, when the Smax is equal or greater than 0.25L the girder system resulted to an individual lateral torsional buckling as shown in Figure 3 (b) and (c). Meanwhile, for girder systems with Smax less than 0.25L, buckling mode observed were either global lateral torsional vertical buckling or web local buckling as seen in Figure 3 (a) and (d) respectively. Web local buckling only occurred for girder systems with high degree of curvature.

4.1 Varying Span Length-to-Depth Ratio, L/d

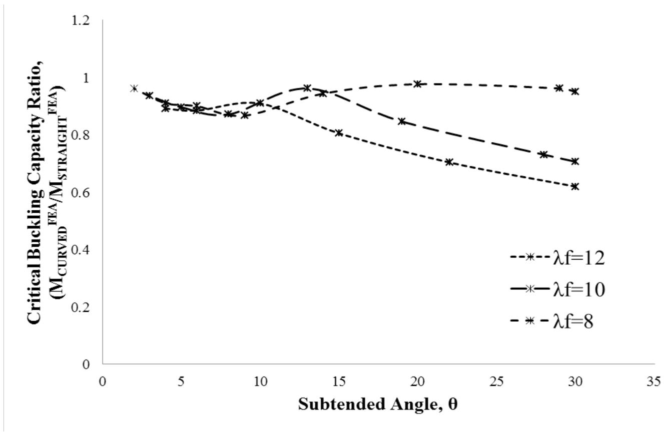
Previous research on multi-girder systems suggested values of L/d to be within the range of 15 to 255. Results for varying L/d were presented the same manner as the varying λfas shown in Figure 6 and 7.



