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Analysis of Post-tensioned Rectangular and Trapezoidal Box Girder Bridges and its behaviour in Horizontal Curvature Condition

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Abstract— *Bridge is an important part of any Highway / Infrastructure which helps to connect two major cities / districts/ towns/ States. Bridge is a key element in any transportation system which provides easy access over physical obstacles like road, valley, water bodies etc. without closing the way underneath. In recent times with evolution of Flyovers, Interchanges, Metro rail projects because of which the horizontally curved box girder bridges are widely used to overcome congested traffic problems and meet complex road alignments. Now the alignment may observe a curvature hence it is required to include structures in curvature. Hence in this paper, analysis of a two cell post-tensioned rectangular and trapezoidal box girder bridge is presented by varying radii of curvature(0m, 50m, 75m, 100m, and 125m) using finite element based software(MIDAS). Finite element models were developed for both bridges and for all radii of curvatures keeping material properties, span, boundary conditions and tendon profiles as constant parameters. All the models were analyzed for self-weight, including load of wearing coat and crash barrier, and live loads specified by Indian Road Congress (IRC) namely IRC 70R and IRC Class A loading. Responses in terms of torsional moment, longitudinal moment, support reactions, displacements, and stresses were determined for developed models and compared for both bridge sections. Results show considerable difference in the values of torsional moment, displacements and stresses but with no significant difference in longitudinal moment.*

Keywords— *box-girder, horizontal curvature, torsion, finite element analysis, rectangular section, trapezoidal section.*

I. INTRODUCTION

The rapid infrastructural development and increasing rate of urbanization leads road alignment issues become more critical and to resolve such issues and to make smooth passage of congested traffic, the need for construction of complex transportation systems has increased. Although, the construction of bridges curved in the plan is the most economical choice to satisfy these demands.

The curved bridges are not only subjected to flexural moment but also a torsional moment which developed by curvature effect even under gravitational load. A box girder is well suited for horizontally curved bridges, because it consist closed section of the top and bottom flanges connected by vertical or inclined webs which provide high torsional stiffness against torsional effect induced by curvatures and also flexural stiffness to resist bending effect that occurred in the bridge deck [1].

Box girder bridges are constructed by steel, reinforced concrete and pre-stressed concrete sections. Now days, pre-stressed concrete sections are widely used due to its ability of long span construction and slender sections. The introduction of pre-stressing enables designers to limit developed stresses by optimum combination of tensioned high strength steel and high strength concrete which improves response of structure against external loadings [2]. Box girder bridges are classified according to their cross section (c/s) and number of cells. Box girder can be constructed as a single cell, two cell or multi cells. Box girder constructed monolithically with deck called as closed box girder and box girder in which deck constructed separately called open box girder. According to cross section details box girder classified into rectangular, trapezoidal and circular box girder [3]. Figure 1 shows different type of box girder.

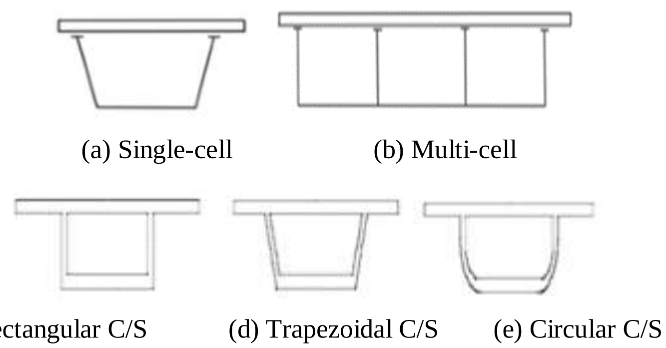

Fig.1 Different types of box girders.

A. Structural Action of Box Girder

The structural action of box section under the loading consist four principle modes, bending, torsion, distortion and shear lag [4].

1) Bending: Bending is occurring in longitudinal and transverse direction in the box girder. When structure is symmetrically loaded e.g. self-weight, superimposed dead load like footpath, carriageway and crash barrier load are symmetrical about vertical centroidal axis of box section then torsion does not occur in the box section. This is true for horizontally straight in plane bridges only. This axis symmetric load is resisted by simple bending of box girder which creates flexural stresses on top and bottom flanges of box section. If top and bottom flanges of box section connected by shear webs and both flanges bend in transverse direction then it called transverse bending of box section.

