International Journal of Civil and Structural Engineering Research ISSN 2348-7607 (Online)
Vol. 3, Issue 2, pp: (1-10), Month: October 2015 - March 2016, Available at: www.researchpublish.com

Analysis and Design of Prestressed Concrete Box Girder by Finite Element Method (3 Cells & 1 Cell)

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Abstract: **The design of a highway bridge is critically dependent on standard norms of a particular region or country and criteria like loadings and support conditions. Naturally, the importance of highway bridges in a modern transportation system would imply a set of rigorous design specifications to ensure the safety, quality and overall cost of the project. This paper discusses the parametric study of two different cross-sections of box-girder for same loading conditions to find the most economical cross-section. The design standard of India, IRC was followed in design of Box-girder superstructures subjected to IRC class AA loading. Optimized Cross-sections was found by comparing the different design parameters. As result of this exercise it was found that bending moment and stresses for self-weight and superimposed dead load were different for different cross-section. The cross section with minimum value of bending moment requires less steel to counter the bending stresses. Less reinforcement leads to the most economical cross-section for box girder. The result shows the multi cell box girders are costlier as compare to the single cell box girder, when the loading and support condition were kept same for both the cross-section. Analysis is carried out using the MIDAS Civil Software which is based on finite element method of analysis.**

Keywords: **Pre-stressed Concrete, Box-girder, IRC loading.**

1. INTRODUCTION

For design of Highway and Railway Bridge superstructures there are many codes used around the world and most of the countries have their own code depending on the natural conditions and the surrounding environmental factors, such as the seismic effects, heavy rainfall, heavy snowfall, mountainous terrain, different types of vehicle used in country etc. Indian bridge engineers refer IRC (Indian Road Congress) standard for the structural design. In this study two box-girder cross-sections were designed with different cross section- i) Pre-stressed concrete box girder with three cells, ii) Pre-stressed concrete box girder with single cell. The design parameters were kept same for both of the cross-sections. Moving load as per IRC-6: 2000 were considered for both the cross-section and standard moving load IRC Class AA was applied. Comparison was done between the results of both the box-girder cross-sections.

Problem Statement: - Design a box girder for 2 lane national highway bridge, with following parameters:-

- Support condition:- simply supported
- Span length:- 30 m
- Width of carriageway:- 7.5m
- Width of foot path:- 1.25m
- Total width of segment:- 10m
- Moving load :- IRC class AA loading

2. THREE CELLS PRE-STRESSED CONCRETE BOX GIRDER

To achieve our goal first we model a three cells pre-stressed concrete box girder cross-section. Following are the various details of three cell box-girder cross-section.

1. Material Properties And Allowable Stress:

Concrete properties: Grade: M60

Tendon Properties:-

Pre-stressing Strand: ϕ15.2 mm (0.6"strand)

Yield Strength: f_{py} = 1.56906 X 10^6 kN/m^2

Ultimate Strength: f_{pu} = 1.86326 X 10^6 kN/m^2

Cross Sectional area of each tendon = 0.0037449 m^2

Modulus of Elasticity: Eps = 2 X 10^8 kN/m^2

Jacking Stress: f_{pj} = 0.7fpu = 1330 N/mm2

Curvature friction factor: μ = 0.3 /rad

Wobble friction factor: k = 0.0066 /m

Anchorage Slip: s = 6 mm (At the Beginning and at the End)

2. Cross Section Specification:

3 Cells Concrete Box-Girder with two traffic lanes

Vertical side walls

Top slab thickness = 300 mm

Bottom Slab thickness = 300 mm

External wall thickness = 300 mm

Internal Wall thickness = 300 mm

Span = 30m

Total width = 10m Road (Including 1.25m of foot path both side)

Width of Carriage way = 7.5m

Wearing coat = 80mm

Cross-sectional Area = 7.65 m^2

I_{xx} = 1.241 X 10^1 m^4

I_{yy} = 4.405 m^4

I_{zz} = 5.553 X 10^1 m^4

Center: y = 5 m

Center: z = 1.0633 m

Thickness of web (As per IRC: 18 – 2000):

The thickness of the web shall not be less than d/36 plus twice the clear cover to the reinforcement plus diameter of the duct hole where'd' is the overall depth of the box girder measured from the top of the deck slab to the bottom of the soffit or 200 mm plus the diameter of duct holes, whichever is greater.

