Strength and Stability Analysis of Horizontally Curved I-Girder

Aswathy K V[1], Sunilkumar N[2]

[1] PG Scholar, Department of Ship Technology
Cochin University of Science and Technology, Kochi, India
aswathy11kv@gmail.com

[2] Associate Professor, Division of Civil Engineering
Cochin University College of Engineering Kuttanad
Cochin University of Science and Technology, Kochi, India
sunilkumarn@cusat.ac.in

ABSTRACT — *Horizontally curved girders are used in the construction of highway bridges and interchange facilities. The use of curved girders in curved bridges results in longer spans and fewer piers. Due to its curvature, the behavior of curved I-girder is different from that of straight I-girder. The curvature creates a geometrically unstable situation and it introduces torsional effects in addition to the vertical bending effects. This paper presents the analysis of strength and stability of horizontally curved steel I-girder by the Finite Element Method (FEM). The straight and curved I-girders have been analysed in the finite element analysis software and a comparison is made between the structural behaviors of those girders.*

Keywords — Curved I-girder, steel girder, strength, stability, finite element analysis.

1. INTRODUCTION

Modern high speed highway systems have created complex roadway alignments which control the bridge geometry and it results in bridges with curved alignments. Extensive research conducted from the late 1960s until today have allowed many of the complications involved with these structures to be identified, and permitted significant advancements in structural design efficiencies [1]. The use of steel I-section curved girders is commonly used because of their economy and ease of construction.

The construction of horizontally curved steel I-girder bridges is more complex than construction of corresponding straight steel I-girder bridges of similar span. Prior to the adoption of curved bridges as a solution to the curved roadway alignment**,** designers used to place a series of straight girders for the curved geometry. The use of curved girders in curved bridges results in longer spans and fewer piers and therefore the number of intermediate supports, expansion joints and bearing details can be reduced. Hence the overall cost of the curved girder system is less compared to a series of straight girders. Continuous curved girder permits reduction in the slab overhang of outside girder [2, 3]. Furthermore curved bridges result in an aesthetically superior structure. But the curvature greatly complicates the behavior and design considerations of curved I- girders used in bridges [4].

2. STRUCTURAL BEHAVIOUR

The structural behavior of horizontally curved I-girders is known to be quite different from straight I-girders because of the non-uniform torsion due to the curvature. The torsion in curved girders results from the fact the center of loading of each span in a curved girder is offset from the chord line drawn between the supports for that span. This offset represents an eccentricity which, when multiplied by the vertical load, results in a torsional moment which varies longitudinally along the span of the girder [5, 6]. The addition of torsion results in significant warping and distortional stresses within the member cross sections. The warping stresses and the vertical bending stresses result in higher stresses acting on curved beams when compared with straight beams [7, 8]. The total state of shear stress in an I-shaped girder is a combination of vertical shear stress, horizontal shear stress, St. Venant torsional shear stress (typically relatively small), and warping shear stress. Furthermore, secondary members such as cross frames that provide stability in straight bridges become primary load carrying members in curved bridges. They connect the girders together and create an efficient structural system for resisting the torsional loads [9]. The cross frames transfer load from the interior girders to the girder on the exterior of the curve.

3. DESCRIPTION OF THE STRUCTURE

3.1 Straight I-girder

The straight I-girder has a span of 11.6 m. The top and bottom flanges are 546.6 x 22.99 mm and 546.4 x 23.04 mm respectively. The web has a thickness of 8.53 mm and depth is 1.217 m. The vertical stiffeners at the support called the bearing stiffeners are 300 x 25.4 mm [10]. The cross-sectional dimensions are given in the Fig. 1.