2) Torsion: The axel loads of live load vehicle are mostly eccentrically placed on the bridge deck. This eccentrically placed axis symmetrical loading produces torsion in the box girder. To understand clearly, consider P1 and P2 are equivalent reactions resulting from vehicular live load acting on webs of the box girder. These two load components are resolved into symmetrical and unsymmetrical load combinations as shown in figure 2. The symmetrical load component (p1+p2)/2 does not create any torsional effect, it causes longitudinal bending only, while load component (p1-p2)/2 produces torsion in the section. Another reason of torsion is curvature of bridge in horizontal in plane. To counteract resultant torsion, internal forces as shown in figure 3 are generated in the box girder. The elemental torsion theory is used to evaluate St. Venant shear stresses and associate warping stresses generated in section due to pure torsion. Due to high torsional stiffness of box section only a little twist is observed in box section under pure torsion effect. Under the torsional loading, forces are applied on plate element tend to deform cross-section. This will cause formation of distortional stresses in transverse direction and warping stresses in longitudinal direction.

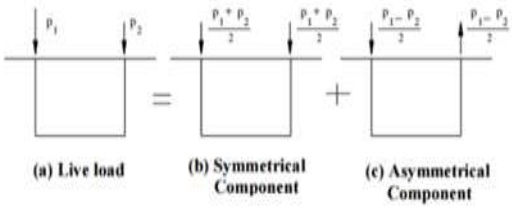

Fig. 2.Live load resolution.

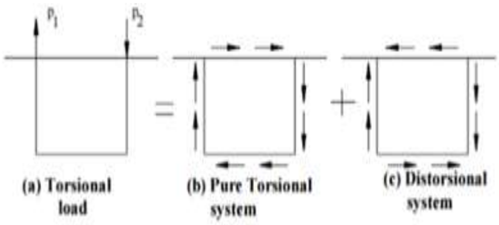

Fig. 3.Torsional load resolution.

3) Distortion: Distortion of box section is occurs, when vertical shear force across a cell causes the slab and webs to flex independently out of plane. Diaphragms are provided in cross-section of box girder to eliminate distortion of section. The distortion cannot be uniform along the span of the deck. It is minimum or zero at the location of diaphragm. Also, distortion can be overcome by increasing distortion stiffness of box section by constructing sloping webs to the box section.

4) Shear lag: The flange of the box section experience large amount shear flow transmitted by vertical webs of box section causes in plane shear deformation of flange plates. This will results lag of longitudinal displacement of centre portion of flange from displacement of flange portion near to web. This lag causes out of plane warping called shear lag. In case of girder with wide flange experienced increase in bending stresses near the web called as positive shear lag. If bending stresses are away from the flange is increases and reduces near the web is called as negative shear lag.

II. OBJECTIVE

The main objective of this work is to investigate the effect of varying horizontal radius of curvature in post-tensioned rectangular and trapezoidal box girder under self-weight and moving load as per IRC 6:2016.

III. MODELING AND ANALYSIS

For this analytical study, finite element modeling approach was adopted. The span length (40m), deck width (12m) and box height (2m) are similar to all models. Also, material properties, boundary conditions and tendon profiles are kept constant. Post-tensioning system of pre-stressing was considered and 12 post-tensioned tendons are modeled for each box girder model. Total five models with different radius of curvature are prepared in MIDAS Civil for each cross-section i.e. radius of curvature = 50m, 75m, 100m, 125m and 0m models.

A. Cross-section Properties

The preliminary dimensions of both rectangular and trapezoidal box girder are calculated as per IRC 18:2000 (Design Criteria for Pre-stressed Concrete Road Bridges). Table1 gives the cross-sectional details of box girder and figure 4 (a) & (b) shows typical cross-section and tendon location of rectangular and trapezoidal box girder. Also, 90 mm diameter sheathing duct is considered constant for all models.

