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Analysis of RCC curved box girder bridges

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Analysis of RCC box girder bridge is carried out for three different box girder sections, i.e. single, double and triple cells using finite element technique by linear static method of analysis. Bridge models are studied with the variation of degree of curvature, which is varied from 0° to 60° at an interval of 6°. Load cases considered are dead load and live load conforming to Indian Road Congress (IRC). The variation of bending moment, torsional moment, shear force and deflection is studied which are found to be increased with curvature. It has been estimated that the increased deflection in single, double and triple cell box girder bridges is about 295%, 280% and 245%, respectively, in between 0°(straight) and 60° curved bridges. This study states that the design of curved bridges is not a simple task which needs to be performed with utmost care.

Keywords: Degree of curvature, FEM, IRC loading, Multi-cell section, RCC box girder

1 Introduction

Bridge is a man-made construction utilized for carrying the moving loads or other in order to pass through an obstacle. The required passage may be for pedestrians, a road, a railway, a pipeline, a canal, etc. and obstacle can be rivers, valleys, sea channels, and other constructions, such as bridges themselves, buildings, railways, or roads, etc. RCC box girder is extensively used in bridges due to its high torsional rigidity. Thin webs are connected with flanges as a box like geometry in order to reduce the self-weight. Box girder sections being thin walled i.e., deformable sections, out of plane deformation takes place due to which elementary beam theory is no longer applicable to these sections. Shear lag effect in the sections results in unpredictable extra longitudinal displacement at the junction of web and flange[1]. The geometric layout of bridges sometimes necessitates curved bridges for smooth and comfortable transition. However, sometimes due to required alignment layout and site restrictions, it becomes necessary to provide bridges curved in layout. Curved bridges are often chosen to be circular if possible in combination with other (spiral, parabola, etc.) curves as transition curve. But in curved bridges, torsion plays a vital role and then it require attention for the design and also due to the combination of torsion with bending moment, the resultant bending moments are higher than that of straight bridges. Elastic analysis of straight box-girder bridges can be simplified by analyzing longitudinal bending, transverse bending, torsion, shear and warping. The global response is obtained by superimposing the effect of all these individual response. However, using methods like orthotropic plate theory, grillage method, folded plate method, finite difference method, finite strip method, and finite element method, the overall structural response may be obtained without decoupling the structural actions[2]. In case of horizontally curved bridges, structural response of the curved bridges becomes more complex due to the coupling of developed torsional moments along with longitudinal moments. For such complications, several provisions have been developed in international codes.

These codes also stipulate some cases under which curved bridges can be analyzed as an equivalent straight bridge. AASHTO-LRFD bridge design specifications[3], and the AASHTO specifications for horizontally curved Bridges[4] specify that the curved bridges can be treated as straight bridges with curvature angle up to 12°. Li, Tham and Cheung[5] stated that the finite element method is a versatile tool for the analysis of curved box girder bridges. Authors pointed out that since each element has a large degree of freedom, thus it would limit its application in large structures for manual analysis. In order to overcome these limitations, authors used finite strip method which is again limited to simple boundary conditions and geometry. Heins and Oleinik[6] analyzed the single and multi-span curved single box beam-bridge. The

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*Corresponding author (E-mail: prpal@mnnit.ac.in) governing differential equation for cross-sectional deformation was solved using the finite difference numerical technique. Sarode and Vesmawala[7] studied the horizontally curved single cell box girder for flexure, torsion and stability using LUCAS FEA software considering dead load, super imposed load and live load (as per IRC) by fixing L/D ratio and by varying the span and radius of curvature for a single cell section. DeSantiago, Mohammadi and Albaijat[8] analyzed the curved bridges using finite element analysis to determine its bending moment, torsional moment and deflection. Authors concluded that the torsional moments develop in the girder of bridge. Luo and Li[9] calculated the shear lag effects for curved box girder bridges and concluded that the derived theoretical formulas are more applicable than the Vlasov's method, which can be applied to evaluate the shear lag in straight and curved box girder bridges effectively. Gupta, Agarwal and Pal[10] studied the free vibration analysis of different box girder bridges using finite element analysis. Authors concluded that the fundamental frequency of small sections (i.e., small width and less number of cells) is not affected significantly by curvature of bridge. Křístek, Bažant, Zich and Kohoutková[11] presented the long-term deflection behavior of a pre stressed concrete box girder bridges. Measuring small deflections over the first few years, the engineers expect that the deflections remain small, but it is an unpleasant surprise that, after several years, the deflections suddenly accelerate. Although, many researchers have studied the box girder bridges in single and multi-cell, and the effect of curvature on it, but for the comparison of single and multi-cell box girder bridges, there is still need of more research. Also a few studies is available in literature in which the Indian standard loading is considered. This brings motivation to work on curved bridges with IRC loading standards.