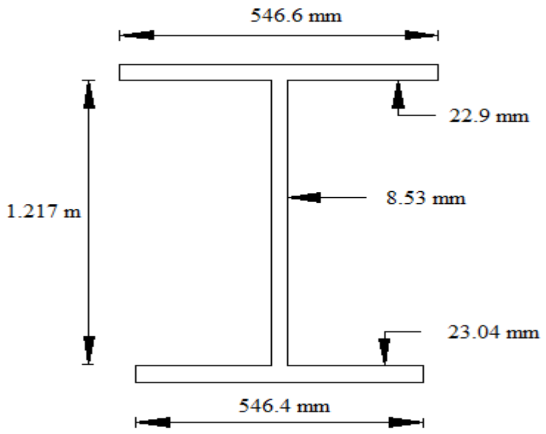

Figure 1: Cross-section of the I-girder

3.2 Curved I-girder

The curved I-girder has a curved length of 11.6 m and a radius of 63.63 m [10]. The cross-sectional dimensions are same as that of straight girder. In addition to the bearing stiffeners vertical intermediate stiffeners of 200 x 16 mm have been provided at mid span, 1/4th and 3/4th span of the curved girder for the analysis. The location of the stiffeners has shown in the Fig. 2.

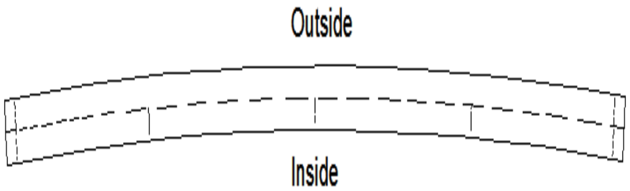

Figure 2: Top view of the curved I-girder

3.3 Finite Element Discretization

The finite element method (FEM) is the most popular simulation method to predict the physical behavior of systems and structures. Since analytical solutions are in general not available for a class of problems in engineering, numerical methods have been evolved to find a solution for the governing equations of the individual problem. The straight and curved girders with and without stiffeners have considered. Bearing stiffeners are provided at the supports. Figures 3 and 4 show typical finite element models used in this research. The models are constructed in the ANSYS 12.1 software using four-node shell element with six degrees of freedom at each node viz., translations in the x, y, and z directions, and rotations about the x, y, and z-axes [11]. In the construction of the Finite Element Analysis (FEA) models, ten elements are used through the width of the flanges, and through the depth of the web in all the girders. The modulus of elasticity of steel is 2.1×10^5 N/mm^2. Poisson's ratio is 0.3. Material density is 7850 kg/m^3.

