A

Dissertation Report on

Parametric Study of Structural Response of Post Tensioned Box Girder Skewed Bridge

Submitted

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in

Civil - Structural Engineering

by

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CERTIFICATE

This is to certify that, Mr.Kulkarni Pranav Mohan (Roll No-1724001) has successfully completed the dissertation work and submitted dissertation report on "Parametric Study of Structural Response of Post Tensioned Box Girder Skewed Bridge" for the partial fulfillment of the requirement for the degree of Master of Technology in structural engineering from the Department of civil engineering, as per the rules and regulations of Rajarambapu Institute of Technology, Rajaramnagar, Dist: Sangli.

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DECLARATION

I declare that this report reflects my thoughts about the subject in my own words. I have sufficiently cited and referenced the original sources, referred or considered in this work. I have not misrepresented or fabricated or falsified any idea/data/fact/source in this my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute.

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ABSTRACT

Bridges are essential and hierarchical structures and facility required for the activity of a general public. Bridges are a key element especially on the planets' urban communities and towns where either conduits or natural barriers counteract transport to the opposite side. Due to geometric and space constrains, when the crossing intersects with an angle other than 90°, then skewed bridges have proved to be useful. In this paper, analysis of a single cell post-tensioned rectangular, trapezoidal box girder and double cell post-tensioned rectangular and trapezoidal box girder bridge is done for varying skew angles (0° to 60°, with 100 intervals) using finite element-based software (CSI Bridge). Models of finite element for both rectangular and trapezoidal box girder bridges were done, with varying skew angle and keeping material properties, boundary conditions constant. All the models were analyzed for self-weight and vehicular load (IRC Class A loading) as per IRC 6:2016. Parameters such as torsional moment, longitudinal moment, displacements and stresses were studied for developed models and compared for both cross sections of box girder. Analysis show significant difference in the values of torsional moment, displacements and stresses. Rectangular box girder with double cell shows better performance when subjected to applied loading

Keywords: prestress concrete, box-girder, skew angle, torsion, finite element analysis, rectangular section, trapezoidal section.

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NOMENCLATURE

Ixx	Moment of inertia ar5round X-axix
kN	kilo-Newton
m	metre
Pa	Pascal
w/	with
Y	Depth of neutral axis
Z	Section Modulus

ABBREVIATIONS

FEM	Finite Element Method
FEA	Finite Element Analysis
CSi	Computer & Structure Inc.
3D	3-Dimensional
fck	Characteristis Strength of Concrete
Ec	Young's Modulus of Concrete
IRC	Indian Road Congress

Chapter 1

Introduction

1.1 General

Bridges are a very important component of day to day transport. People daily use flyovers, underpasses, small bridges over a canal or also a big bridge over a river. Bridges, along with making our transport easy and quick, also contribute in making the city/town beautiful. Many bridges are point of attraction in major cities across the world.

There are variety of bridges, some are very simple and some are too much complex viz. skew bridges. When the crossing intersects with an angle other than 90°, due to geometric and space constrains, then skewed bridges have proved to be useful. Thus, as a structural engineer, one should have a thorough knowledge about the factors affecting the design criteria of skewed bridge. Figure 1.1 shows right bridge model and Figure 1.2 shows skewed bridge model.

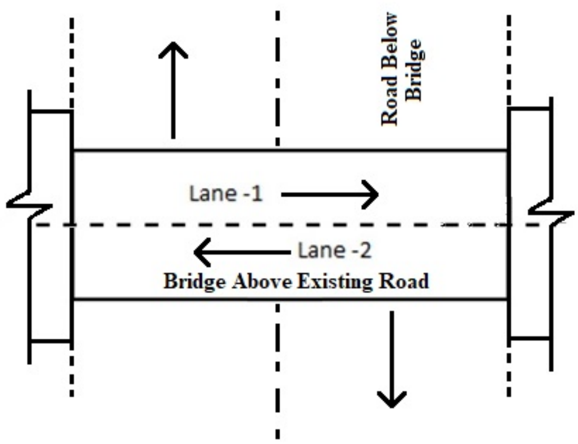

Figure 1.1: Plan of right bridge model

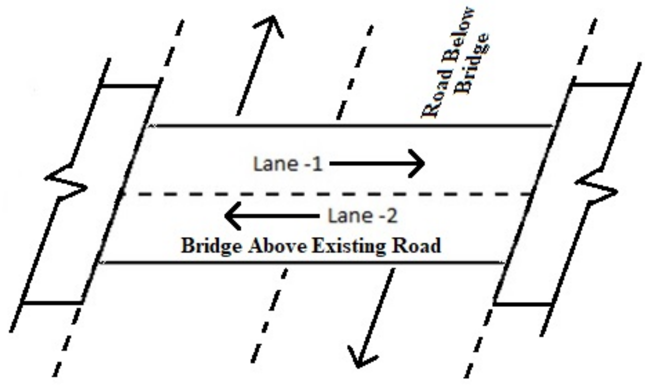

Figure 1.2: Plan of skewed bridge model

Because of skew angle induce in bridge the structural performance is highly affected, as torsional moment is generated [1]. Bridges with small skew angles can be designed as right bridges [2]. But large skew angle in bridges requires special attention.

The present study focuses on the parametric study of prestressed concrete box girder bridges with various skew angles.

1.1.1 General Behaviour of Box Girder

Generally, in right bridges load are transferred equally to the supports, but in the case of skewed girder bridge the behaviour is altered. The loads have tendency to take shortest path to reach the support, thus forces concentrate at obtuse corner of the deck and acute corner receive less reaction. Figure 1.3 shows the path taken by the load in the case of skew girder.

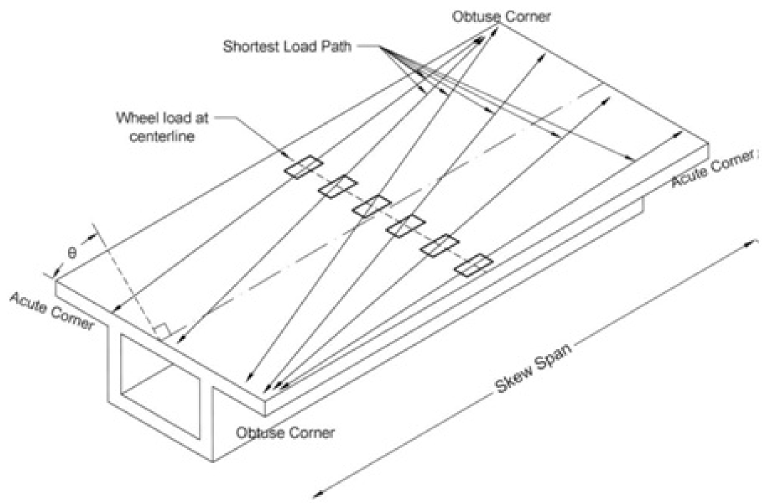

Figure 1.3: Load Path of Skewed Bridge

Courtesy - Internet Source (https://www.google.com/imgres?imgurl=x-raw-image)

According to previous researches on this topic, it is understood that skew bridges are prone to more damage with respect to right bridges. Torsion in generated due to presence of skew angle, in the girder. We know that box girder has good torsional rigidity, thus only box girders are considered in this work.

1.2 Outline of Report

The dissertation report is divided into following chapters. These chapters describe the different work conducted for study.

Chapter 1: This chapter is an introduction which consists of basic information regarding box girder bridges and its structural behaviour.

Chapter 2: In this chapter literature regarding box girder bridges and finite element analysis of box girder bridges under different loadings. Also, research gap, objectives of studyand methodology included in this chapter.

Chapter 3: This chapter includes brief introduction of finite element method and validation of CSi Bridgesoftware using problem on box girder bridges from "Prestressed concrete" book by N Krishna Raju.

Chapter 4: This chapter includes details of cross-sectional properties, material properties, boundary conditions and loading conditions are discussed.

Chapter 5: In this chapter all the results obtained after analysis of all the finite element models in software are discussed using tables and graphs.

Chapter 6: This chapter includes conclusions after analysing different box girder models.

1.3 Closure

In this chapter general introduction about the box girder is given. Also the general structural behaviour of box girder is discussed. Also, this chapter includes outline of dissertation report.

Chapter 2

Literature Review

2.1 General

In this chapter, present studies and practices adopted by many researchers are reviewed. Research gap obtained after reviewing the studies is also discussed. Objectives of the present study are listed. Methodology adopted is also discussed.

2.2 Review of Previous Studies:

Demeke B. Ashebo et al. (2007), "Evaluation of dynamic loads on a skew box girder continuous bridge Part I: Field test and modal analysis"

In this paper existing skew continuous box girder bridge was tested using three-axel heavy truck. Static and dynamic bending moment is observed. Relation between strain and bending moments is determined. Effect of skewness on static and dynamic behaviour of the bridge as well as load distribution in the transverse direction is obtained from experimental and theoretical modal analysis. It is found that the influence of skew angle of range 0^0-30^0, in both static and dynamic behaviour of the bridge, is very small. Skew angle of this bridge is 27^0 and it behaves like right bridge. This belongs to the low width to span ratio of the bridge. This paper suggests designers that during analysing a skew bridge, considering the width to span ratio of the bridge is important to determine the extent of the influence of the skew on the structural behaviour of the bridge.

X. H. He et al. (2012), "Skewed concrete box girder bridge static and dynamic testing and analysis"

In this paper testing and analysis of 1:8 scale model of actual high-speed railway bridge between Beijing and Shanghai is done. The bridge is three span continuous prestressed concrete box girder having 45^0 skew. Static and dynamic testing is done. Displacement, stresses, natural frequency, mode shape and damping ratio were obtained experimentally and compared to results obtained from finite element analyses. This paper focuses on the performance of structures at service load levels for which response remains linearly elastic. It is concluded that, as skew angle increases, vertical bending moment and deformation decrease, but torsional stresses increase. Skew angles more than 45^0 are not recommended for skewed bridges.

Nabil Grace et al. (2011), "Flexural behavior of side-by-side box-beam bridge: A comparative study"

This paper compares identical box-beam bridge models reinforced and prestressed with different types of reinforcement. Two half scaled model with 30^0 skew are prepared. One is reinforced with carbon fiber composite cable and other is reinforced with conventional prestressed steel strands. Four box beams placed adjacent to one another and connected by means of transverse post tensioning forces at transverse diaphragms, shear keys and deck slabs. Similar behavior is observed of load distribution and strain distribution at both uncracked and cracked stages. Flexural response is also similar in both cases. Deck slab crushing failure occurred in CFCC reinforced model, while yielding of steel strands occurred in conventional model. Ultimate strength of CFCC reinforced model is greater than conventional model.

Kang Jun-tao et al. (2005), "A new method on resolving the rotation in the plane of skew bridge"

In plane rotation due to skewness of bridge is a common phenomenon. Conventional methods like providing lateral bearing or to setup pins doesn't give satisfactory results. In this paper slant-leg rigid frames with 60^0 skew and without abutment, supporting continuous prestressed concrete box-girder bridge is analysed. The lateral horizontal displacement and rotation of bridge at supports are studied. Three causes resulting rotation in the bridge is suggested viz. i) Longitudinal brake forces and longitudinal seismic forces. ii) Lateral wind force and lateral seismic force. iii) Temperature variation, concrete shrinkage, creep and prestressing force etc. It is concluded that slant-leg rigid frame without abutment eliminates in plane rotation of skew bridge.