(a) Number of girders = 2

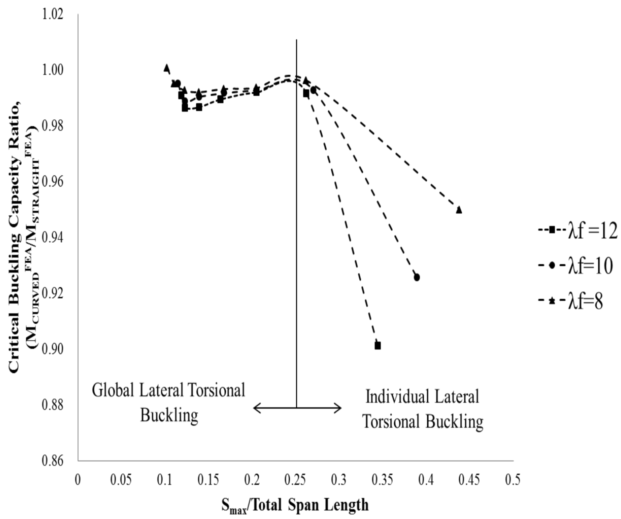


(b) Number of girders = 3

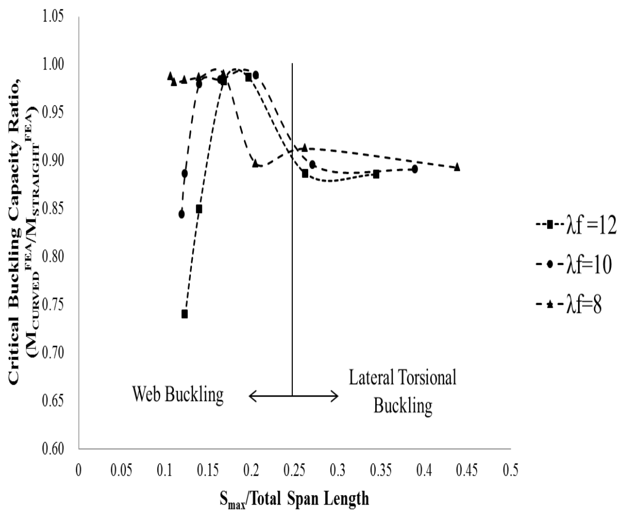


(c) Number of girders = 4

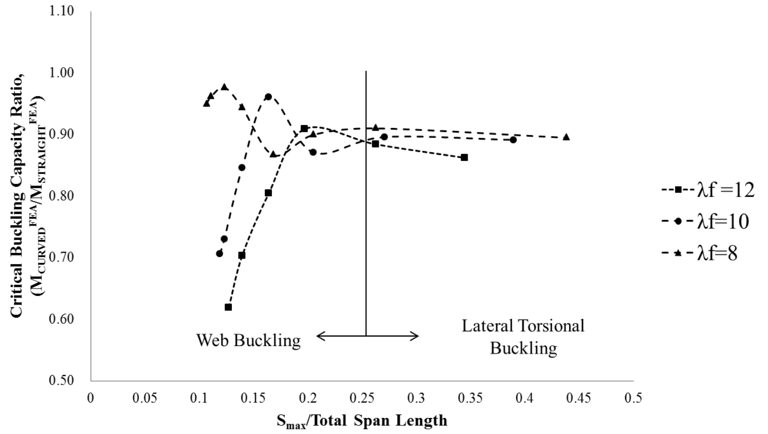
Figure 4. Critical buckling capacity ratio versus subtended angle of horizontally curved I-girder systems with varyingflange width-to-thickness ratio (λf = 12, 10, 8).



(a) Number of girders = 2

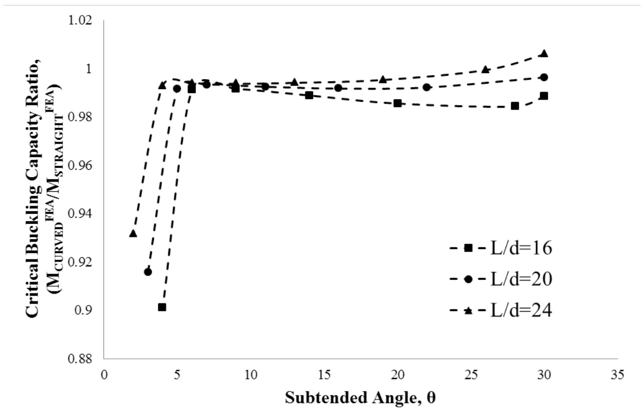


(b) Number of girders = 3

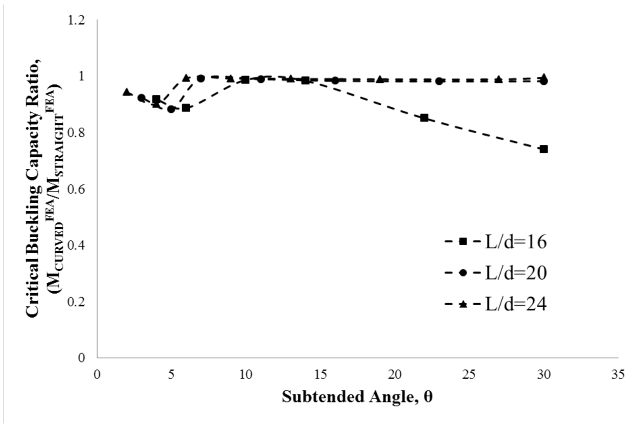


(c) Number of girders = 4

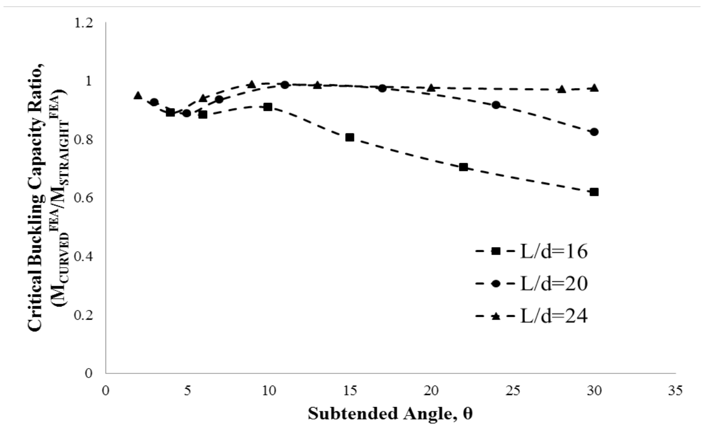
Figure 5. Critical buckling capacity ratio versus Smax/total span length of horizontally curved I-girder systems with varying flange width-to-thickness ratio (λf = 12, 10, 8).