The aim of present study is to investigate the behavior of box girder bridges with the variation of curvature. To achieve the goal, analysis of the box girder bridges for different sections (i.e., single, double and triple cell) with the effect of curvature is carried out.

2 Methodology

In this study, three different bridge sections are modelled for investigation. The analysis is carried out by finite element method for both dead and live loads. A box girder bridge model, shown in Fig. 1, is adopted herein for validation. The similar model was considered by Gupta and Kumar[12]. SHELL element is used for modelling the single cell Reinforced Concrete (RC) box-girder bridge. SHELL element is having four nodes with six degrees of freedom at each node.

The simply supported box-girder bridge having a span of 27.4 m, width of 10.8 m and overall depth of 2.96 m is considered. The clear carriageway width is 10.4 m. The thickness of web is 360 mm and the thickness of top and bottom flanges is 250 mm and 280 mm, respectively. The material properties considered are presented in Table 1.

Pin support is provided at left interior support and roller support is provided at remaining three supports. The box-girder bridge is analysed for dead load (DL) and Indian Road Congress (IRC)[13] 70R tracked vehicle live load (LL), which is applied at a minimum distance of clear spacing of 1.2 m from the kerb. The mesh size of shell element is taken as 20 cm in both longitudinal and transverse directions. Curve angle of the bridge is varied from 0° to 48° at an interval of 12°, introduced at both supports. The absolute bending moment due to both DL and LL is determined in both the girders and the results obtained are compared. Figure 2 shows the variation of absolute bending moment due to both DL and LL with curve angles in both outer and inner girders, respectively. It is observed that the bending moment increases with curvature in outer girder and decreases in inner girder for both the cases of load.

The similar type of models with different sectional properties is considered in this study for investigation. Three box girder sections of span 30m each are

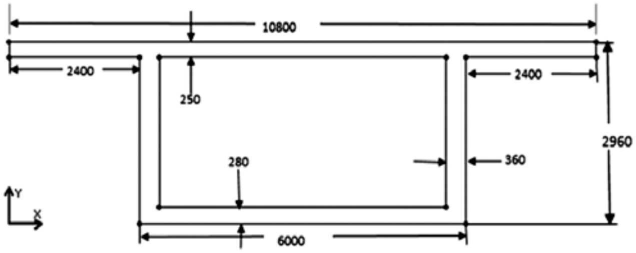

Fig. 1 — Cross section of box-girder bridge (dimensions are in mm).

Table 1 — Material properties

Material properties	Concrete	Steel
Grade	M25	Fe415
Unit weight (kg/m^3)	2500	7850
Modulus of elasticity (MPa)	25×10^3	2×10^5
Poisson's ratio	0.2	0.3

considered and the cross sections of each are shown in Fig. 3. Here, the simple supported boundary conditions are achieved by providing hinge and roller on each side of each girder (or the web of the section) of the bridge.

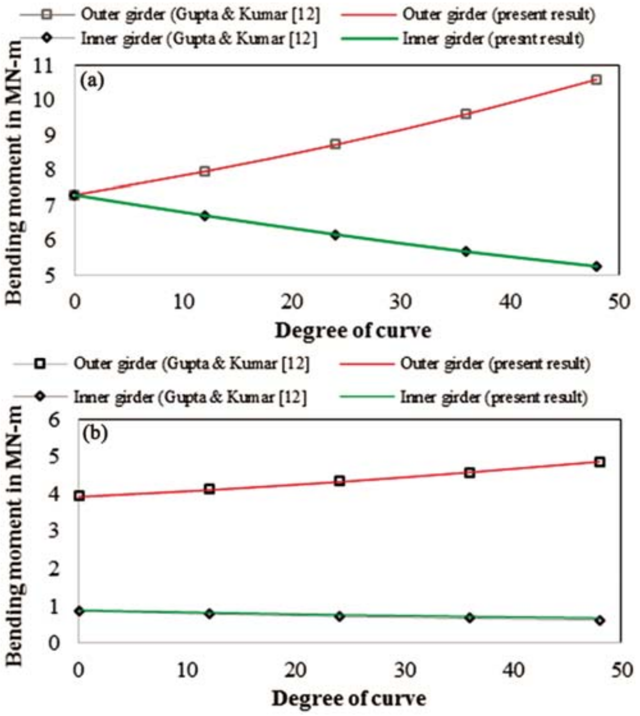

Fig. 2 — Comparison of results for (a) dead load and (b) live load.