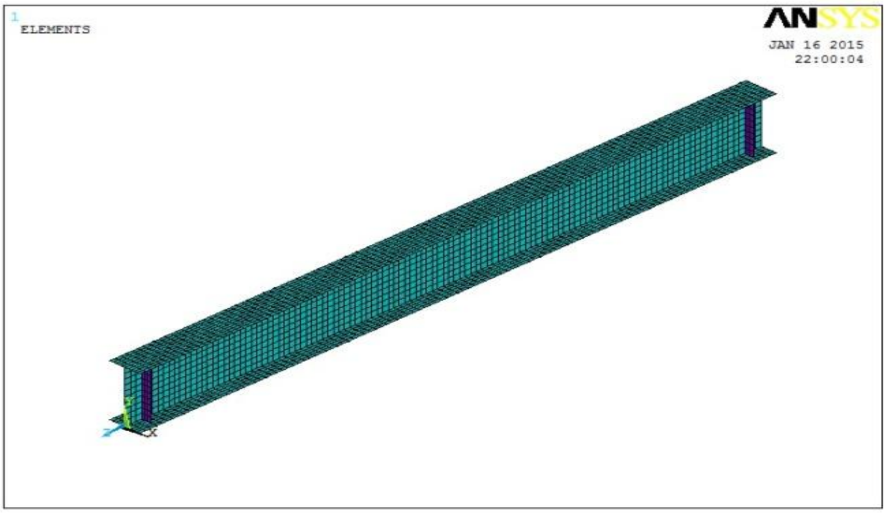

Figure 3: Meshed model of the straight I-girder

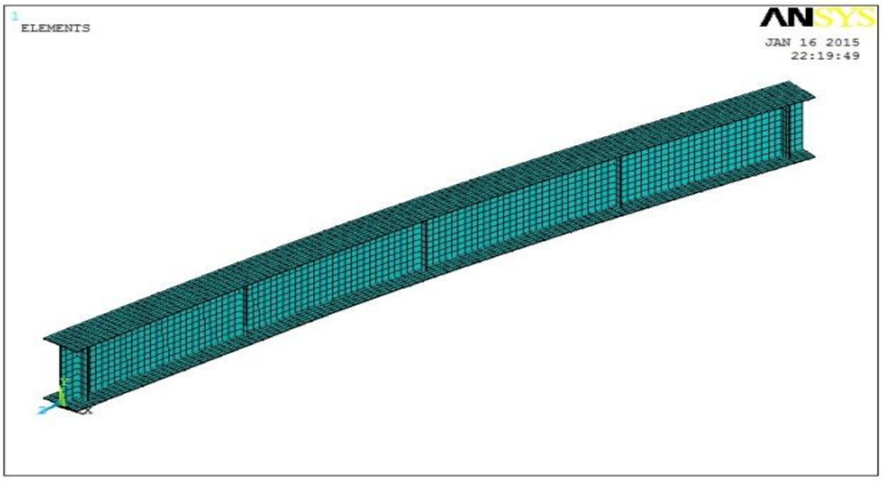

Figure 4: Meshed model of the curved I-girder with three intermediate stiffeners

4. LOADS AND BOUNDARY CONDITIONS

The supports are provided at the two ends of the girder in which one edge is hinged and the other is roller supported. In order to bring the effect of lateral restraints, the degree of freedom in the lateral direction is restrained near the top and bottom flanges of the stiffener at the inside curvature of the girder. A total load of 2820 kN [10] is distributed uniformly over the entire span of the girder.

5. RESULTS AND DISCUSSIONS

5.1 Straight I-girder: Comparison with classical method

The straight I-girder is considered as a simply supported beam with uniformly distributed load of 243.103 kN/m (total load of 2820 kN is distributed over the span). The deflection and bending stresses are calculated as per the simple bending theory [12, 13] assuming small linear-elastic displacements. The displacements and bending stress are compared with the finite element analysis using the model and discretization shown in Fig.3. Maximum values of them are given in Table 1 for a quick reference. The contour plot of the vertical deflection of straight I-girder from the ANSYS has been given in Fig. 5.

Table 1: Results from FEA and Simple Bending Theory

	Simple Bending theory	FEA result
Maximum deflection (mm)	-24.92	-24.93
Maximum bending stress (N/mm^2)	235.82	212.00

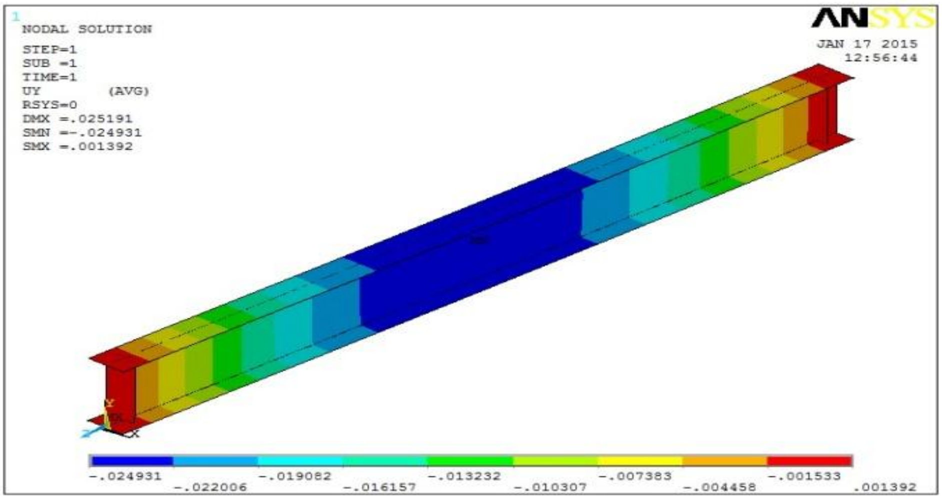

Figure 5: Contour plot of the vertical deflection of straight I-girder

5.2 Curved I-girder:

The FEA result of curved I-girders is given in the Table 2. The contour plot of the vertical deflection of curved I-girder from the ANSYS has been given in Figures 6 to 8.