(a) Number of girders = 2

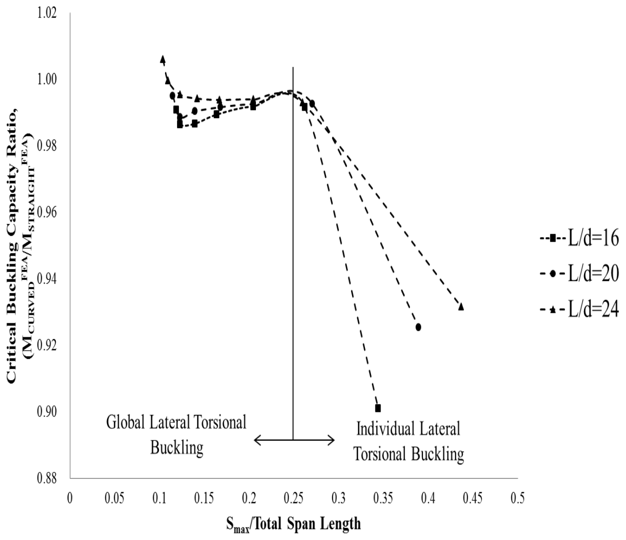


(b) Number of girders = 3

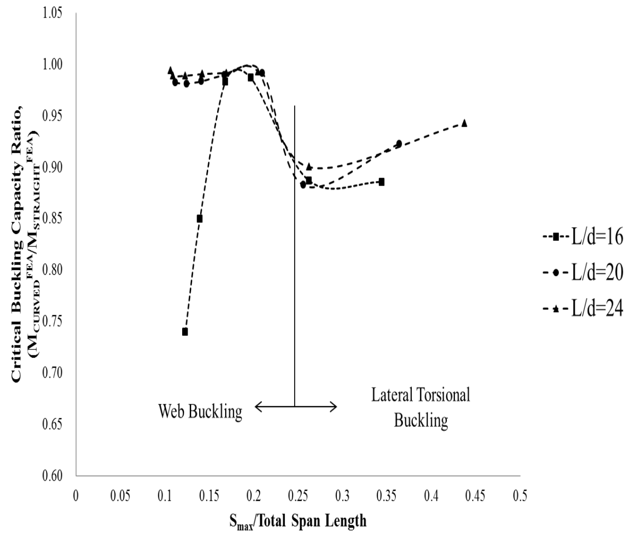


(c) Number of girders = 4

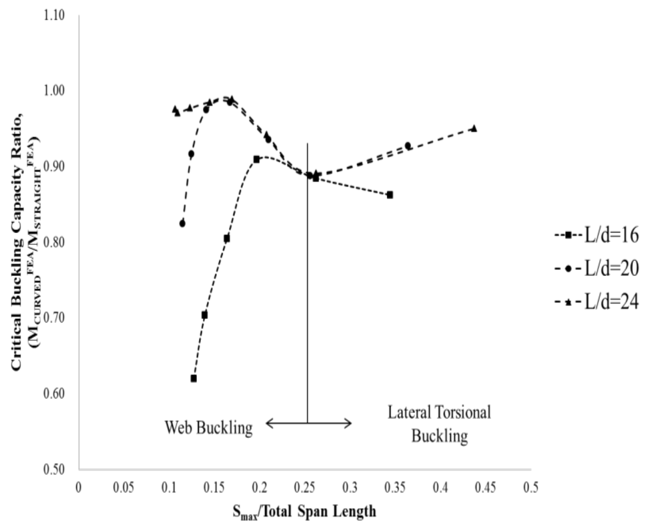
Figure 6. Critical buckling capacity ratio versus subtended angle of horizontally curved I-girder systems with varying flange span length-to-depth ratio (L/d = 16, 20, 24).