Mohamed Soliman et al. (2000), "Warping displacement of skew reinforced concrete box girder bridge"

In this paper influence of skew angle on warping displacement and the vertical reaction of skew box girder bridges is observed. A non-linear finite element program is developed for determination of reaction and warping displacement. Three models with exactly same dimension and reinforcement were analysed for different skew angle, viz. 0^0, 25^0, 45^0. Warping displacement are observed to be less at acute corner and more at obtuse corner. The vertical reaction is greater at obtuse corner as compared to acute corner. The vertical reaction also increases with increase in skew angle.

S. B. Singh & Tanmay Gupta (2017), "Linear response of pre-stressed concrete skewed box beam bridge girder using CFRP tendons"

In this paper, impact of skewness and reinforcement levels on deflection of bridge girder are studied. Numerical modelling of bridge has been verified with results of a research paper. The software used for analysis is CsiBridge. It is observed that, deflection decreases with increase in skew angle. At 60^0 skew angle with tendon area range of 97 to 113mm^2, minimum deflection was observed. Torsion increases with increase in skew angle. It is concluded that, to reduce the deflection of bridges with greater skew angles, CFRP tendons would be more effective than steel tendons.

2.3 Research Gap

After carrying out study on the recent literature for prestressed box girder bridge, by considering parameter skewness of bridge, the gap observed is discussed in detail below:

1. Effect of different cross-sectional dimension of the skewed box girder on its structural performance is not discussed yet.
2. Effect of different shapes i.e. trapezoidal, rectangular, circular used for skewed box girder bridge and its structural response for static loading is yet to be discussed.

2.4 Objectives

Following are the objectives of present dissertation work:

1. To analyse the post tensioned box girder bridge by varying skew angle and cross section.
2. To interpret the behaviour of post tensioned box girder skewed bridge.
3. To develop guidelines for selection of box girder cross section based on results derived from the analysis.

2.5 Closure

This chapter reviewed the literature regarding box girder bridges. Also, this chapter covers research related to skewed bridges. From the literature review it is observed that most researchers use finite element analysis method for analysis of bridges.

Chapter 3

Methodology Adopted

3.1 General

In this chapter methodology adopted for achieving the objectives of this project work is discussed. It is necessary to complete following steps to reach the objectives of the research work.

3.2 Methodology adopted

1. **Collecting literature on skew bridge and decide outline of project work:**
   From national and international journals, web source, text books, reference books, Indian Standard provision codes and Indian Road Congress codes for analysis and design of proposed work and record data from organization to get acquainted with past researches are collected.

2. **Establishing 3D model of prestressed concrete skewed box girder bridge in finite element software:**
   Preparation of 3D bridge model with data from a reference book is done to validated the software model. An approach is finalised so that all further modelling is done with the validated modelling steps.

3. **Modelling prestressed concrete box girder bridges with different skew angles i.e. 0^0 to 60^0 and varying cross section:**
   Preparation of single cell and double cell rectangular and trapezoidal cross-sectional models for varying skew angle from 0^0 to 60^0, with 10^0 intervals,

using FEM based CSi Bridge software.

4. **Analysing and compile the results obtained:**
   Analysis is carried out for all the skew angle models with single cell and double cell rectangular and trapezoidal cross-sectional models and results are obtained.

5. **Derive the conclusion as per results:**
   Conclusions are discussion based on comparative results obtained from analysis.

3.3 Methods of analysis

Complex bridge design needs to identify the internal forces within the bridge which are generated by the applied loading and how the bridge material will behave structurally. Analysing the stresses acting in the bridge elements is the aim of the analysis of such structures and to verify that the bridge material properties have the required stiffness and strength. Following are some of the methods which are used for analysis of box girder:

1. Grillage analogy Method
2. Finite strip method
3. Finite element method

The method of analysis adopted in this work is finite element method.

3.4 Finite element method

The Finite Element Method (FEM) is based on numerical technique. In this method, whole structure is divided into small parts which is called as elements. All elements are considered to be connected at nodes. Finite element method consists different type of elements such as beam element, plate element, shell element and solid element. Each element contains material and geometrical properties. The material properties inside an element are assumed to be constant.

To analyse any structure/domain first discretization is carried out, then stiffness matrix for each element is prepared. Also, nodal load vector for each element is prepared. All element matrices are assembled in single matrix as per there orientation and connectivity to each other called as global stiffness matrix. The equation of equilibrium is used to solve this global stiffness matrix and find out nodal displacement of each element. These obtained displacement results are back substituted to find out stresses and forces in the structure. The ability to solve any type of loading and boundary condition problem makes finite element analysis more versatile than other type of method of analysis.

3.5 Closure

This chapter includes brief introductory part of various steps adopted to achieve objectives of the study. Also, brief introductory part of methods of analysis of bridge superstructures. Finite element method of analysis is explained in this chapter. Chapter 4 includes validation of software results.

Chapter 4

Validation of Software Results

4.1 General

To study the actual behaviour of any structure it is required to determine the basic properties of that structure like reactions, displacements, stresses etc. and these properties can be determined by the analytical methods. In this chapter, for validation of software results, a problem from "Prestressed Concrete" book by N Krishna Raju is modelled and analysed in finite element software i.e. CSi Bridge.

4.2 Validation of Finite Element Model

For validation, an example of prestressed box girder from the book on Prestressed concrete by N Krishna Raju was modelled and analysed in CSi Bridge software. CSi Bridge is a finite element software specifically used for analysis and design of all types of bridges. Fig. 4.1 shows the details of cross section of the multi cell box girder. The bridge has two continuous spans of 50m each. Width of the road way is 7.5m with footpaths of width 1.25 on either side of road. Thickness of top and bottom slab is 300mm. It is a multicell box girder with cell dimensions of 2m wide by 2m deep. Material properties of girder are given as follows.

- Grade of Concrete = M60
- Density of Concrete = 24 kN/m^3

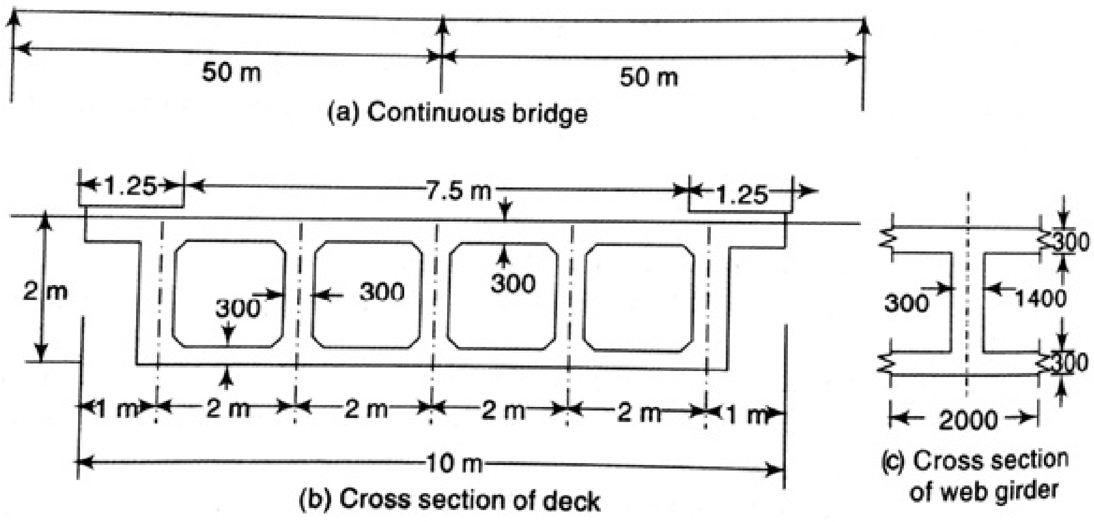

Figure 4.1: Cross-section of Box Girder

4.3 3D Model of Bridge

Figure 4.2 shows 3D Model of 2 Span Box Girder Bridge.

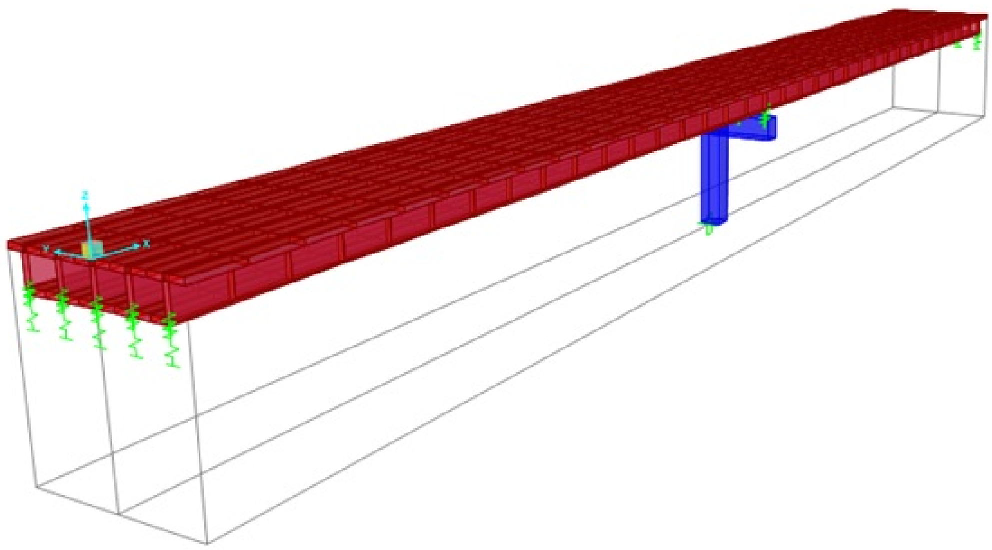

Figure 4.2: 3D Model of 2 Span Box Girder Bridge

The maximum longitudinal moment generated due to dead load, live load and wearing coat in box section model, are compared with the values calculated in the book Prestressed concrete by n Krishna Raju. The results are shown in Table 4.1 with % error. Similar approach is used for modelling of box girder bridges throughout this project.

Table 4.1: Comparison of Longitudinal Moment

Location	Prestressed Concrete by N Krishna Raju	Present Study	% Error	Unit
Mid-span section	11931	11951	0.167	kN-m
Mid-support section	17419	16662	-4.347	kN-m

4.4 Closure

In this chapter above validation was done by modelling a solved problem from the book "Prestressed concrete" by N Krishna Raju, in CSi bridge software. Longitudinal moment generated in the model and from the problem is compared, the percentage difference of the results are within 5%.

Chapter 5

Modelling and Analysis

5.1 General

This chapter deals with modelling details of box girder e.g. cross-section details, material properties, boundary conditions and loading condition etc. Steps for modelling of bridge girder in the software is also discussed in this chapter.

5.2 Properties and Support Condition

The analysis is carried out for rectangular and trapezoidal cross-sections with single cell and double cell with varying skew angle.The material properties and boundary condition are kept constant for all models. The span of bridge is 40m and width is 9.75m.

5.2.1 Material Properties

The material properties used for models are given below,

Characteristic Strength of concrete (fck) -	40 MPa
Young's Modulus of concrete (Ec) -	$5000\sqrt{40}$MPa
Density of Concrete -	25 kN/m^3

5.2.2 Cross-Section Properties

The dimensions of single cell and double cell of rectangular and trapezoidal box girder are finalised as per IRC 18:2000 (Design Criteria for Pre-stressed Concrete Road Bridges). The details of cross sections are given in Table 5.1. Diagrams for typical cross section of single cell and double cell of rectangular and trapezoidal girder are shown in Figure 5.1, 5.2, 5.3 and 5.4.