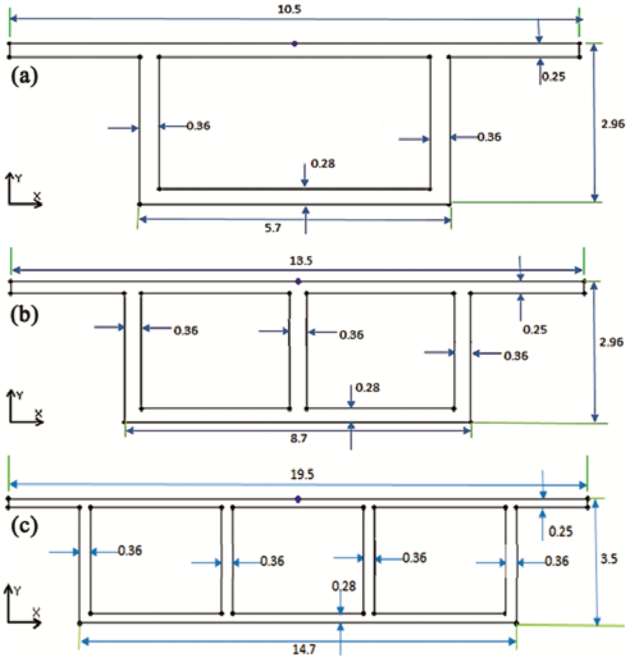

Fig. 3 — Cross sections of box girder bridge for (a) single cell section, (b) double cell section and (c) triple cell section.

Different bridge models are established by varying the degree of curvature for the root bridge geometry considered. The central curvature angle (θ) of the bridge is varied from 0° to 60° at an interval of 6°, as shown in Fig. 4, while all other parameters (i.e., span, radius of curvature) of the bridge models have been kept same as the root bridge for better assessment of the effect of curvature.

A convergence study is carried out to get an appropriate mesh size in a single cell box girder bridge. Table 2 presents the results of maximum vertical deflection, which is found to be converging at 18 cm mesh size.

Bridge sections are modelled as an area element using a finite element enabled software SAP2000. The models are discretized by four noded SHELL elements having six degree of freedom at each node. The bridge is analyzed for dead load and vehicular load conforming to IRC 6[13]. Load combination for vehicular loads is chosen from tables 6 and 6A of IRC 6: 2017. The analysis is performed for three different box girder bridge sections and the response of the bridges is observed for flexure, torsion, shear and deflection.

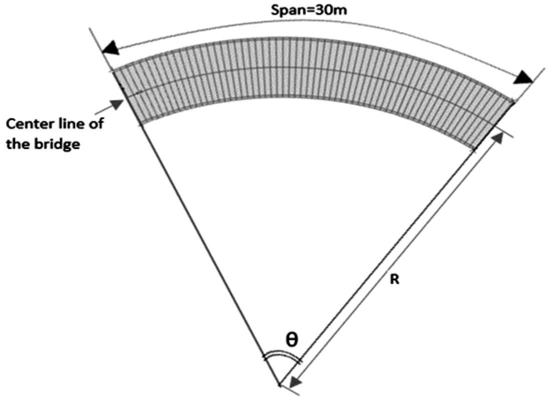

Fig. 4 — Curved bridge showing reference parameter.