(a) Number of girders = 2



(b) Number of girders = 3



(c) Number of girders = 4

Figure 7. Critical buckling capacity ratio versus Smax/total span length of horizontally curved I-girder systems with varying flange span length-to-depth ratio (L/d = 16, 20, 24).

Figure 6(a) shows critical buckling capacity ratio of 0.90 to 0.99. Figure 6(b) shows critical buckling capacity ratio of 0.74 to 0.99. Figure 6(c) shows critical buckling capacity ratio of 0.62 to 0.98.

In Figure 7 same trend was observed in the girder systems with varying L/d and varying λ_f. Graphs show that there is a significant decrease in the buckling strength when S_{max}/L is equal or greater than 0.25. Also, when the S_{max} is equal or greater than 0.25L the girder system resulted to an individual lateral torsional buckling as shown in Figure 3 (b) and (c). However, for girder systems with S_{max} less than 0.25L, buckling mode observed were either global lateral torsional vertical buckling or web local buckling as seen in Figure 3 (a) and (d) respectively. Again, web local buckling only occurred for girder systems with high degree of curvature.

5. Conclusions

The investigation on the buckling capacity using the computed maximum spacing showed that cross-frame spacing has significant effect on the buckling capacity of curved I-girder systems. The findings suggest that the current Smax equation, Eq. (1), needed an additional limit of less than or equal to 25% pf the total span length between vertical supports or 0.25L in order to prevent lateral torsional buckling of the exterior girder. The suggested limit based on the findings along with the equation is shown as follows:

$$S_{max} = L\left[-\ln\left(\frac{Rb_f}{2000L^2}\right)\right]^{-1.52} \leq 0.25L$$

Moreover, critical buckling modes retrieved from the finite element analysis resulted to web local buckling which shows another limitation for the current equation. In summary, when designing for the cross-frame spacing of horizontally curved bridges it is important to check for the lateral torsional buckling capacity of the girder system to prevent buckling failures caused by insufficient number of cross-frames.

Lastly, the research can be supplemented by providing additional information on the limitation of the existing equation in terms of deflection. Looking into this, new equation or limitation can be suggested for better guide on designing for cross-frame spacing limit of horizontally curved bridges.

6. Acknowledgment

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7. References

1. Linzell D, Hall D, White D. Historical perspective on horizontally curved i-girder bridge design in United States. Journal of Bridge Engineering, ASCE.2004; 9(3):218–29.
2. Doust S. Extending integral concepts to curved bridge systems. Civil Engineering Theses, Dissertations, and Student Research. 2011; Paper 41:10-22.
3. Yoo C, Kang Y, Davidson J. Buckling analysis of curved beams by finite element discretization. Journal of Engineering Mechanics, ASCE. 1986; 122(8):762–70.
4. Schelling D, Namini A, Fu C. Construction effects on bracing oncurved i-girders. Journal of Structural Engineering, ASCE. 1989; 115(ST9):2145–65.
5. Yura J, Helwig T, Herman R, Zhou C. Global lateral buckling of i-shaped girder system. Journal of Structural Engineering, ASCE. 2008; 134(9):1487–94.
6. Zhao Q, Yu B, Burdette E. Effects of cross-frame on stability of double i-girder system under erection. Journal of the Transportation Research Board. 2010; 2152:57–62.
7. Yoo C, Litrell P.Cross-bracing effects in curved stringer bridges. Journal of Structural Engineering, ASCE.1986; 112(9): 2127–40.
8. Davidson J, Keller M, Yoo C. Cross-frame spacing and parametric effects in horizontally curved i-girder bridges. Journal of Structural Engineering, ASCE. 1996; 122(9):1089–96.
9. ABAQUS/Standard User's Manual (Ver.6.7-2). Hibbit, Karlsson and Sorenson, Inc. Pawtucket, R.I. 2008.
10. Adamakos T, Vayas I, Petridis S, Iliopoulos A. Modeling of curved composite i-girder bridges using spatial systems of beam elements. Journal of Constructional Steel Research. 2011; 67:463–70.
11. American Association of State Highway and Transportation Officials (AASHTO). Guide specifications for horizontally curved highway bridges. 3rd edition. Washington, D.C. 2003.