Table 5.1: Details of Cross-section Box Girder

Sr. No.	**Property**	**Single cell Rectangular**	**Double cell Rectangular**	**Single cell Trapezoidal**	**Double cell Trapezoidal**
1	Area (A)	8.0 m^2	8.0 m^2	7.76 m^2	7.72 m^2
2	Y bottom	1.4457 m	1.4457 m	1.5005 m	1.502 m
3	I xx	6.00 m^4	6.00 m^4	5.4406 m^4	5.4273 m^4
4	Z top	6.289 m^3	6.289 m^3	6.0486 m^3	6.0447 m^3
5	Z bottom	4.152 m^3	4.152 m^3	3.6259 m^3	3.6137 m^3

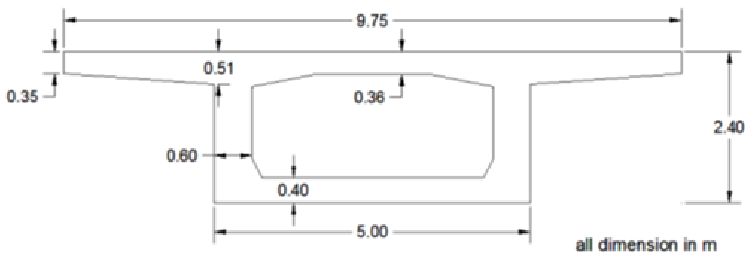

Figure 5.1: Typical Cross-Section of Single Cell Rectangular Box Girder

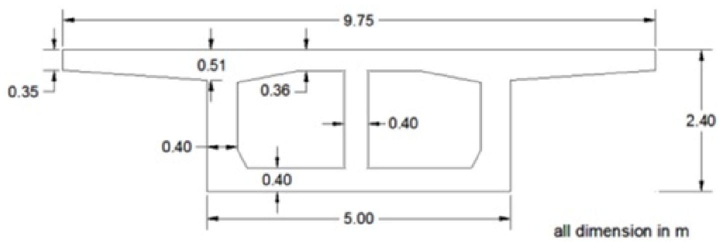

Figure 5.2: Typical Cross-Section of Double Cell Rectangular Box Girder

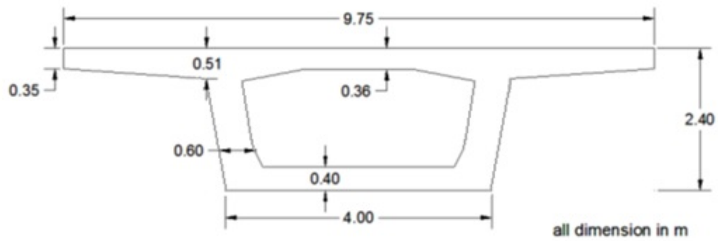

Figure 5.3: Typical Cross-Section of Single Cell Trapezoidal Box Girder

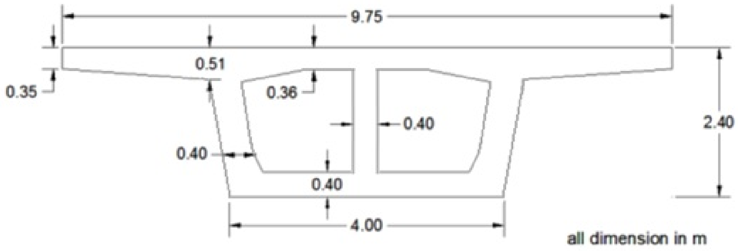

Figure 5.4: Typical Cross-Section of Double Cell Trapezoidal Box Girder

3D Models for single cell and double cell of rectangular and trapezoidal girder are shown in Figure 5.5, 5.6, 5.7 and 5.8.

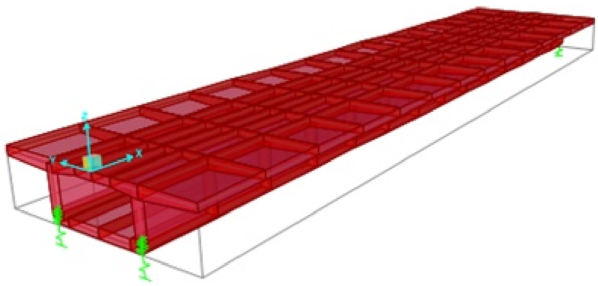

Figure 5.5: 3D model of Single Cell Rectangular Box Girder

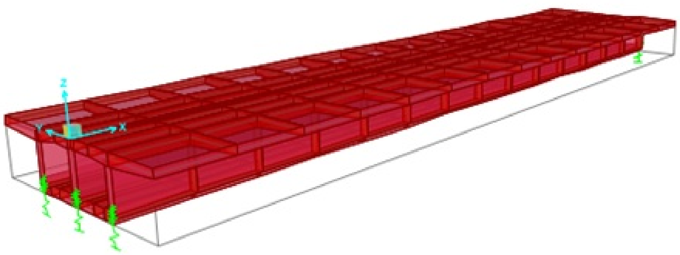

Figure 5.6: 3D model of Double Cell Rectangular Box Girder

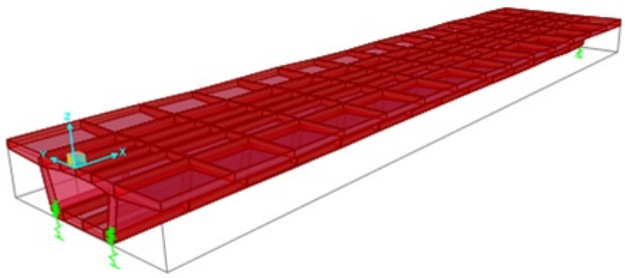

Figure 5.7: 3D model of Single Cell Trapezoidal Box Girder

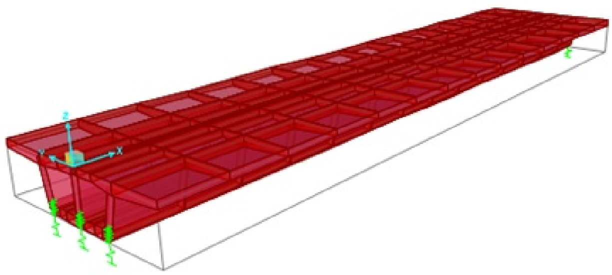

Figure 5.8: 3D model of Double Cell Trapezoidal Box Girder

5.2.3 Boundary Conditions

Bridge girders are supported at bottom of web. Box girder with two cells have six support bearings, with three support bearings on each end.Similarly, box girder with single cell have four support bearings, with two support bearing at each end. Girder at one end are simply supported and another end have roller support.Figure 5.9 girder boundary conditions 3D model.

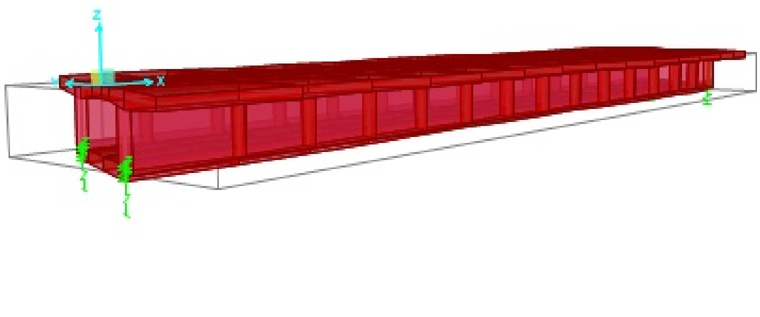

Figure 5.9: Girder Boundary Conditions

5.3 Skewness in Box Girder

The box girder with varying skewness are modelled.Material properties and boundary conditions are kept constant. For single cell and double cell of rectangular and trapezoidal cross-section seven bridge girder were modelled each. Bridges with skew angle 0° to 60° with 100 intervals were modelled in the software. Figure 5.10 and 5.11 shows the typical view of skewed, single cell and double cell of rectangular and trapezoidal box girder in CSi Bridge software.

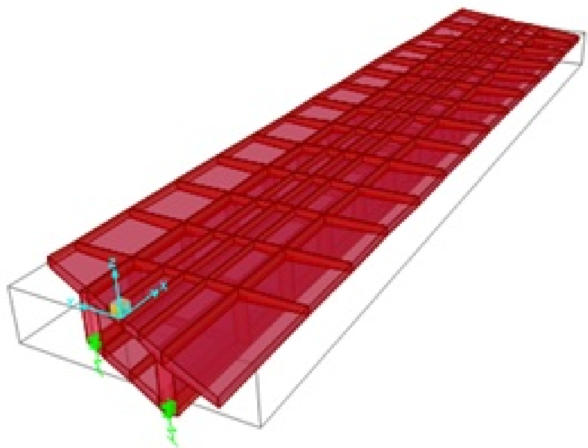

Figure 5.10: Typical Rectangular Skewed Model

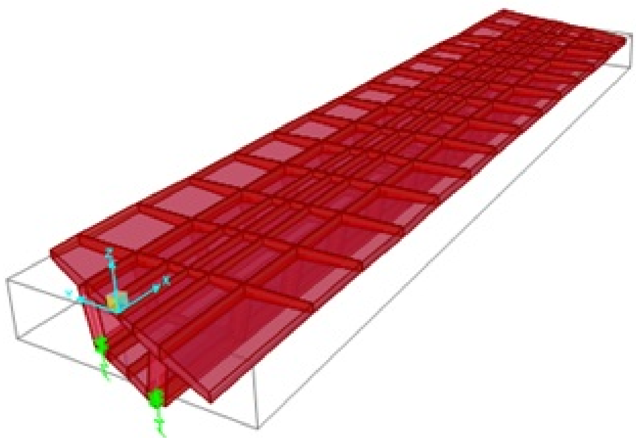

Figure 5.11: Typical Trapezoidal Skewed Model

5.4 Loading Conditions

In this study, the girder is subjected to dead load by considering the density of concrete i.e. 25 kN/m^3. Live load considered is as per IRC 6:2016.As perIRC 6:2016 for the width of bridge, live load to be applied on the girder is IRC class A on both the lanes. Earthquake load and Wind load is not considered for analysis. The dead load is calculated and applied automatically to model by the software.

- **IRC Class A loading**

IRC Class A type loading consist of wheeled load consisting of a truck with trailers of specified axle spacing and loads as shown in Figure 5.12. The heavy-duty truck with two trailers transmits loads from 8 axles. The magnitude of load is varying from minimum 27 kN to maximum 114 kN.

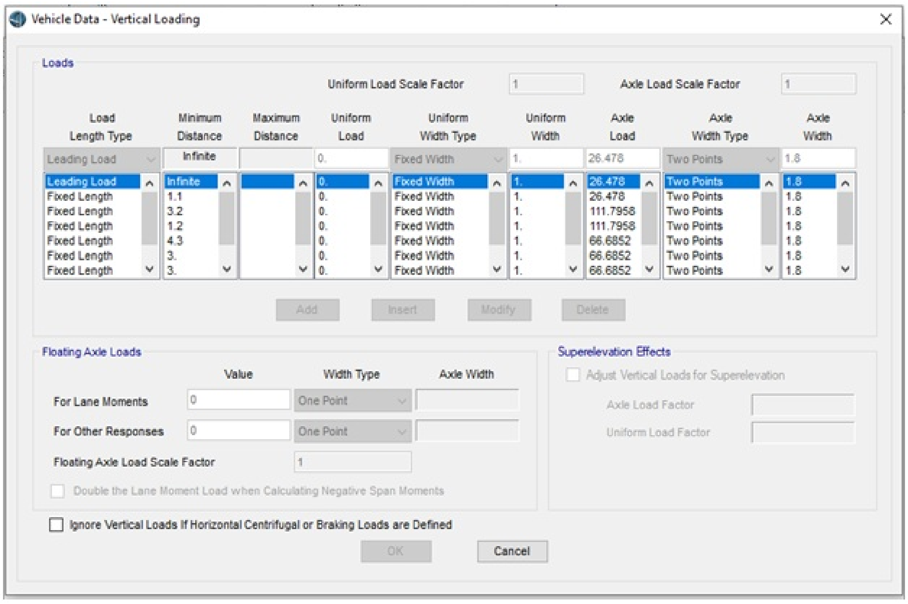

Figure 5.12: IRC Class A Loading Details

5.5 Analysis for Elimination of Skewness of Girder

Analysis of seven models for 0° to 60° skew angles is done by modelling the box girder with increased span for elimination of the skewness in box girder. Span of girder was increased by providing supports along line normal to center line of girder, at extreme ends of girder as shown in Figure 5.13. All other parameters such as material properties and boundary conditions are kept same for all models. Table 5.2 shows increased spans of girders.