Thickness of the web in model = 300 mm > permissible value (hence safe)

Thickness of Bottom Flange (As per IRC: 18 – 2000):

The thickness of the bottom flange of box girder shall be not less than 1/20th of the clear web spacing at the junction with bottom flange or 200 mm whichever is more.

Thickness of the bottom flange in model = 300 mm > permissible value (hence safe)

Thickness of Top Flange (As per IRC: 18 – 2000):

The minimum thickness of the deck slab including that at cantilever tips be 200 mm. For top and bottom flange having pre-stressing cables, the thickness of such flange shall not be less than 150 mm plus diameter of duct hole.

Thickness of the Top Flange in model = 300 mm > permissible value (hence safe)

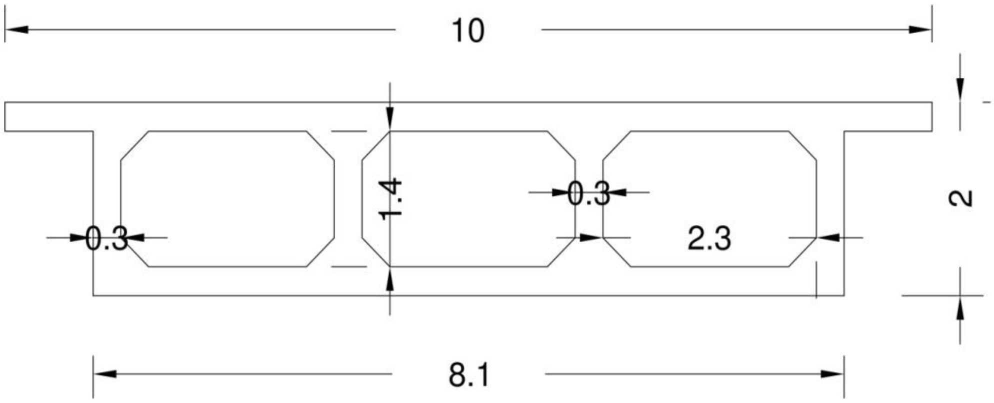

Fig.1 Cross-sectional details of 3 cells Concrete Box Girder (all dimension are in meter)

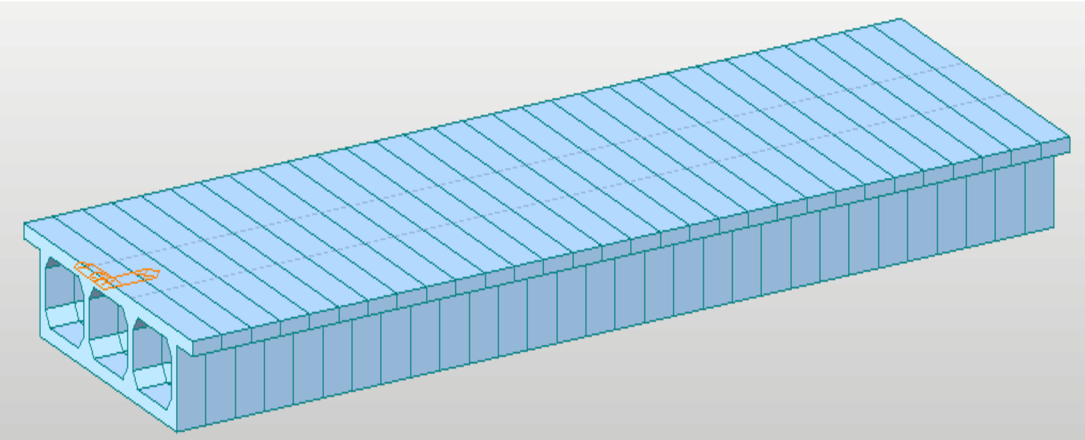

Fig.2 Perspective view of 3 cells Concrete Box Girder

3. Loading On Box Girder

The various type of loads, forces and stresses to be considered in the analysis and design of the various components of the bridge are given in IRC 6:2000 (Section II) But the common forces are considered to design the model are as follows:

The model is designed by considering IRC Class AA loading **(for complete detail refer IRC 6: 2000, Clause no 207.1, Page no. 10)**

4. Calculation of Ultimate Strength (As per IRC:18-2000):

i) Failure by yield of steel (under-reinforced section)

$$\mathbf{M_{ult} = 0.9 d_b A_s F_p}$$

ii) Failure by crushing concrete

$$\mathbf{M_{ult} = 0.176\ b\ d_b\ 2f_{ck}}$$

Ultimate Moment of Resistance (Analysis Result):

- **Positive Moment**

Check for moment of resistance, $(M_{Ed} \leq M_{Rd})$

Designed value of the applied internal bending moment $M_{Ed} =$ 18375.546kN.m

(From analysis of the model)

Designed Moment of resistance, M_{Rd}

$M_{Rd} = F_c . a_c + F_s . a_s + \sum(F_{pi} . a_{pi})$ = 145662.395kN.m, $(M_{Ed} \leq M_{Rd})$

Hence, Structure is safe.

- **Negative Moment**

Check for moment of resistance, $(M_{Ed} \leq M_{Rd})$

Designed value of the applied internal bending moment $M_{Ed} =$ 0.00kN.m

(From analysis of the model)

Designed Moment of resistance, M_{Rd}

$M_{Rd} = F_c . a_c + F_s . a_s + \sum(F_{pi} . a_{pi})$ = 164050.427kN.m, $(M_{Ed} \leq M_{Rd})$

Hence, Structure is safe.

Shear reinforcement (As per IRC 18: 2000 Clause 14.1.4):

When *V*, the shear force due to ultimate load is less than $V_c/2$ then no shear reinforcement need to be provided. Minimum shear reinforcement shall be provided when *V* is greater than $V_c/2$ *in* the form of links

$$\frac{A_{sv}}{S_v} X \frac{0.87F_{yv}}{b} = 0.4MP$$

When shear force *V*, due to ultimate load exceeds V_c, the shear reinforcement provided shall be such that