Table 2 — Convergence study

Mesh size (cm)	Deflection (mm)
60 × 60	10.768
50 × 50	10.792
40 × 40	10.829
35 × 35	10.842
30 × 30	10.853
25 × 25	10.870
22 × 22	10.880
20 × 20	10.887
18 × 18	10.895
17 × 17	10.900
16 × 16	10.903
15 × 15	10.905

3 Results and Discussion

A parametric study is carried out to examine the effect of curvature on the simply supported box-girder bridges. It is found that the girders of the bridge do not behave purely simply supported even after providing simply supported boundary conditions. It may be caused due to fixity connection of the girder in between upper and bottom slabs. However, if the entire bridge is modelled by considering a single body, it behaves as simply supported. Results of single cell, double cell and triple cell box girder bridges are summarized as follows:

3.1 Effect of curvature on single cell box girder bridge

Figure 5 shows the variation of maximum bending moment with curvature. It has been estimated that the maximum bending moment of bridge increases about 50%, 32% and 38% in the outer girder and decreases about 23%, 14% and 17% in the inner girder for dead load, live load and combination of both the loads, respectively. Figure 6 shows the variation of maximum torsional moment with curvature. It has been estimated that the maximum torsional moment increases about 193%, 65% and 120% in the outer girder and increases about 90%, 40% and 47% in the inner girder. Figure 7 shows the variation of maximum shear force with curvature. It has been estimated that maximum shear force increases about 109%, 85% and 44% in the outer girder and deceases about 16%, 14% and 43% in the inner girder. Figure 8 shows the comparison of deflection with permissible value due to combined effects of dead load and live load.

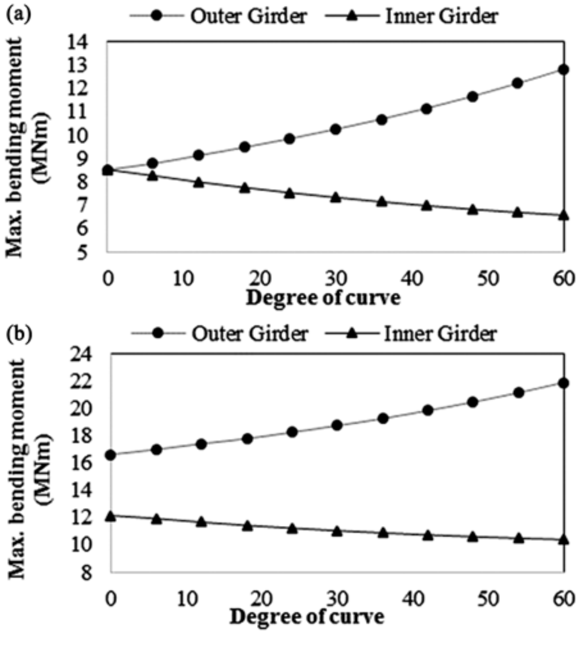

Fig. 5 — Maximum bending moment with curvature for (a) dead load and (b) live load.

3.2 Effect of curvature on double cell box girder bridge

In the double cell box girder bridge, Fig. 9 shows the variation of maximum bending moment with curvature. It has been estimated that maximum bending moment increases about 59%, 30% and 40% in the outer girder, increases about 19%, 17% and 18% in the middle girder and deceases about 36%, 23% and 30% in the inner girder for dead load, live

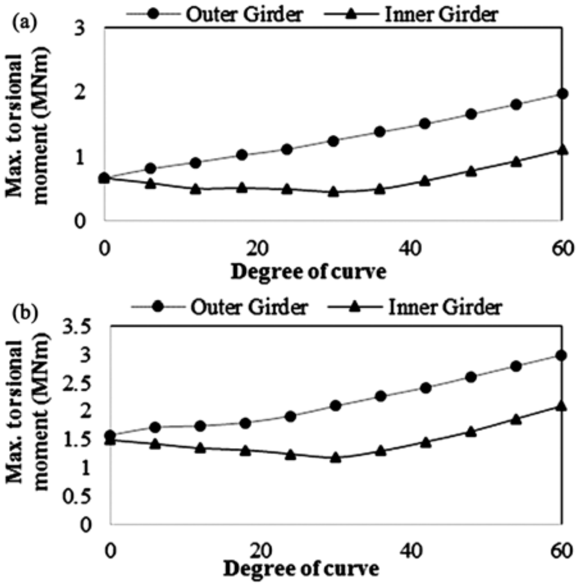

Fig. 6 — Maximum torsional moment with curvature for (a) dead load and (b) live load.