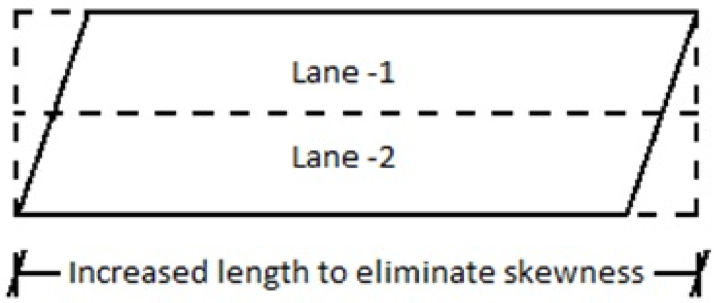

Figure 5.13: Skewed Bridge Converted to Right Bridge by Increasing Span

Table 5.2: Increased Spans of Girders (m)

Sr. No.	**For Skew Angle**	**Increased Span**
1	0	40
2	10	41.76
3	20	43.64
4	30	45.77
5	40	48.39
6	50	51.92
7	60	57.32

5.6 Analysis of girder with 40m wide road below

It can be observed that as the skew angle increases, the width of road below the girder decreases. So to keep the width of road, below the girder, constant, analysis of girder models for 0° to 60° skew angles with 40m spacing between the support was done. Span of bridge girder was increased to provide 40m spacing between supports as shown in Figure 5.14. Increased spans are listed in Table 5.3.

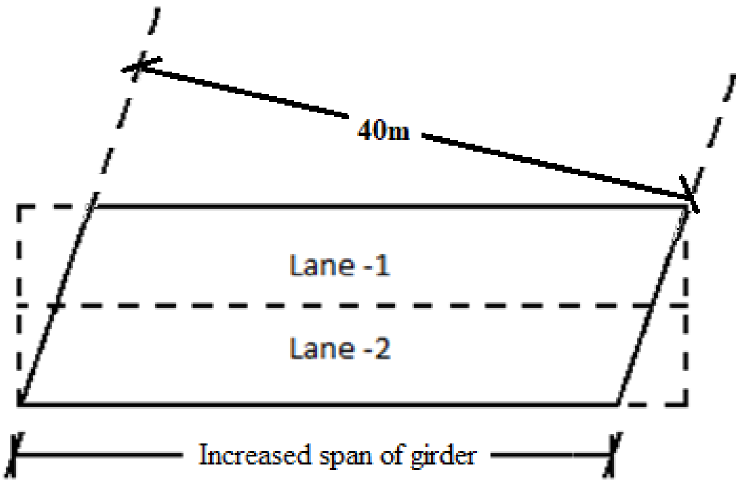

Figure 5.14: Increased span of girder over 40m wide road below

Table 5.3: Increased Spans of Girders to maintain 40m wide road below (m)

Sr. No.	For Skew Angle	Increased Span
1	0	40
2	10	40.62
3	20	42.57
4	30	46.19
5	40	52.22
6	50	62.23
7	60	80

5.7 Modelling of Box Girder in CSi Bridge

In this section, the modelling of box girder in CSi Bridge softwareis explained in brief.The steps are also shown in short in form of flow chart in Figure 5.15. Following are the steps involved in modelling of box girder.

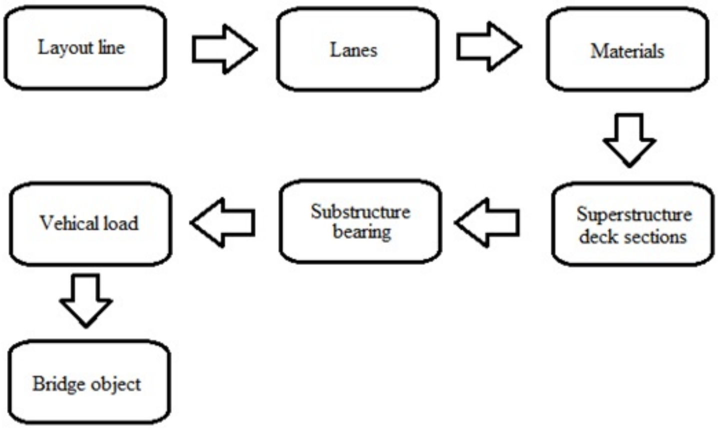

Figure 5.15: Flow Chart of Steps Involved in Modelling The Box Girder in CSi Bridge Software

5.7.1 Define Layout Line of Bridge

Path Layout → Layout line

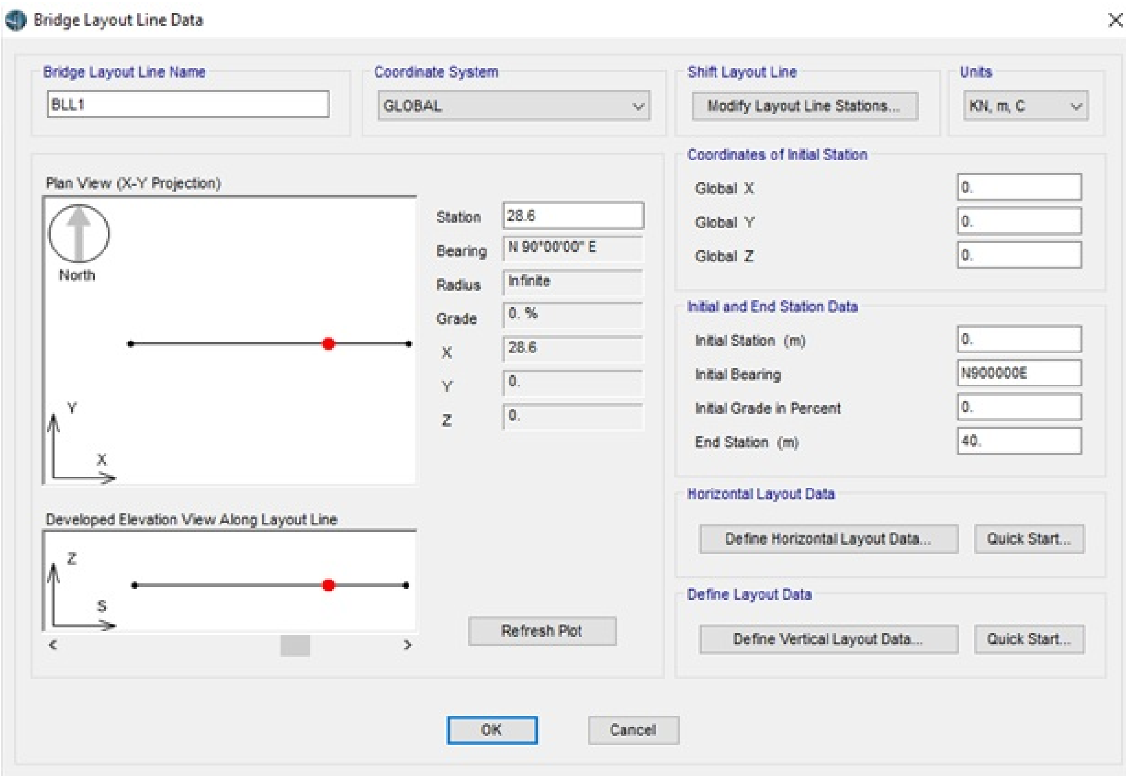

Figure 5.16: Layout Line of Bridge

Above Figure 5.16 shows Layout Line of Bridge.

First the layout line is to be defined for modelling the bridge. In the layout tab of software centre line of bridge, length and curves can be defined. In this project, straight bridge with 40m span is defined.

5.7.2 Define Lanes of Bridge

Path Layout → Lanes

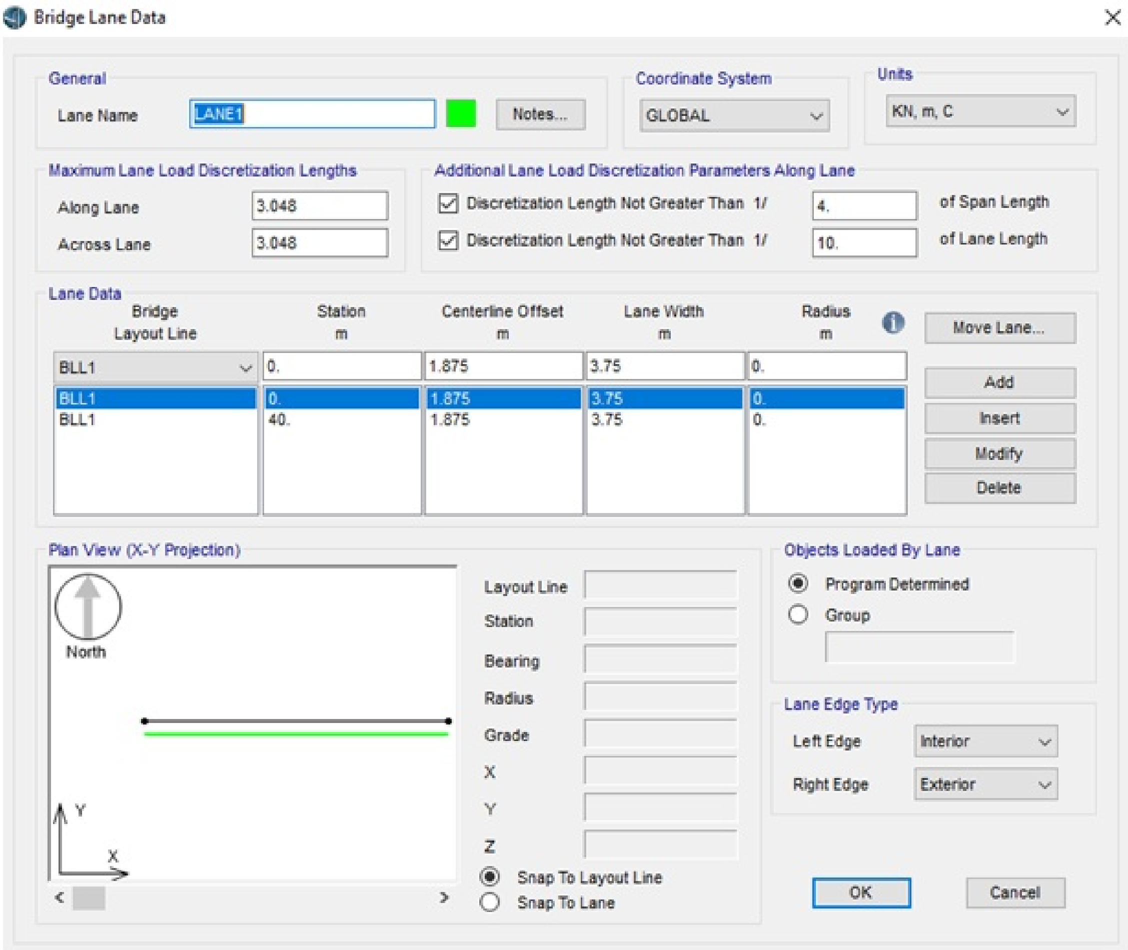

Figure 5.17: Lanes on Bridge

Above Figure 5.17 shows Lanes on Bridge.