$$\frac{A_{sv}}{S_v} = \frac{V - V_c}{0.87fy_v d_t}$$

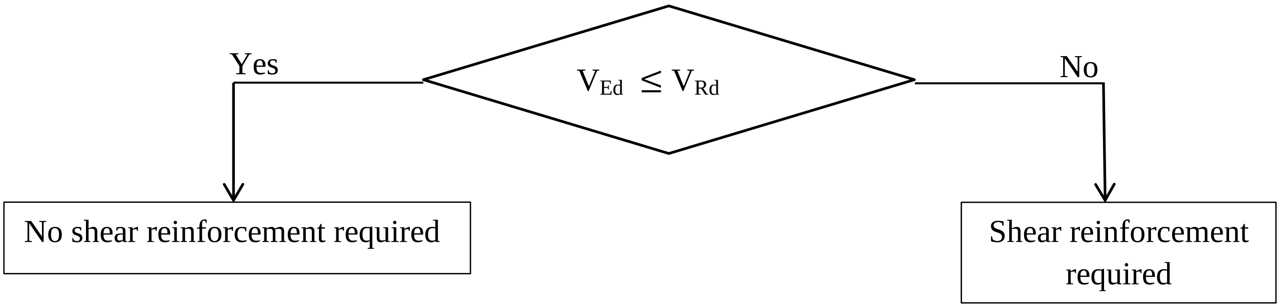

Fig.3 Flow-chart for shear reinforcement

Designed value of the applied internal shear force V_{Ed} = 319.454kN

Designed shear force,

V_{Rd} = (I・bw / S)・√ ((fctd)2 + αl・σcp・fctd) ≥ (vmin + k1・σcp)・bw・dp

= 5234.389kN

$V_{Ed} < V_{Rd}$

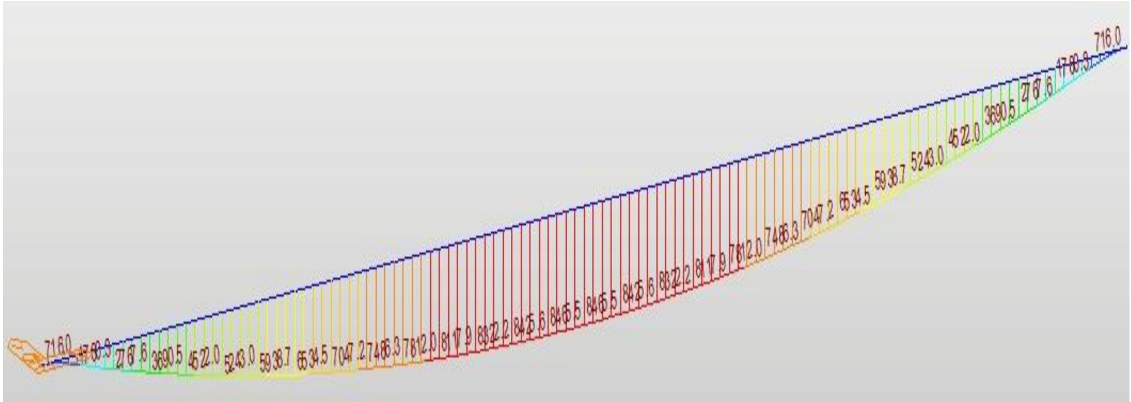

Fig.4 Beam Diagram 3 cells Concrete Box Girder

Maximum Bending moment at element 15 i.e. Middle of the section = **8465.5 kN.m**

Maximum Deflection at element 15 = 7.862 mm

Total consumption of concrete for 3 cell box girder = **229.5 m^3**

Steel Consumption for 3 cell box girder = **24.922 MT**

Total Consumption of Strand for 3 cell girder = **360.496 m**

3. SINGLE CELL PRE-STRESSED CONCRETE BOX GIRDER

Now we model a single cell pre-stressed concrete box girder cross-section. Following are the various details of single cell box-girder cross-section.

1. Material Properties And Allowable Stress:

Concrete properties: Grade: M60

Tendon Properties:

Pre-stressing Strand: ϕ15.2 mm (0.6”strand)

Yield Strength: f_{py} = 1.56906 X 10^6 kN/m^2

Ultimate Strength: f_{pu} = 1.86326 X 10^6 kN/m^2

Cross Sectional area of each tendon = 0.0037449 m^2

Modulus of Elasticity: Eps = 2 X 10^8 kN/m^2

Jacking Stress: f_{pj} = 0.7fpu = 1330 N/mm2

Curvature friction factor: μ = 0.3 /rad

Wobble friction factor: k = 0.0066 /m

Anchorage Slip: s = 6 mm (At the Beginning and at the End)

2. Cross Section Specification:

1 Cell Concrete Box-Girder with two traffic lanes

Trapezoidal Shape

Top slab thickness (Tapered) = at the center 300 mm & at corner 200 mm

Bottom Slab thickness = 200 mm

External wall thickness = 300 mm

Span = 30m

Total width = 10m Road (Including 1.25m of foot path both side)

Width of Carriage way = 7.5m

Wearing coat = 80mm

Cross-sectional Area = 4.620 m^2

I_{xx} = 5.199 X 10^1 m^4

I_{yy} = 2.353 m^4

I_{zz} = 2.652 X 10^1 m^4

Center: y = 5 m

Center: z = 1.355 m

Thickness of web (As per IRC: 18 – 2000):

The thickness of the web shall not be less than d/36 plus twice the clear cover to the reinforcement plus diameter of the duct hole where'd' is the overall depth of the box girder measured from the top of the deck slab to the bottom of the soffit or 200 mm plus the diameter of duct holes, whichever is greater.