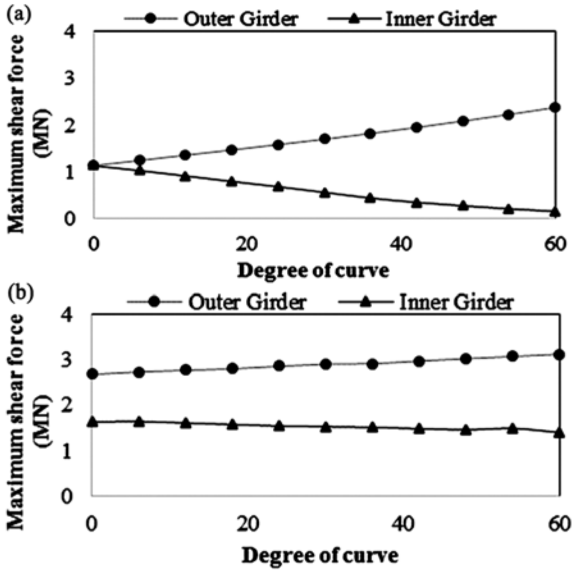

Fig. 7 — Maximum shear force with curvature for (a) dead load and (b) live load.

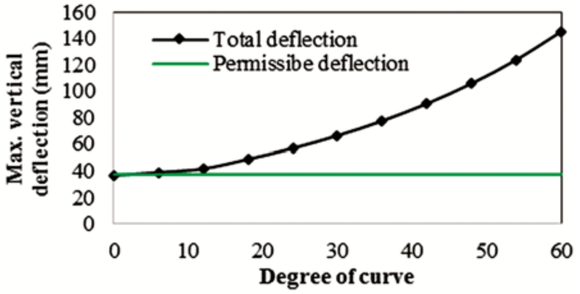

Fig. 8 — Comparison of deflection with permissible value.

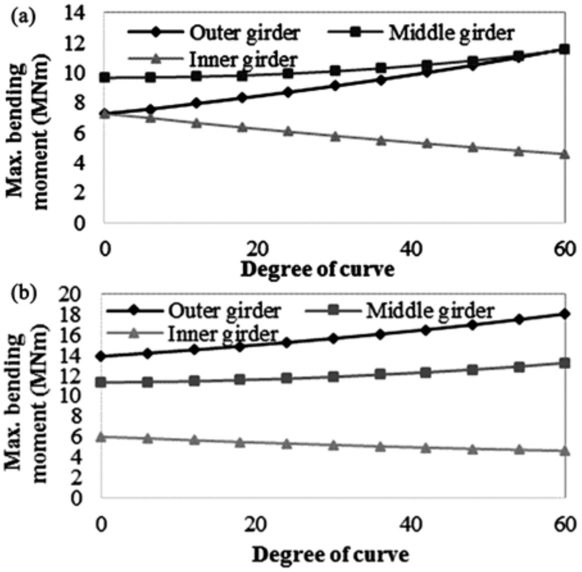

Fig. 9 — Maximum bending moment with curvature for (a) dead load and (b) live load.

load and combination of both the loads, respectively. Figure 10 shows the variation of maximum torsional moment with curvature. It has been estimated that maximum torsional moment increases about 248%, 50% and 93% in the outer girder and increases about 165%, 192% and 181% in the inner girder. In the middle girder, torsion increases about 195% due to live load and 400% due to combined of both the loads. Figure 11 shows the variation of maximum shear force with curvature. It has been estimated that maximum shear force increases about 115%, 16%and 45% in the outer girder and increases about 3%, 5% and 5% in the middle girder. In the inner girder, it decreases about 79% due to dead load and increases about 165% due to live load. However due to combination of both the loads, shear force is found to be decreased about 8%. Figure 12 shows the comparison of deflection with permissible value due to combined effects of dead load and live load.

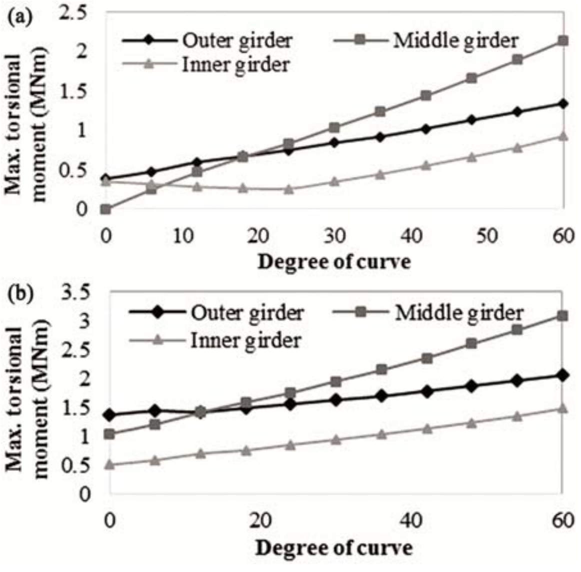

Fig. 10 — Maximum torsional moment with curvature for (a) dead load and (b) live load.