Once the layout line is defined for the bridge, the lanes along that layout line is to be defined. In the model, two lanes of width 3.75m are defined on either sides of the layout line.

5.7.3 Define Materials of Bridge

Path Components → Properties → Materials

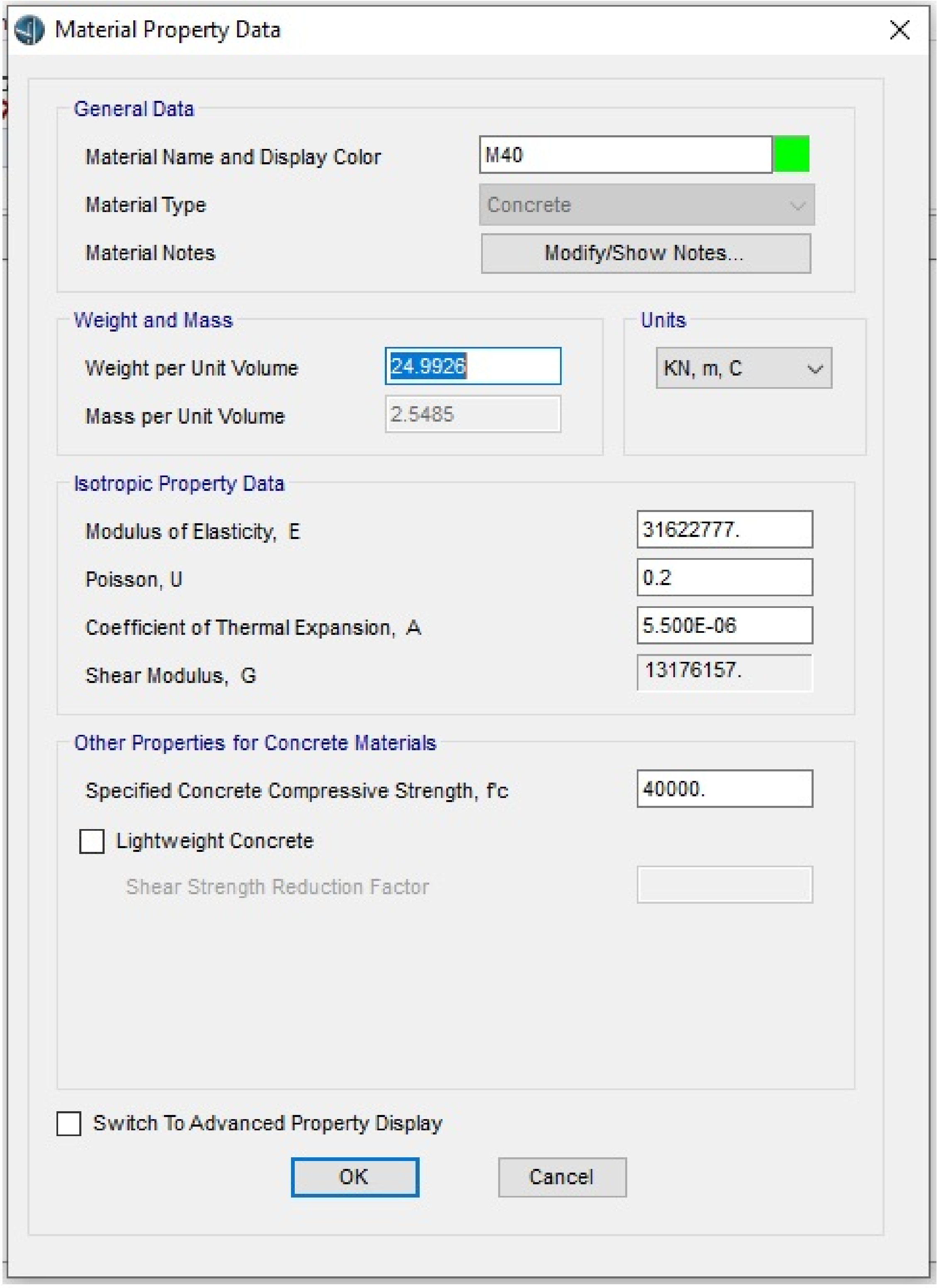

Figure 5.18: Material Properties – Concrete

Figure 5.18 shows material properties of concrete.

To calculate the self-weight of the bridge material properties of concrete is defined. M40 concrete was selected from the data base of material in software, as per countries and respective codes.

5.7.4 Define Cross Section of Bridge

Path Components → Superstructure → Deck Sections

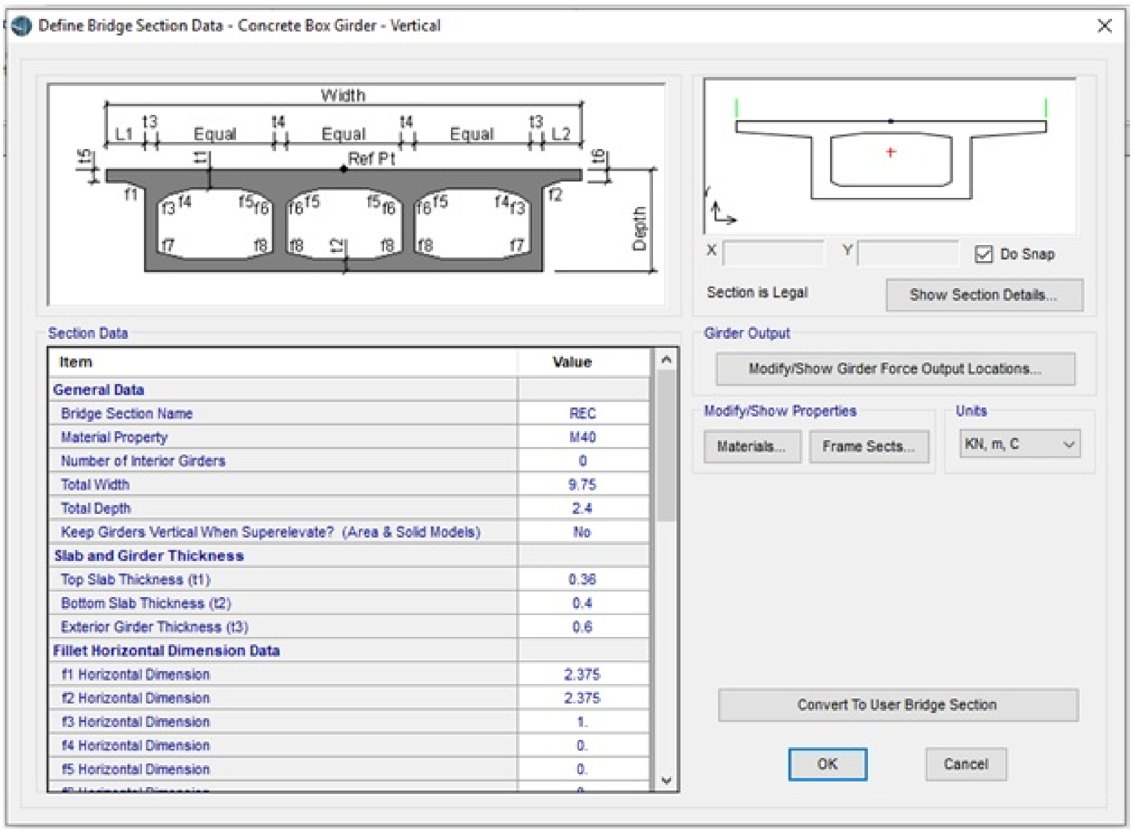

Figure 5.19: Cross Section of Bridge

Figure 5.19 shows cross section of bridge.

In Superstructure deck section tab, all general type of bridge cross sections are available. Dimension are to be given as per our problem.

5.7.5 Define Support of Bridge

Path Components → Substructure – Bearings

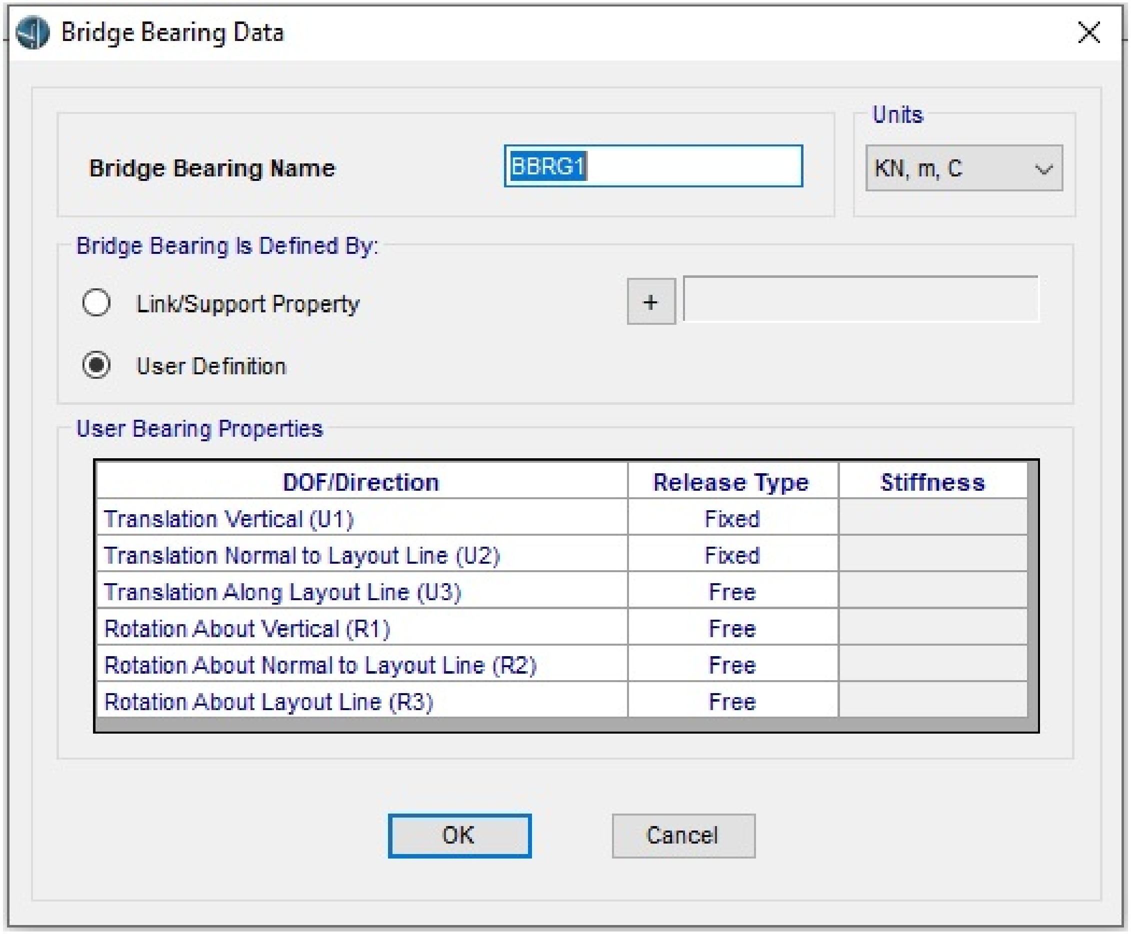

Figure 5.20: Support Bearing

Figure 5.20 shows Support Bearing.

Support bearings are provided at bottom of web of box girder. Two bearings at each ends of girder is defined.