Thickness of the web in model = 300 mm > permissible value (hence safe)

Thickness of Bottom Flange (As per IRC: 18 – 2000):

The thickness of the bottom flange of box girder shall be not less than 1/20th of the clear web spacing at the junction with bottom flange or 200 mm whichever is more.

Thickness of the bottom flange in model = 300 mm > permissible value (hence safe)

Thickness of Top Flange (As per IRC: 18 – 2000):

The minimum thickness of the deck slab including that at cantilever tips be 200 mm. For top and bottom flange having pre-stressing cables, the thickness of such flange shall not be less than 150 mm plus diameter of duct hole.

Thickness of the Top Flange in model = 300 mm > permissible value (hence safe)

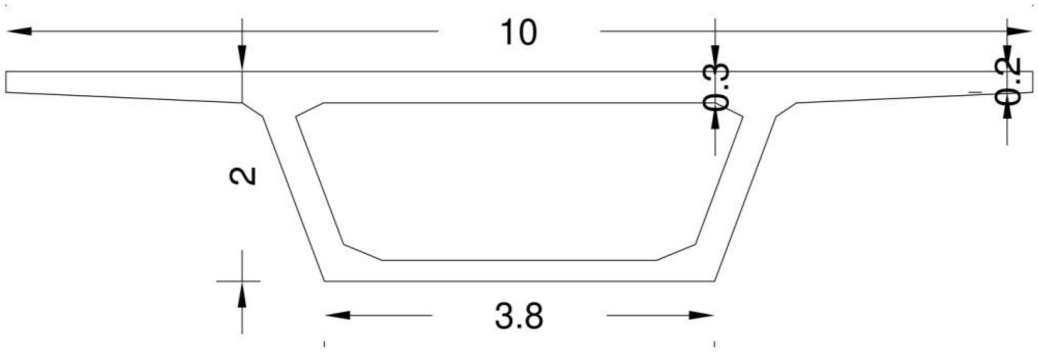

Fig.5 Cross-sectional details of Single cells Concrete Box Girder (all dimensions are in meter)

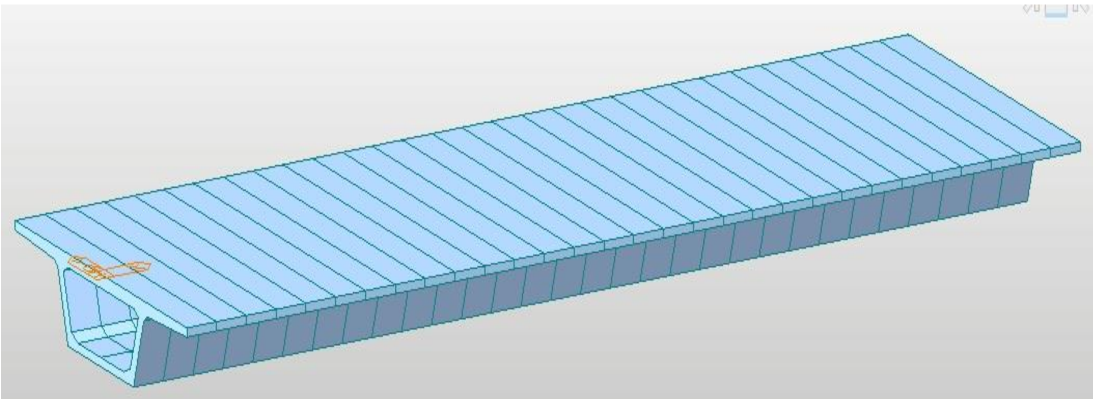

Fig.6 Perspective view of Single cells Concrete Box Girder

3. Loading On Box Girder:

The various type of loads, forces and stresses to be considered in the analysis and design of the various components of the bridge are given in IRC 6:2000 (Section II) But the common forces are considered to design the model are as follows:

The model is designed by considering IRC Class AA loading **(for complete detail refer IRC 6: 2000, Clause no 207.1, Page no. 10)**

Calculation of Ultimate Strength (As per IRC: 18-2000, Clause no. 13):

i) Failure by yield of steel (under reinforced section)