TABLE I

CROSS-SECTION PROPERTIES OF BOX GIRDER

Sr. No.	**Property**	**Rectangular Cross-Section**	**Trapezoidal Cross-section**
1	Top slab Thickness	0.3 m	0.3 m
2	Bottom Slab Thickness	0.3 m	0.3 m
3	Thickness of Web	0.3 m	0.3 m
4	Haunch size	350 mm horizontal 150 mm vertical	350 mm horizontal 150 mm vertical
5	Area (A)	7.35 m2	7.33 m2
6	Y top	0.8613 m	0.8307 m
7	Y bottom	1.1387 m	1.1693 m
8	I xx	4.482 m4	4.26 m4
9	I yy	6.963 m4	6.694 m4
10	Z top	5.204 m3	5.128 m3
11	Z bottom	3.936 m3	3.643 m3

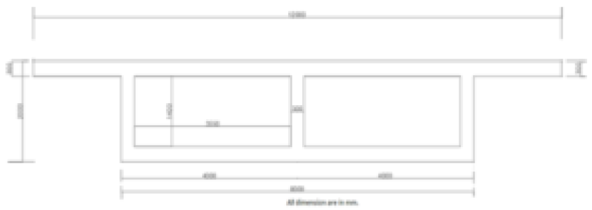

Fig. 4 (a) Typical cross-section of rectangular box girder.

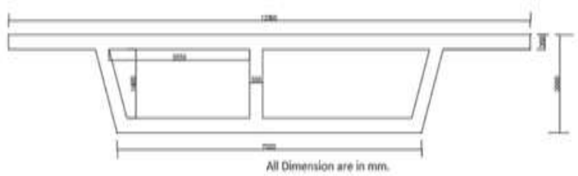

Fig. 4 (b) Typical cross-section of trapezoidal box girder.

B. Material Properties

The material properties used for models are given below.

- Grade of Concrete - M50
- Characteristic Strength (fck) -50 Mpa
- Young's Modulus (Ec) -3.5535e^7 KN/m2
- Density of Concrete -23.6 KN/m3
- Grade of steel - Fe 500
- Poisson's Ratio (υ) - 0.2
- Coefficient of thermal expansion -1.853e^-4 1/C
- 20 T 15 7 ply high tension steel with low relaxation is used for pre-stressing.

C. Loading Conditions

In this study, different types of loads are used for analysis of structure such as dead load, superimposed dead load and moving load as per IRC6:2016. Earthquake load and Wind load is not consider for analysis. In superimposed dead load, crash barrier load having height of 1m and thickness 0.5 m is applied. A 75 mm thick wearing course load is applied by calculating load intensity per meter. For curved bridge decks, centrifugal force is calculated for each axel and applied to the models. Also, breaking force is applied as per IRC 6:2016 clause 211.

IRC 70 R and IRC Class A loading is applied to the entire box girder model and live load combinations are considered as per IRC 6:2016 clause 204. In this study, three live load combinations are adopted for the analysis of all box girder models. Following are live load cases used for analysis of box girder models.

1) Case 1: one lane of IRC 70R loading + one lane of IRC Class A loading.

2) Case 2: three lanes of IRC Class A loading.

3) Case 3: IRC 70 R loading on mid-lane.

D. Finite element models

Total 100 elements are used for model development. To transfer effect of deck loading to the support node, rigid elastic links were used. Figure 5 (a) and (b) shows developed finite element models of rectangular and trapezoidal cross-sections with horizontally curved in plane.

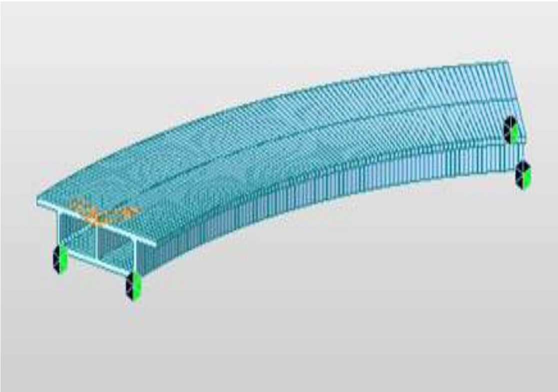

Fig. 5 (a) Curved rectangular model.