5.7.6 Define Live Load on Bridge

Path Loads → Vehicles

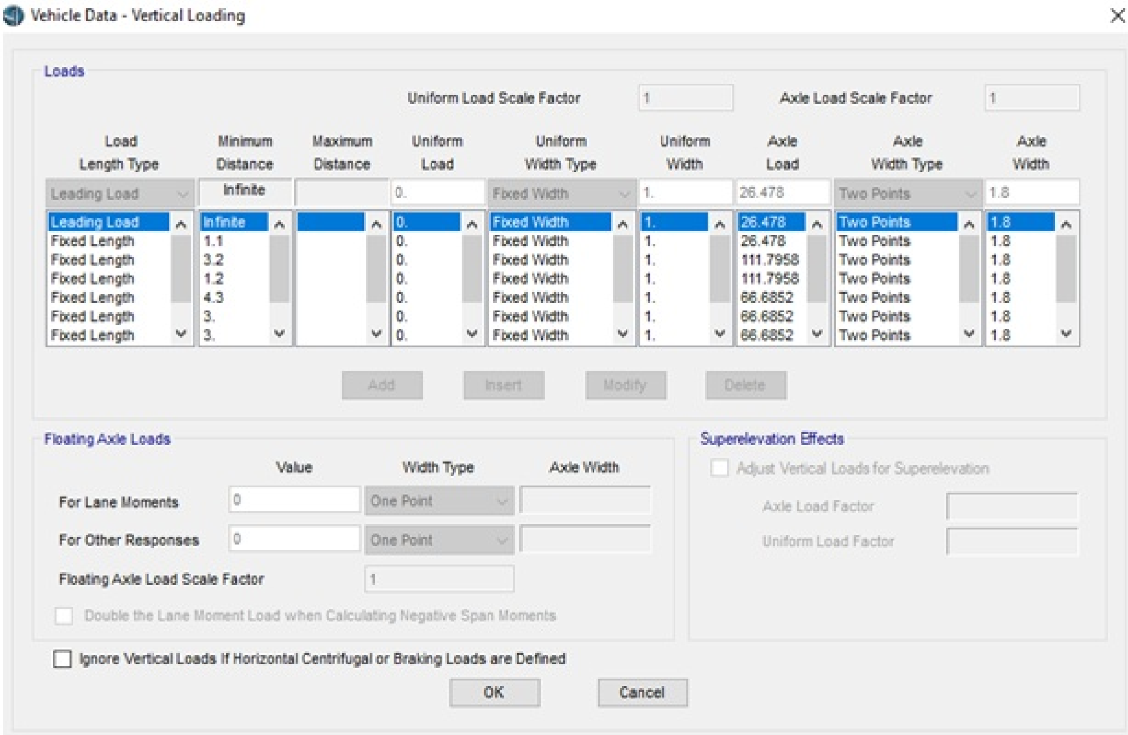

Figure 5.21: IRC Class A Loading

Figure 5.21 shows IRC Class A Loading.

Vehicle load is selected from the data base of vehicle loads in software as per countries and respective codes. IRC class A loading is considered as per IRC 6: 2016.

5.7.7 Define Bridge Object

Path Bridge → Bridge Objects

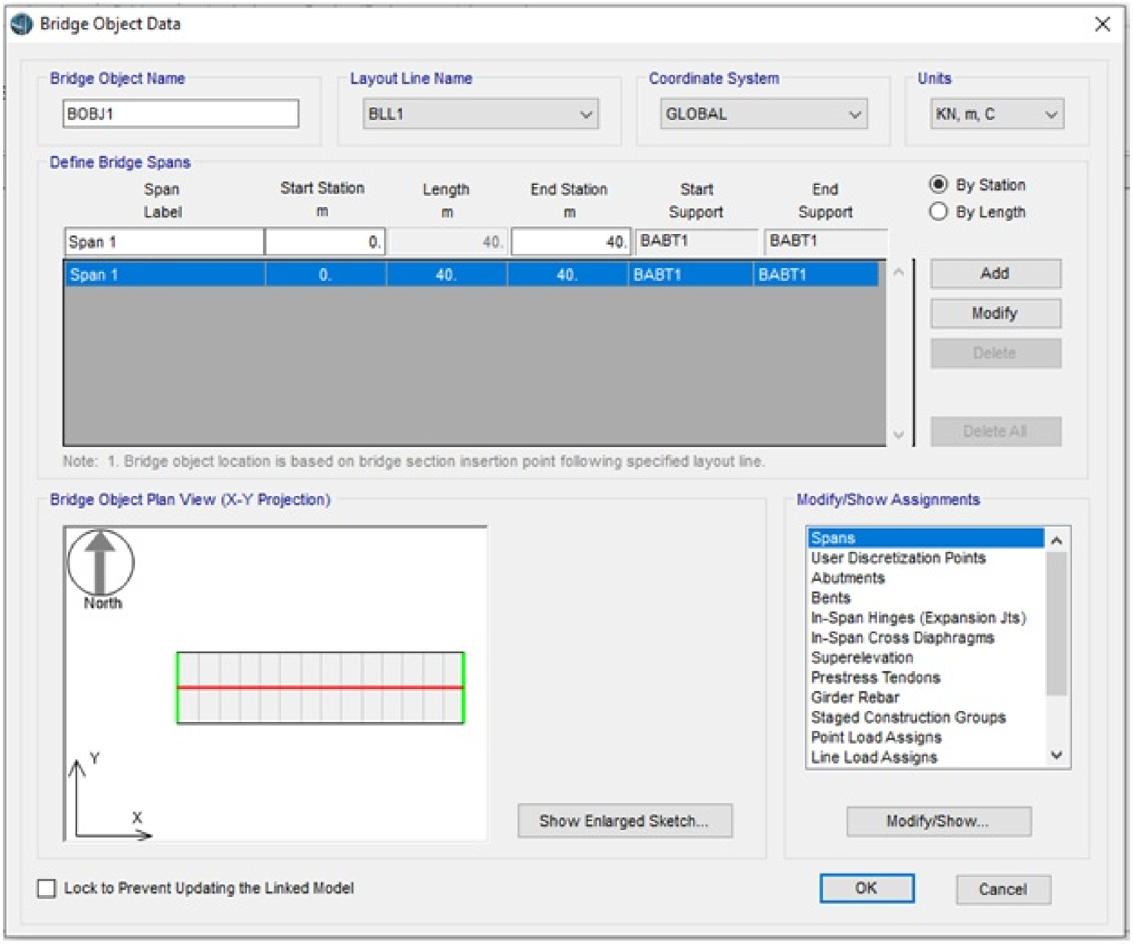

Figure 5.22: Bridge Object

Figure 5.22 shows bridge object.

All the elements defined above are compiled and a bridge object is defined. Skew angle of abutments are also defined in this tab.

5.8 Response of structure

After completing the modelling and analysis of single cell and double cell of rectangular and trapezoidal cross section box girders, following are the responses observed:

5.8.1 Response of Bridge with 0^0 skew

Figure 5.23 shows torsional behaviour of 0^0 skew angle bridge with single cell rectangular cross section.

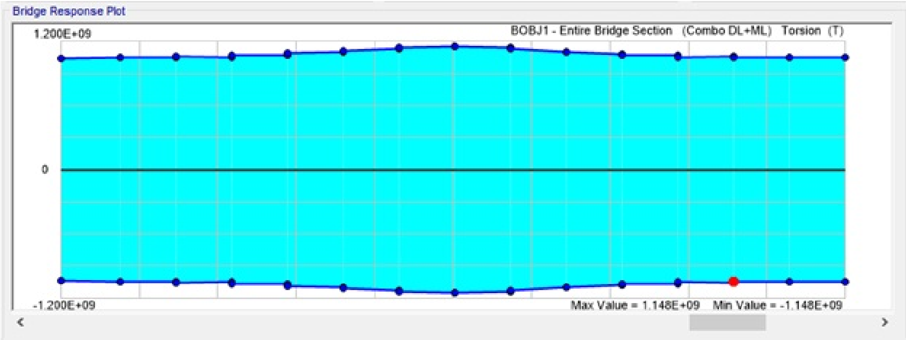

Figure 5.23: Torsional Moment of 0^0 skewed rectangular girder

Figure 5.24 shows deflection of 0^0 skew angle bridge with single cell rectangular cross section.

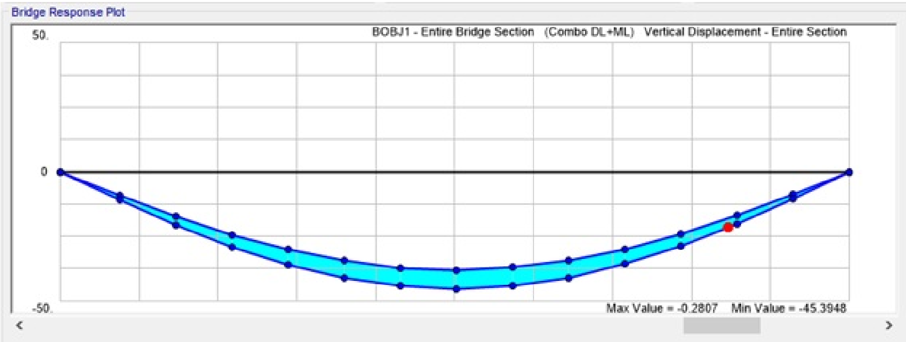

Figure 5.24: Deflection of 0^0 skewed rectangular girder

Figure 5.25 shows longitudinal moment of 0^0 skew angle bridge with single cell rectangular cross section.

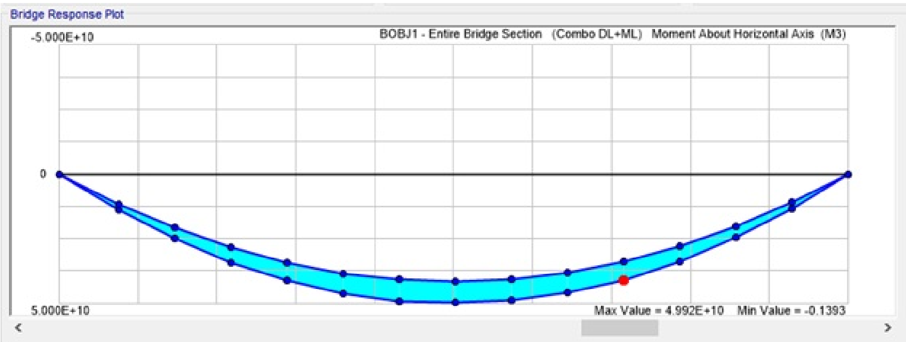

Figure 5.25: Longitudinal moment of 0^0 skewed rectangular girder

Figure 5.26 shows stresses at top and bottom of 0^0 skew angle bridge with single cell rectangular cross section.

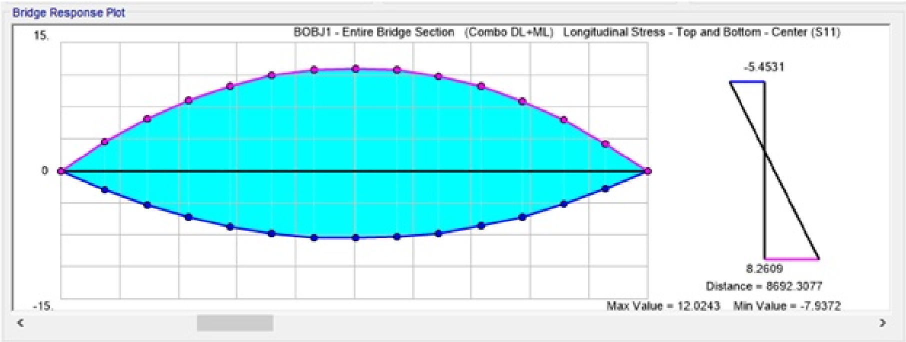

Figure 5.26: Stresses of 0^0 skewed rectangular girder

5.8.2 Response of Bridge with 30^0 skew

Figure 5.27 shows torsional behaviour of 30^0 skew angle bridge with single cell rectangular cross section.