$\mathbf{M_{ult} = 0.9 d_b A_s F_p}$

ii) Failure by crushing concrete

$\mathbf{M_{ult} = 0.176\ b\ d_b\ 2 f_{ck}}$

4. Ultimate Moment of Resistance (Analysis Result):

➢ **Positive Moment**

Check for moment of resistance, $(M_{Ed} \leq M_{Rd})$

Designed value of the applied internal bending moment $M_{Ed} =$ 14893.728kN.m

(From analysis of the model)

Designed Moment of resistance, M_{Rd}

$M_{Rd} = F_c . a_c + F_s . a_s + \sum(F_{pi} . a_{pi})$ = 85812.438kN.m, $(M_{Ed} \leq M_{Rd})$

Hence, Structure is safe.

➢ **Negative Moment**

Check for moment of resistance, $(M_{Ed} \leq M_{Rd})$

Designed value of the applied internal bending moment $M_{Ed} =$ 0.00kN.m

(From analysis of the model)

Designed Moment of resistance, M_{Rd}

$M_{Rd} = F_c . a_c + F_s . a_s + \sum(F_{pi} . a_{pi})$ = 103656.221kN.m, $(M_{Ed} \leq M_{Rd})$

Hence, Structure is safe.

Shear reinforcement (As per IRC 18: 2000 Clause 14.1.4)

When ($V= V_{Ed}$), the shear force due to ultimate load is less than ($V_c/2 = V_{Rd}$) then no shear reinforcement need to be provided. Minimum shear reinforcement shall be provided when ($V= V_{Ed}$) is greater than ($V_c/2 = V_{Rd}$) *in* the form of links

$$\frac{A_{sv}}{S_v} X \frac{0.87 F_{yv}}{b} = 0.4 MP$$

When shear force ($V= V_{Ed}$), due to ultimate load exceeds V_c, the shear reinforcement provided shall be such that

$$\frac{A_{sv}}{S_v} = \frac{V - V_c}{0.87 f y_v d_t}$$

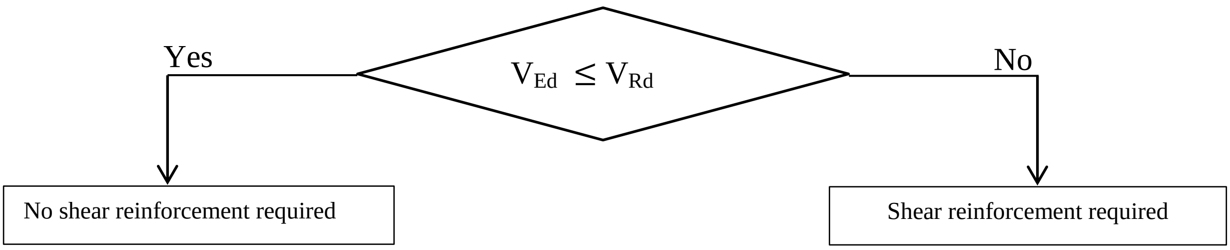

Fig.7 Flow-chart for shear reinforcement

Designed value of the applied internal shear force V_{Ed} = 600.456kN

Designed shear force,

$V_{Rd} = (I \cdot bw / S) \cdot \sqrt{((fctd)2 + \alpha l \cdot \sigma cp \cdot fctd\ )} \geq (vmin + k1 \cdot \sigma cp) \cdot bw \cdot dp$