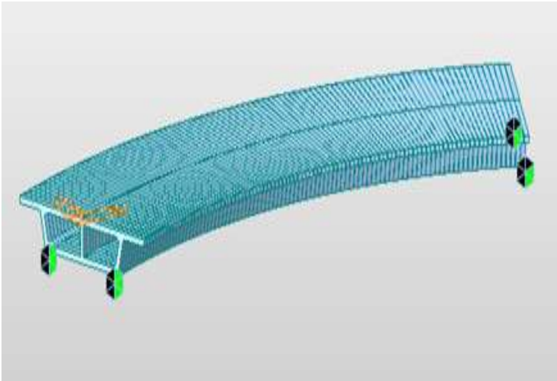

Fig. 5 (b) Curved trapezoidal model.

IV. Results and Discussion

The response of both the cross-section under varying radius of curvature are discussed in terms of torsion moment, longitudinal moment, deflection, reactions and stresses at top and bottom of the section.

A. Torsional moment

Table no. 1 shows summation of maximum torsional moment due to self-weight and live load for both cross-section under different radius of curvature.

TABLE II

MAXIMUM TORSIONAL MOMENT (KN-M)

Sr. No.	Radius (M)	Rectangular Cross Section	Trapezoidal Cross Section
1	50	24675.01	24365.51
2	75	16026.29	15938.54
3	100	12206.05	12160.29
4	125	10024.19	9994.57
5	0	1760.52	1753.41

It is observed that, the percentage increment of torsional moment under increase in curvature is approximately same for both rectangular and trapezoidal box girders. But there is a difference in magnitude of torsional moment in rectangular and trapezoidal box girder under same radius of curvature. When radius of curvature decreases from 125m to 100m, the torsional moment increases by 17% and for 100m to 75m, torsional moment increased by 27%.The maximum 35% increment in torsional moment is observed, when radius decreases from 75m to 50m.

B. Support reactions

The maximum vertical support reaction for rectangular and trapezoidal box girders under varying radius of curvature are plotted on bar chart in figure no. 6

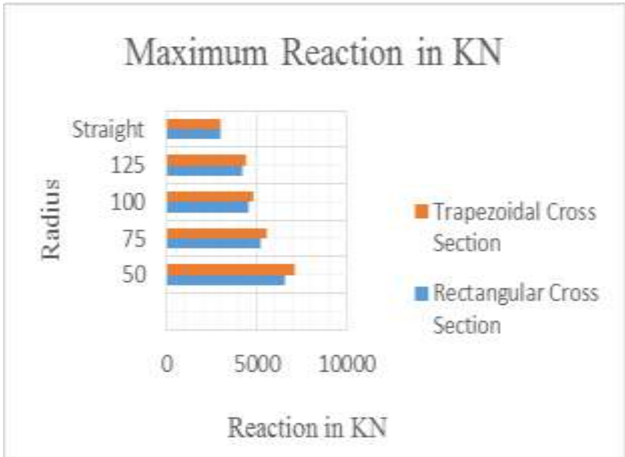

Fig. 6 Maximum support reactions in KN.

When radius of curvature decrease from R=75m to R=50 m, the maximum reaction is increases by 20% in rectangular model and 21.6% in trapezoidal model. It is also seen that, trapezoidal box girder model possesses more support reaction as compared to rectangular box girder model under all radius of curvature.

C. Deflection

Figure no. 7 shows maximum vertical deflection (DZ direction) at mid-span of the box girder for different radii of curvature.

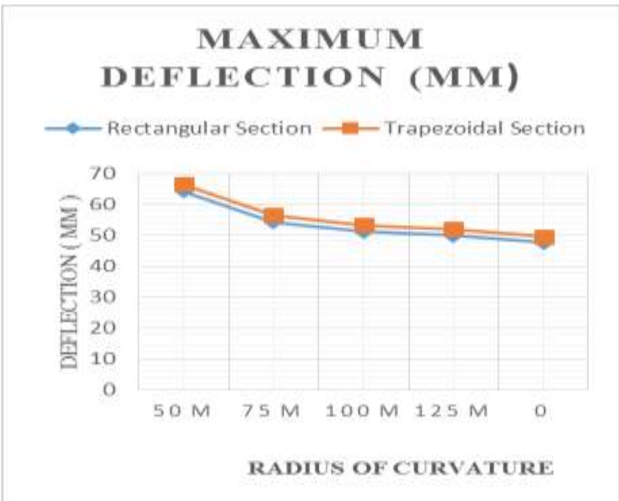

Fig. 7 Maximum deflections at mid-span in mm.