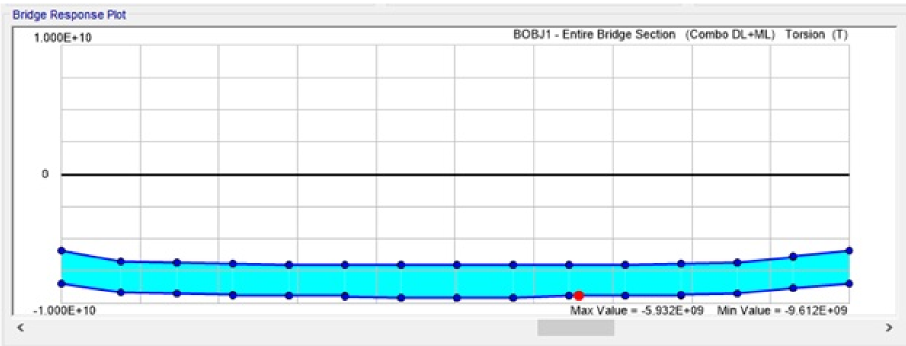

Figure 5.27: Torsional Moment of 30^0 skewed rectangular girder

Figure 5.28 shows deflection of 30^0 skew angle bridge with single cell rectangular cross section.

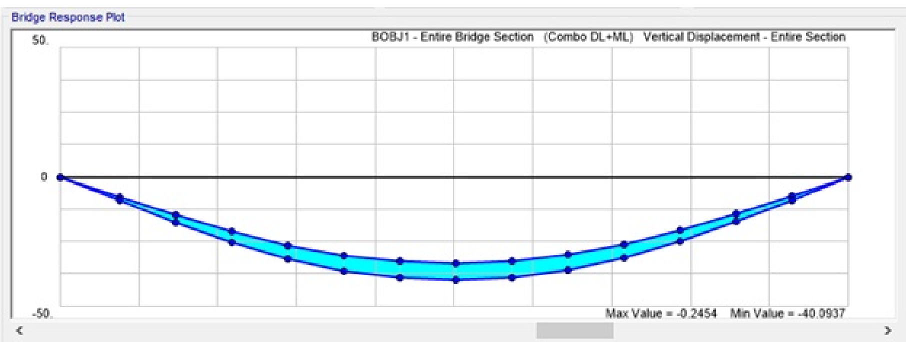

Figure 5.28: Deflection of 30^0 skewed rectangular girder

Figure 5.29 shows longitudinal moment of 30^0 skew angle bridge with single cell rectangular cross section.

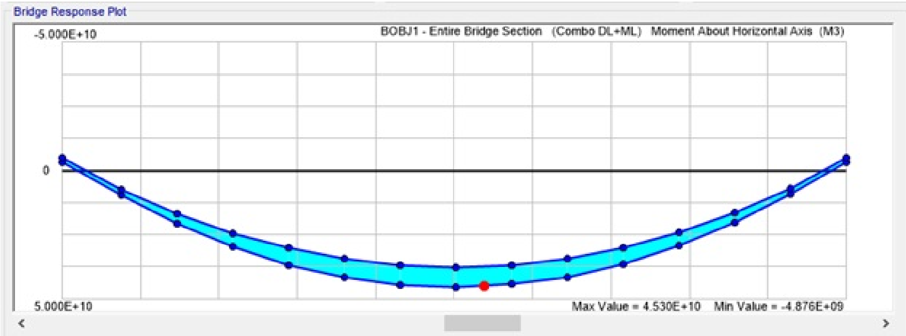

Figure 5.29: Longitudinal moment of 30^0 skewed rectangular girder

Figure 5.30 shows stresses at top and bottom of 30^0 skew angle bridge with single cell rectangular cross section.

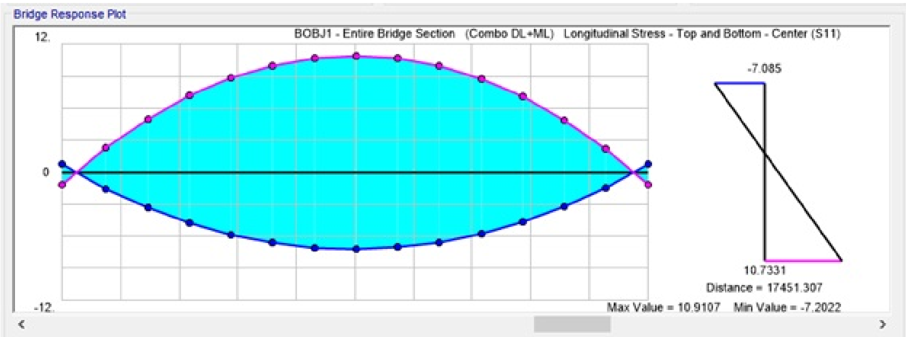

Figure 5.30: Stresses of 30^0 skewed rectangular girder

5.8.3 Response of Bridge with 60^0 skew

Figure 5.31 shows torsional behaviour of 60^0 skew angle bridge with single cell rectangular cross section.

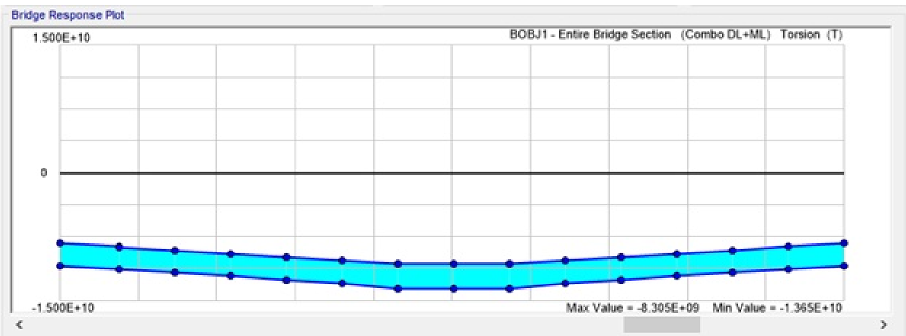

Figure 5.31: Torsional Moment of 60^0 skewed rectangular girder

Figure 5.32 shows deflection of 60^0 skew angle bridge with single cell rectangular cross section.

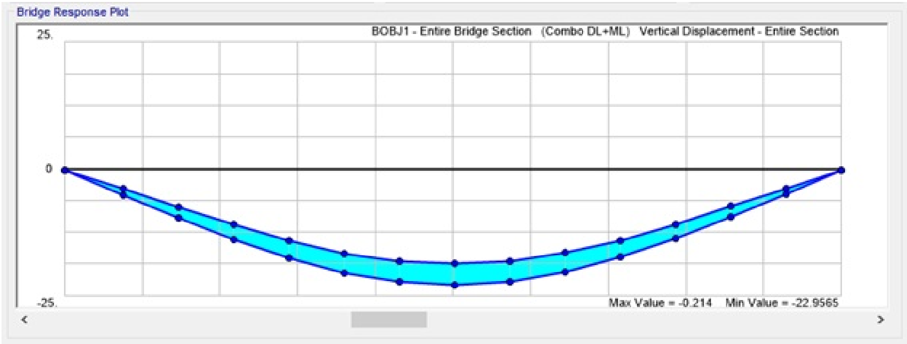

Figure 5.32: Deflection of 60^0 skewed rectangular girder

Figure 5.33 shows longitudinal moment of 60^0 skew angle bridge with single cell rectangular cross section.

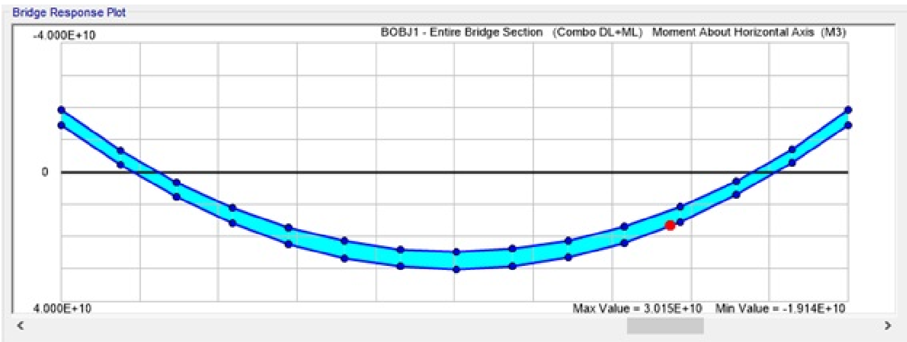

Figure 5.33: Longitudinal moment of 60^0 skewed rectangular girder

Figure 5.34 shows stresses at top and bottom of 60^0 skew angle bridge with single cell rectangular cross section.

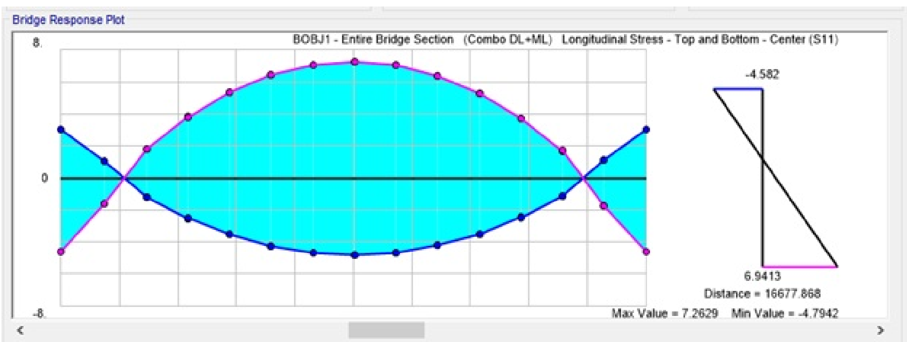

Figure 5.34: Stresses of 60^0 skewed rectangular girder

Similar response of all skew bridges with double cell rectangular, single cell trapezoidal and double cell trapezoidal cross section were obtained, which are discussed and shown in tabular and graphical form in next chapter.

5.9 Closure

In this chapter, details of single cell and double cell of rectangular and trapezoidal box girders cross sections are discussed. Parameters such as material properties, boundary conditions, cross section properties are discussed. Also, this chapter gives details of modelling of bridge girder in CSi Bridge software and general response of girders.

Chapter 6

Results and Discussion

6.1 General

This chapter presents results obtained from finite element analysis, computed for single cell and double cell of rectangular and trapezoidal cross-section under varying skew angle. The parameters considered of all the cross-section under varying skew angle are torsion moment, longitudinal moment, deflection, required prestressing force and stresses at top and bottom of the section.

6.2 Effect of Increased Span on Girder to Avoid Skewness

Table 6.1 shows maximum longitudinal moment generated by live load and self-weight, for single cell trapezoidal cross sections.