= 4668.975kN

$V_{Ed} < V_{Rd}$

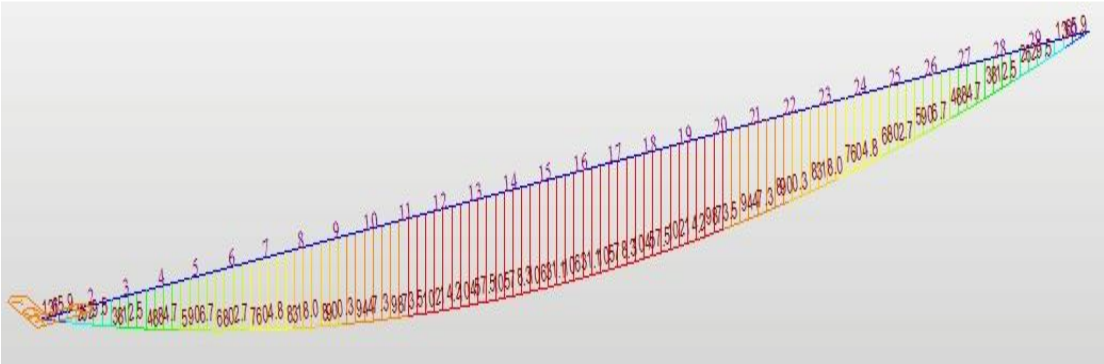

Fig.8 Beam Diagram Single cells Concrete Box Girder

Maximum Bending moment at element 15 i.e. Middle of the section = **6276.96 kN.m**

Maximum Deflection at element 15 = 7.189 mm

Total consumption of concrete for Single cell box girder = 138.6 m^3

Steel Consumption for Single cell box girder = 18.167 MT

Total Consumption of Strand for Single cell girder = 180.285 m

4. RESULTS & DISCUSSION

Table: 1 Comparison between the Results of 3 cells & single cell Box girder

Sr. No.	Parameters	3 cells	1 Cell
1	Bending Moment	8465.5kN.m	6276.96kN.m
2	Maximum Deflection	7.862 mm	7.189 mm
3	Concrete Consumption	229.5 m^3	138.6 m^3
4	Steel Consumption	24.992 MT	18.167 MT
5	Strand Consumption	360.496 m	180.285 m

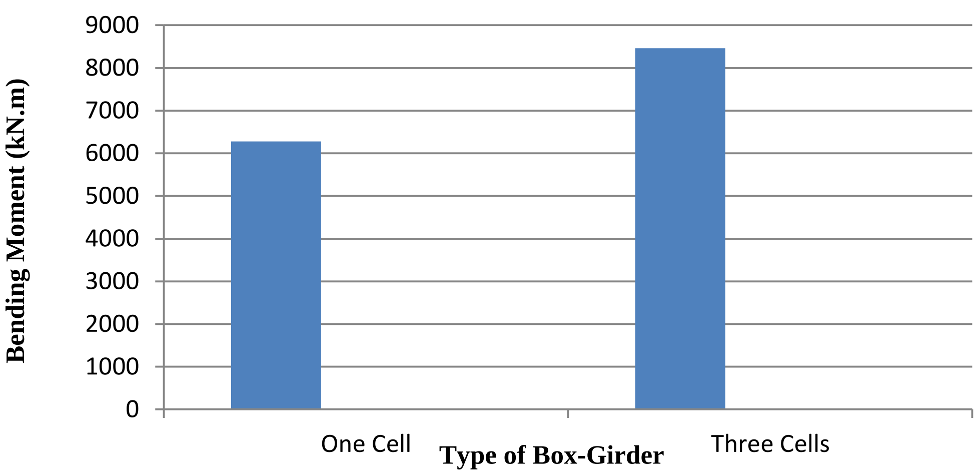

Fig.9 Graph showing comparison between bending moment and types of Box Girder

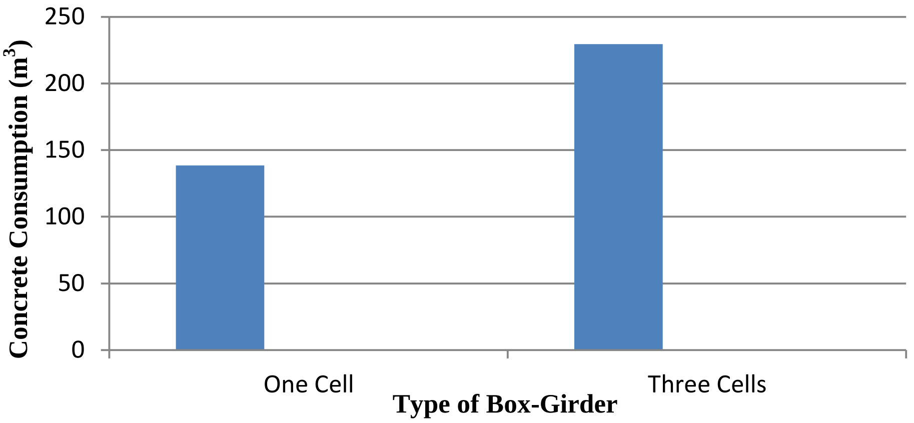

Fig.10 Graph Showing Comparison between Concrete Consumption and Types of Box-Girder