Table 2: Results from FEA of Curved I-girder

		Without stiffeners	One intermediate stiffener	Three intermediate stiffeners
Maximum deflection (mm)	Radial	98.80	5.99	6.01
	Vertical	92.31	27.26	25.93
Longitudinal bending stress at the mid span (N/mm^2)		694	316	246

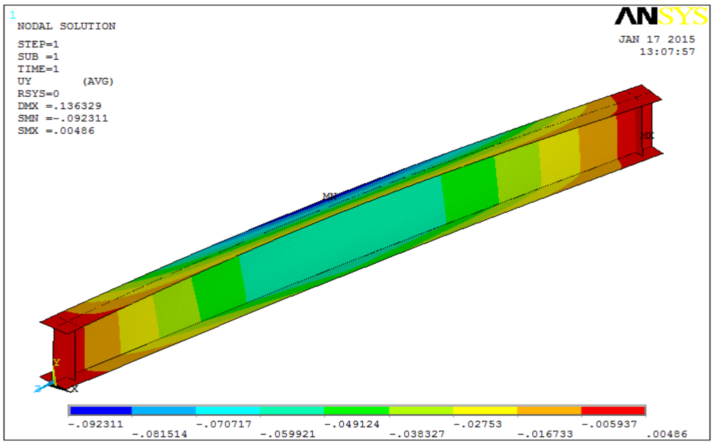

Figure 6: Contour plot of the vertical deflection of curved I-girder without stiffeners

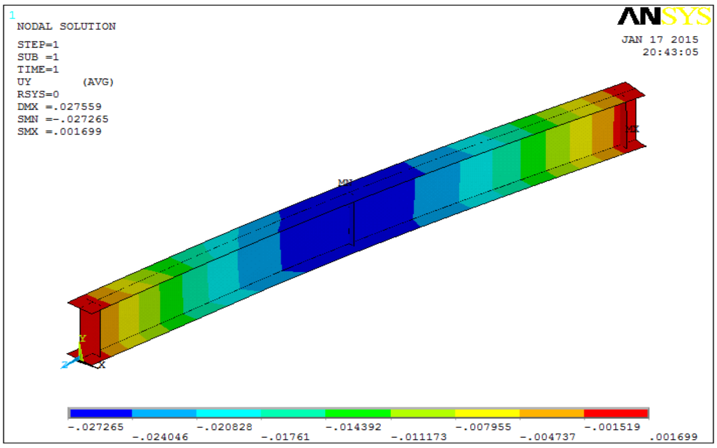

Figure 7: Contour plot of the vertical deflection of curved I-girder with one intermediate stiffener

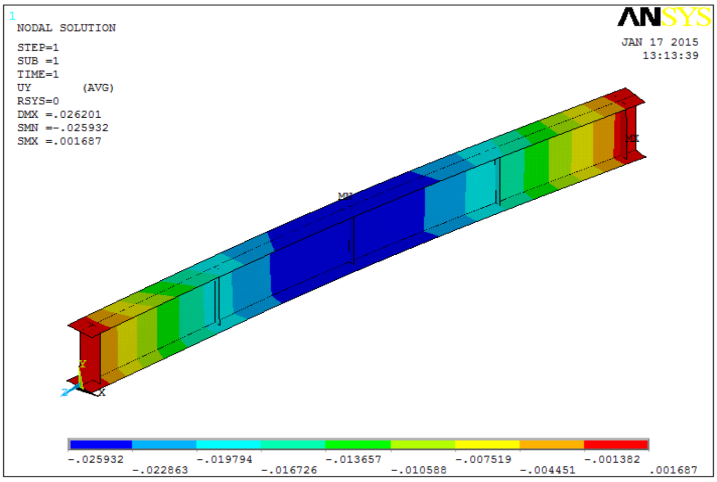

Figure 8: Contour plot of the vertical deflection of curved I-girder with three intermediate stiffeners

The analysis results of the straight I-girder through elementary simple bending theory and the FEM are in close agreement with each other as seen in Table 2. When the thin I-girder is horizontally curved to a radius of 63.63 m, the deflections along all directions shoot up to high numbers compared to the straight girder. The twisting of the I-girder (which is unlikely to happen in a straight girder with symmetrical cross-section and load) also may be noted when horizontal curvature is imposed on it (Fig.8). Hence an intermediate stiffener is provided at the mid span of the curved I-girder for its stability. The provision of the stiffener at the mid span reduces the deflections to a large extent. Also, the bending stresses and the shear stresses are reduced rapidly which is shown in Table 2. In an effort to reduce the stresses and deflections, stiffeners are provided at 1/4th and 3/4th of the span in addition to that at the mid-span, on an experimental basis. Results have shown much decrease in the values of stresses and deflections and moreover they are closer to that of the straight girder.