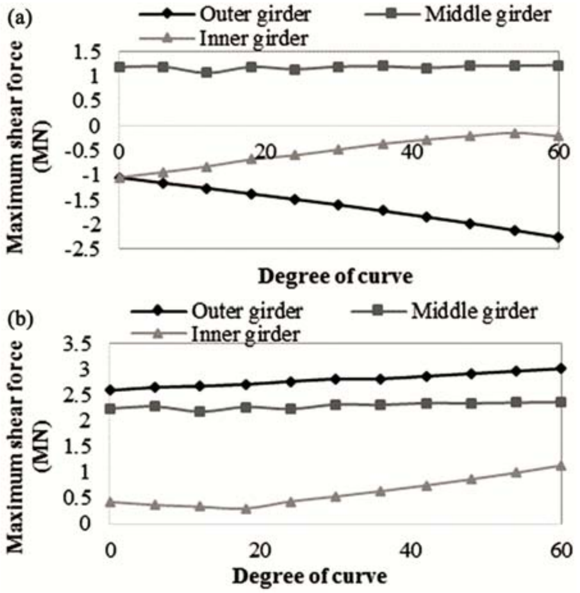

Fig. 11 — Maximum shear force with curvature for (a) dead load and (b) live load.

3.3 Effect of curvature on triple cell box girder bridge

Figure 13 shows the variation of maximum bending moment with curvature. It has been estimated that bending moment is found to be increased by 95%, 35% and 52% in outer exterior girder and 54%, 31% and 39% in outer interior girder due to dead load, live load and combination of both the loads. Bending moment decreases in inner exterior girder by 80%, 51% and 71% while in inner interior girder, it decreases by 8% due to dead load and increases by

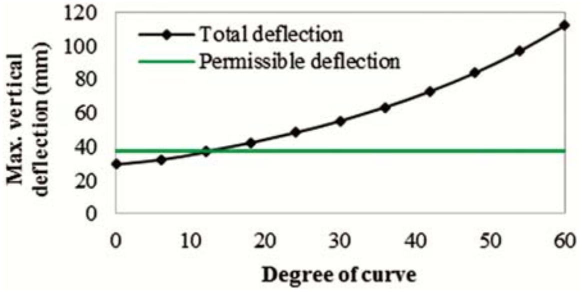

Fig. 12 — Comparison of deflection with permissible value.

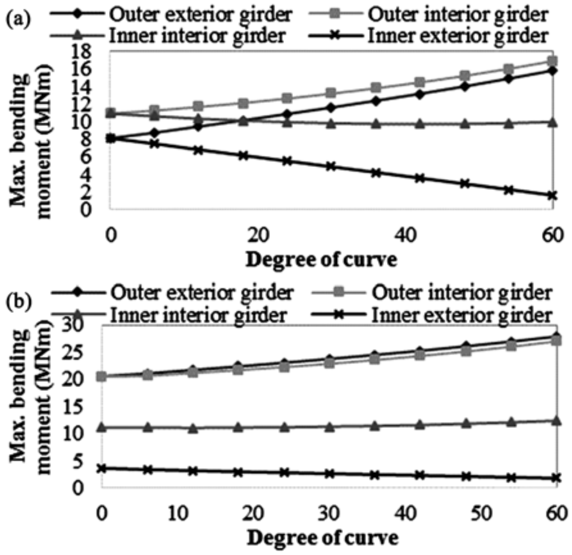

Fig. 13 — Maximum bending moment with curvature for (a) dead load and (b) live load.