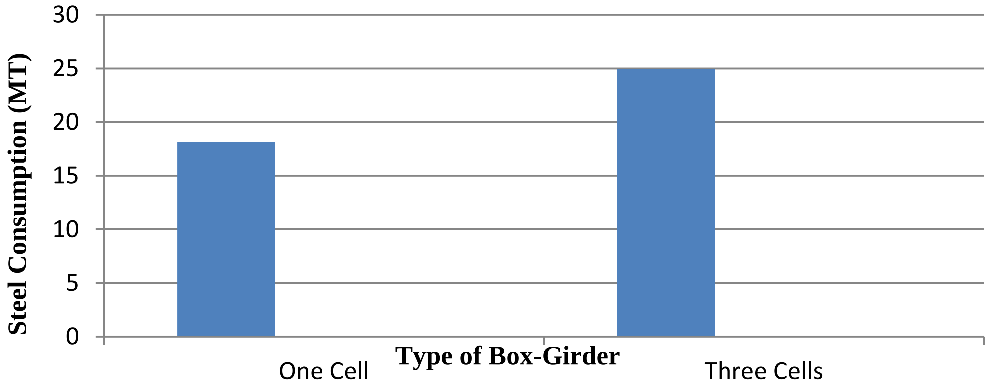

Fig.11 Graph Showing Comparison between Steel Consumption and Types of Box-Girder

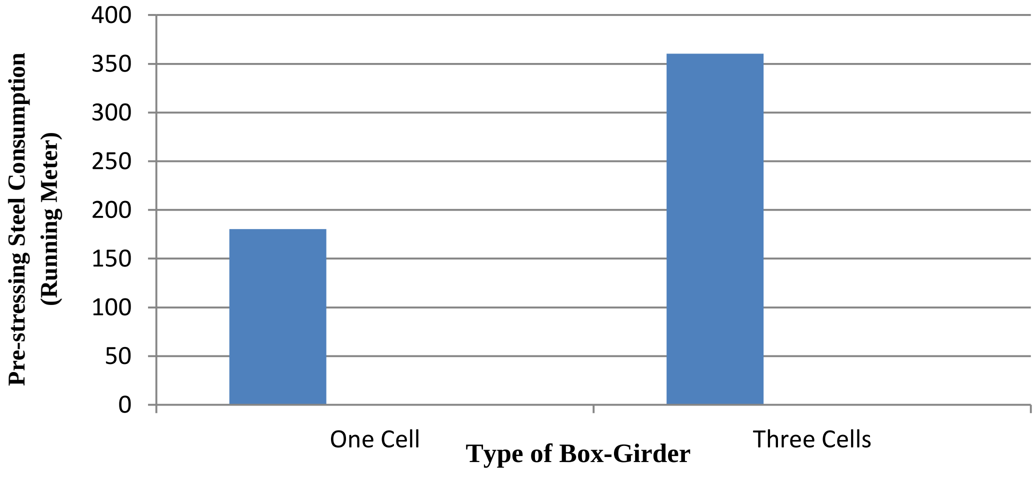

Fig.12 Graph Showing Comparison between Pre-stressing Steel Consumption and Types of Box-Girder

By comparison of the results for consumption of concrete, steel and pre-stressing strands are less for single cell box girder. Shown in the table-1 and graph is drawn with reference to the table.

5. CONCLUSION

A comparative study between three cell and single cell pre-stressed concrete box girder Cross-sections has been done. This study shows that the single cell pre-stressed concrete box girder is most suitable and economical cross-section for 2 lane Indian national highway bridges.

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