A 15% increment in deflection is observed, when radius of curvature decreases from R=75m to R=50m. Similarly, when radius of curvature decreases from R=100m to R=75m, deflection increased by 5%.

D. Longitudinal moment

The variation in magnitude of maximum longitudinal moments (moment due to dead load + live load) between rectangular and trapezoidal box models for different radii of curvatures is shown in table no. 2.

TABLE III

MAXIMUM LONGITUDINAL MOMENT (KN-M)

Sr. No.	**Radius (M)**	**Rectangular Cross Section**	**Trapezoidal Cross Section**
1	50	37130.73	36850.81
2	75	35674.25	35485.5
3	100	35222.32	35023.4
4	125	35027.93	34824.42
5	0	34692	34491.4

It is observed that, increase in curvature or (decrease in radii of curvature) increases longitudinal moment in box girder models. Maximum 3.5% increment in moment is seen when radius of curvature decreases from R=75m to R=50m for both rectangular and trapezoidal cross-section.

E. Stresses

Table no. 3 shows the stresses generated in top and bottom of the box girder for both rectangular and trapezoidal box girder under varying radius of curvature. The negative value represent compression and positive values represent tension in the box girder.

TABLE IV

STRESSES AT TOP AND BOTTOM OF BOX SECTION

Sr.No.	**Radius (M)**	**Rectangular Section**		**Trapezoidal section**	
		Top	**Bottom**	**Top**	**Bottom**
1	50	-8.76	17.79	-8.84	18.91
2	75	-7.6	16.21	-8.51	17.33
3	100	-8.31	15.63	-8.4	16.73
4	125	-8.27	15.34	-8.35	16.44
5	0	-8.19	14.57	-8.27	15.69

It is observed that, as curvature increases the stresses in top and bottom of the section also increases. Trapezoidal cross-section possesses more stresses than rectangular cross-section under same radius of curvature.

F. Pre-stressing force

Table no. 4 shows the pre-stressing force required for rectangular and trapezoidal box girders under different radii of curvature to achieve zero tension condition.

TABLE V

PRE-STRESSING FORCE APPLIED TO EACH TENDON (KN)

Sr. No.	**Radius of curvature (m)**	**Rectangular Cross-Section**	**Trapezoidal Cross-section**
1	R= 50m	4550	4400
2	R=75m	4100	3900
3	R= 100m	3900	3800
4	R=125m	3800	3700
5	Straight	3600	3550

For rectangular cross-section 9% more pre-stressing force is required when radius changes from R=75m to R=50m while for trapezoidal cross-section 11% more pre-stressing force is required.

I. CONCLUSIONS

From the analysis results of rectangular and trapezoidal box girder under different radii of curvature following conclusions are drawn:

1. As curvature increases (radii of curvature decreases), torsion moment, longitudinal moment, support reactions, displacements, stresses are increases in both rectangular and trapezoidal box section.

2. For same radii of curvature maximum torsional moment in rectangular section is increased by 2% than trapezoidal section. This percentage of increment in torsion moment is increases by reducing radius of curvature.

3. Trapezoidal box section consist more support reaction, stresses and displacement as compared to rectangular box section.

4. Cross-section type does not make any significant change in case of longitudinal moments.

5. Rectangular box section required more pre-stressing force than trapezoidal box section to meet serviceability criteria under same loading conditions.

NOMENCLATURE

R	radius of curvature	m
Y top	distance of neutral axis from top of section	m
Y bot.	distance of neutral axis from bottom of section	m
I xx	moment of inertia about X axis	m^4
I yy	moment of inertia about Y axis	m^4
Z top	section modulus for top section	m^3
Z bot.	section modulus for bottom section	m^3

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