The bending stress distribution at the mid span cross-section and shear stress distribution at the end cross-section for the straight and curved I-girders have been shown in Figures 9 to 16.

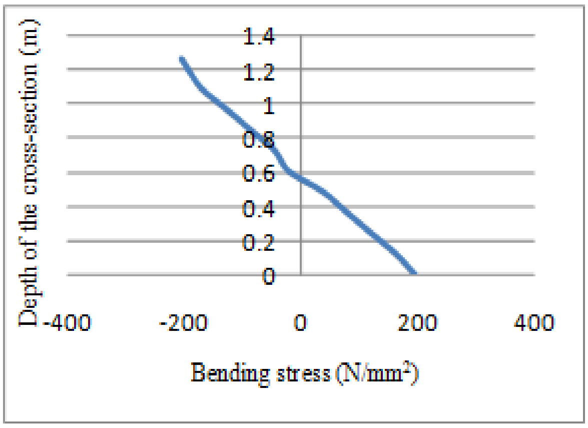

Figure 9 : Bending stress distribution of straight I-girder

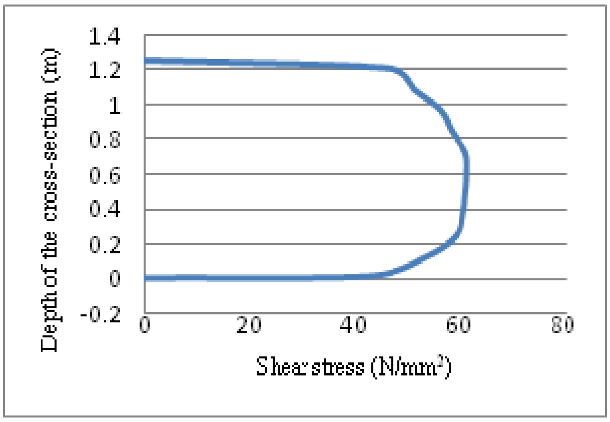

Figure 10: Shear stress distribution of straight I-girder

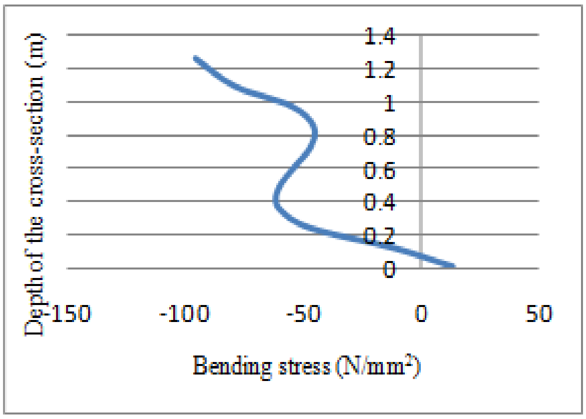

Figure 11: Bending stress distribution of curved I-girder without stiffeners

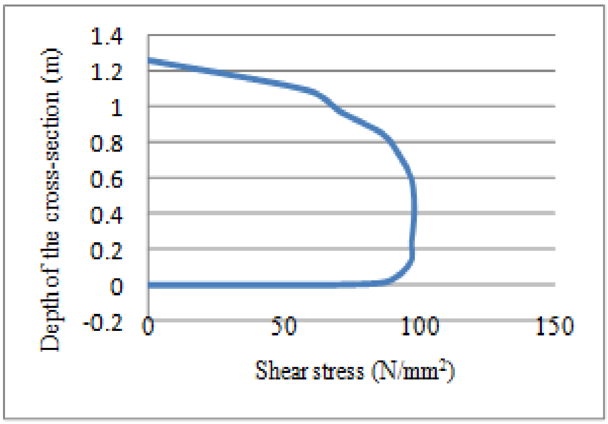

Figure 12: Shear stress distribution of curved I-girder without stiffeners

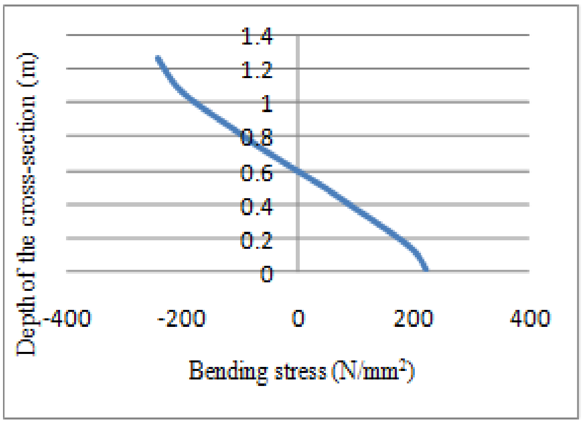

Figure 13: Bending stress distribution of curved I-girder with one intermediate stiffener

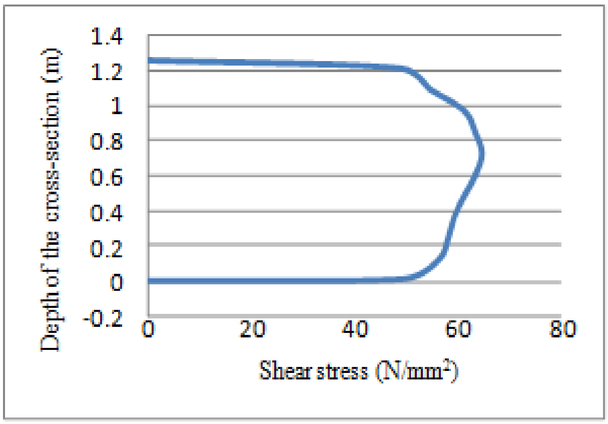

Figure 14: Shear stress distribution of curved I-girder with one intermediate stiffener

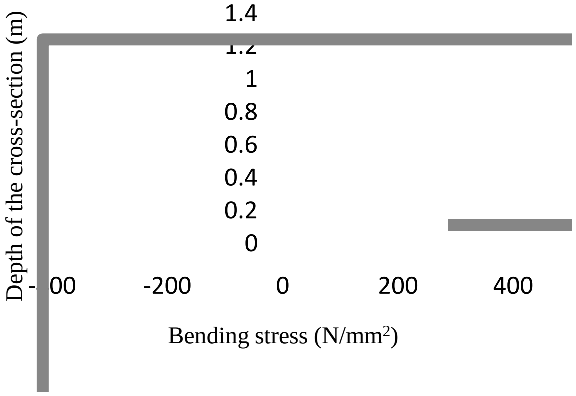

Figure 15: Bending stress distribution of curved I-girder with three intermediate stiffeners

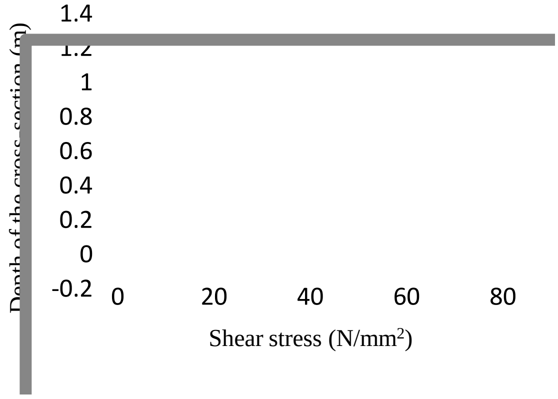

Figure 16: Shear stress distribution of curved I-girder with three intermediate stiffeners

6. CONCLUSIONS

A straight I-girder and three horizontally curved I-girders with and without intermediate stiffeners are analyzed in this paper. The stresses and deflections of curved I-girders are noted and compared with the straight I-girder. The stiffeners and lateral restraints influence the strength and stability of the curved I-girder. The curved I-girder produces excessive bending and shearing stresses and displacements owing to its unsymmetrical bending given by its curvature in comparison with the straight one. Introduction of lateral stiffeners can reduce these excessive stresses and displacements. The local buckling effect owing to the thinness of the web of the girders is under study. It is expected that use of more lateral stiffeners might reduce the local buckling effect. The number of such stiffeners and location of the same are under investigation and the results of the same would be produced, elsewhere.

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