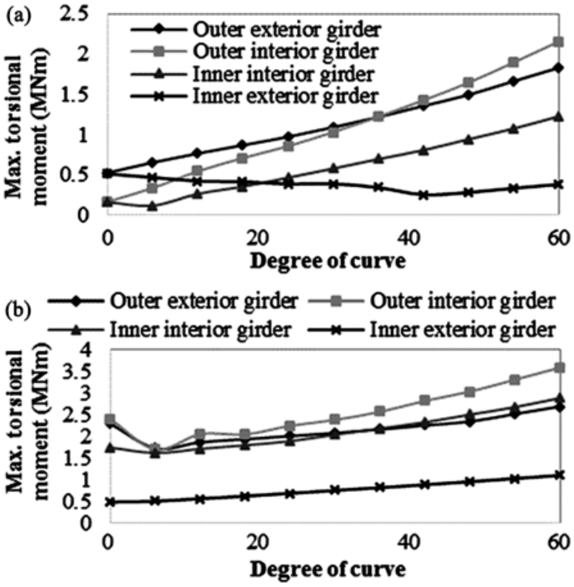

Fig. 14 — Maximum torsional moment with curvature for (a) dead load and (b) live load.

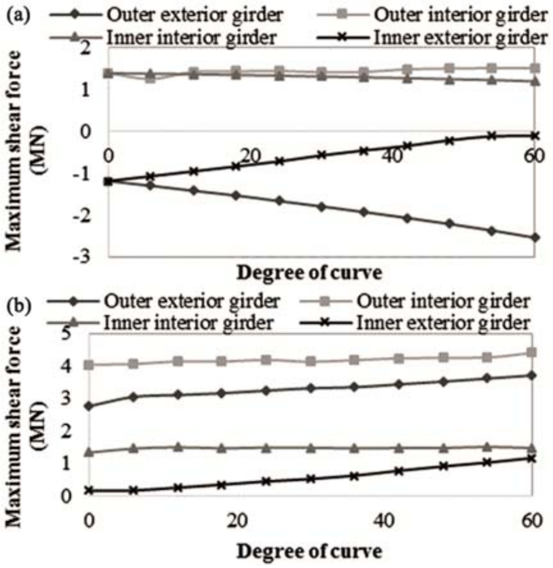

Fig. 15 — Maximum shear force with curvature for (a) dead load and (b) live load.

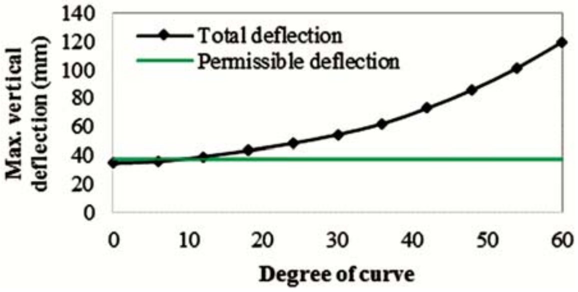

Fig. 16 — Comparison of deflection with permissible value.

11% and 1% due to live load and combination of both the loads. Figure 14 shows the variation of maximum torsional moment with curvature. It has been estimated that torsional moment increases in outer exterior girder by 250%, 17% and 60%, in outer interior girder by 1227%, 49% and 124% and in inner interior girder by 674%, 66% and 116%, while in inner exterior girder, it decreases due to dead load by 25% and increases by 130% and 50% due to live load and combination of both the loads. Figure 15 shows the variation of maximum shear force with curvature. It has been estimated that shear force increases in outer exterior girder by 113%, 34% and 58%, in outer interior girder by 8.5%, 9% and 8.8%. It decreases by 14% and 2% in inner interior girder and 90% and 6% in inner exterior girder due to dead load and combination of both while it increases by 10% in inner interior girder and 610% in inner exterior girder due to live load. Figure 16 shows the comparison of deflection with permissible value due to combined effects of dead load and live load.

4 Conclusions

Based on the study carried out so far, the following conclusions are drawn:

I In curved bridges, both bending moment and shear force increase in outer girder while decrease in inner girder.

II Variation of bending moment with curvature is found to be steeper on the exterior girders in comparison to the interior girders.

III Deflection plot reveals that there is no effect of curvature angle up to 12° for multi-cell box girder bridges.

IV When the degree of curvature is varied from 0° to 60°, deflection is found to be increased which follows a parabolic path. It has been estimated that the increased deflections in single, double and triple cell box girder bridges are about 295%, 280% and 245%, respectively in between 0° and 60° curved bridges.

V The sectional properties of the bridges are required to be modified as the deflection is not satisfying the permissible limit of deflection.

VI Study could be extended by choosing different types of box girder sections like trapezoidal box girder, multi-spine box girder etc.

VII Comparison could be made by keeping the volume of material same for different sections.

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