Table 6.1: Maximum Longitudinal Moment (kN-m)

Skew Angle	**Models With Skewness**	**Models With Increased Span**
0	4.88×10^4	4.88×10^4
10	4.84×10^4	5.30×10^4
20	4.72×10^4	5.74×10^4
30	4.51×10^4	6.30×10^4
40	4.20×10^4	6.98×10^4
50	3.79×10^4	8.00×10^4
60	3.24×10^4	9.64×10^4

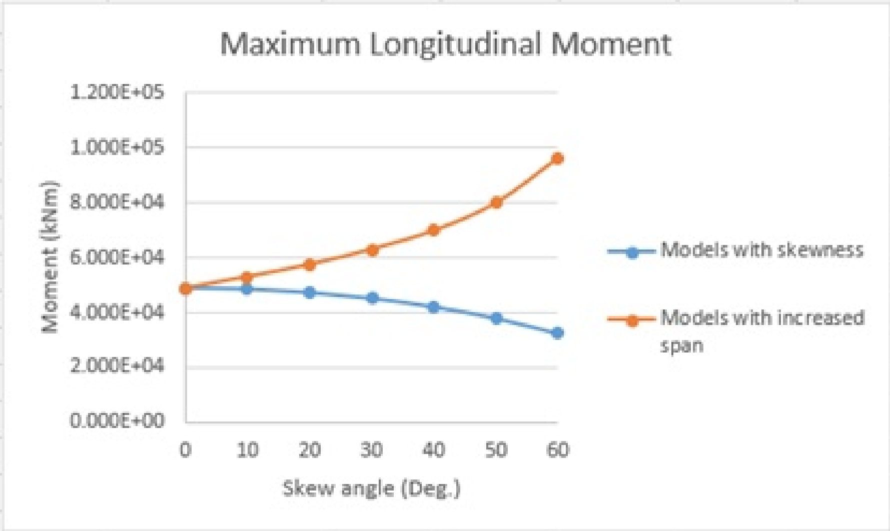

Figure 6.1: Maximum Longitudinal Moment in kN-m

From Figure 6.1, it can be concluded that, there is gradual decrease in the longitudinal moment of girder under skewness. But if the span of box girder is increased, to avoid skewness,values of longitudinal moment show rapid increase. In the case of increased span, longitudinal moment is increased by 197% with respect to constant skew angle.

6.3 Torsional Moment

Table 6.2 shows maximum torsional moment generated by live load and self-weight, for all the cross sections

Table 6.2: Maximum Torsional Moment (N-mm)

Skew angle	Rectangular w/ single cell	Rectangular w/ double cell	Trapezoidal w/ single cell	Trapezoidal w/ double cell
0	1.15 x 10^9	1.12 x 10^9	1.19 x 10^9	1.17 x 10^9
10	4.10 x 10^9	4.10 x 10^9	3.58 x 10^9	3.58 x 10^9
20	6.99 x 10^9	7.04 x 10^9	5.94 x 10^9	6.02 x 10^9
30	9.61 x 10^9	9.77 x 10^9	8.11 x 10^9	8.31 x 10^9
40	1.18 x 10^{10}	1.21 x 10^{10}	9.87 x 10^9	1.02 x 10^{10}
50	1.31 x 10^{10}	1.36 x 10^{10}	1.11 x 10^{10}	1.16 x 10^{10}
60	1.37 x 10^{10}	1.42 x 10^{10}	1.17 x 10^{10}	1.23 x 10^{10}

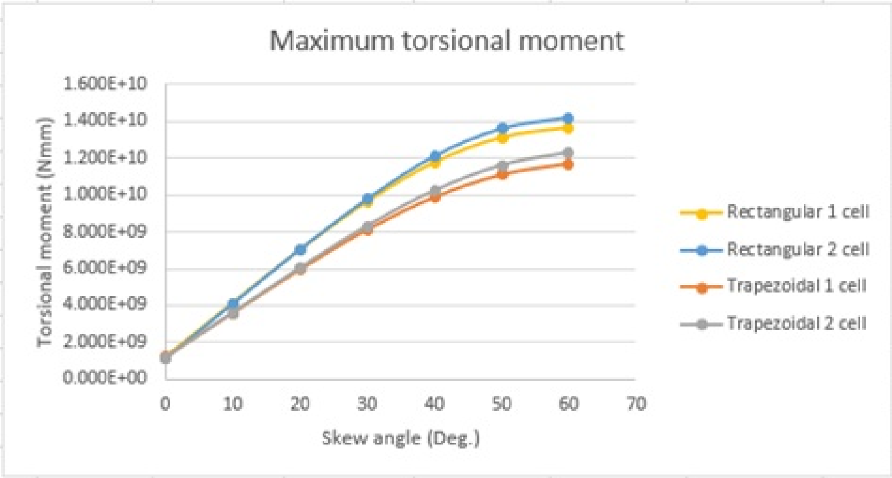

Figure 6.2: Maximum Torsional Moment

From Figure 6.2 it can be concluded that, there is gradual increase in the torsional moment of all cross sections. But the rectangular box girders show greater values of torsional moment as compared to trapezoidal box girders.

Table 6.3 shows maximum torsional moment generated by live load and self-weight, for all the cross sections with increased span.

Table 6.3: Maximum Torsional Moment for increased span (N-mm)

Skew angle	**Rectangular w/ single cell**	**Rectangular w/ double cell**	**Trapezoidal w/ single cell**	**Trapezoidal w/ double cell**
0	1.15 x 10^9	1.12 x 10^9	1.19 x 10^9	1.17 x 10^9
10	4.20 x 10^9	4.19 x 10^9	3.66 x 10^9	3.66 x 10^9
20	7.77 x 10^9	7.83 x 10^9	6.59 x 10^9	6.68 x 10^9
30	1.24 x 10^{10}	1.26 x 10^{10}	1.05 x 10^{10}	1.08 x 10^{10}
40	1.89 x 10^{10}	1.95 x 10^{10}	1.60 x 10^{10}	1.66 x 10^{10}
50	2.89 x 10^{10}	2.99 x 10^{10}	2.49 x 10^{10}	2.60 x 10^{10}
60	4.53 x 10^{10}	4.71 x 10^{10}	4.03 x 10^{10}	4.23 x 10^{10}

Figure 6.3: Maximum torsional moment of increasing span of girder

Figure 6.3 shows that, there is rapid increase in the torsional moment of all cross sections. But the trapezoidal box girders show better values of torsional moment as compared to rectangular box girders.

6.4 Deflection

Table 6.4 displays maximum deflection of single and double cell rectangular, single and double cell trapezoidal box girder for varying skew angle.

Table 6.4: Maximum Deflection (mm)

Skew angle	**Rectangular w/ single cell**	**Rectangular w/ double cell**	**Trapezoidal w/ single cell**	**Trapezoidal w/ double cell**
0	45.4	44.6	48.7	47.7
10	44.8	44.1	48.2	47.2
20	43.1	42.3	46.7	45.6
30	40.1	39.3	44	42.9
40	36.8	34.9	40.2	39
50	30.1	29.1	35.2	33.7
60	23	21.8	28.2	26.4

From Figure 6.4 obtained for maximum deflections, it is been observed that there was a steady decrement with increase in skew angle for all cross sections.

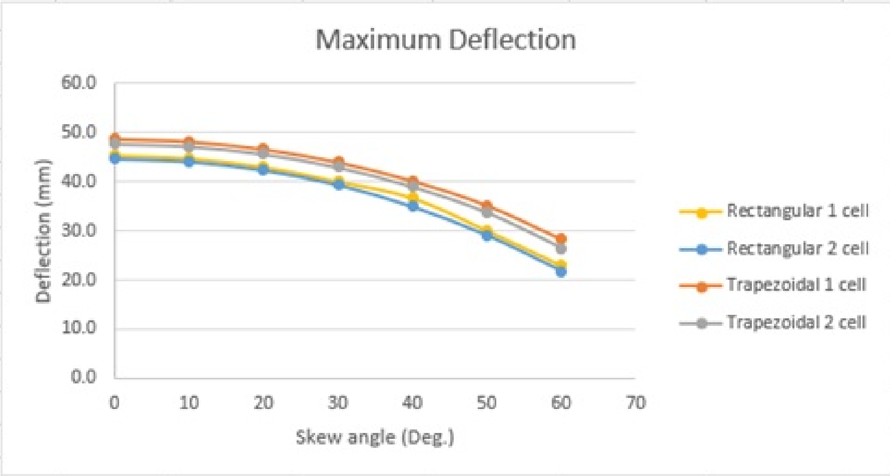

Figure 6.4: Maximum Deflections in mm

Table 6.5 displays maximum deflection of single and double cell rectangular, single and double cell trapezoidal box girder for varying skew angle and increased span.

Table 6.5: Maximum Deflection with increased span of girder (mm)

Skew angle	**Rectangular w/ single cell**	**Rectangular w/ double cell**	**Trapezoidal w/ single cell**	**Trapezoidal w/ double cell**
0	45.4	44.6	48.7	47.7
10	47.4758	46.7	51.1	50
20	54.1	53.2	58.6	57.4
30	68.7	67.5	75.4	73.6
40	97.1	95.2	109	105.6
50	158.2	153.9	181.9	175
60	320.6	308.2	377	357

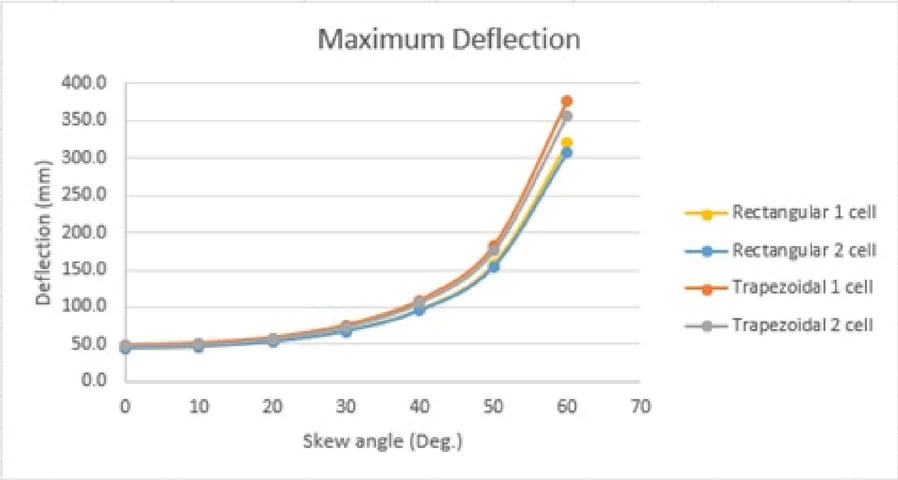

Figure 6.5: Maximum deflections for increased span (mm)

From Figure 6.5 obtained for maximum deflections, it is been observed that there was a steady decrement with increase in skew angle for all cross sections.

6.5 Longitudinal Moment

Table 6.6 shows the change in maximum longitudinal moment between single cell and double cell cross sections of rectangular and trapezoidal box models for various skew angle.

Table 6.6: Maximum Longitudinal Moment (N-mm)

Skew angle	**Rectangular w/ single cell**	**Rectangular w/ double cell**	**Trapezoidal w/ single cell**	**Trapezoidal w/ double cell**
0	4.99 x 10^4	5.02 x 10^{10}	4.88 x 10^4	4.88 x 10^4
10	4.94 x 10^4	4.97 x 10^{10}	4.84 x 10^4	4.84 x 10^4
20	4.79 x 10^4	4.81 x 10^{10}	4.72 x 10^4	4.71 x 10^4
30	4.53 x 10^4	4.54 x 10^{10}	4.51 x 10^4	4.49 x 10^4
40	4.15 x 10^4	4.14 x 10^{10}	4.20 x 10^4	4.16 x 10^4
50	3.66 x 10^4	3.61 x 10^{10}	3.79 x 10^4	3.72 x 10^4
60	3.02 x 10^4	2.93 x 10^{10}	3.24 x 10^4	3.12 x 10^4

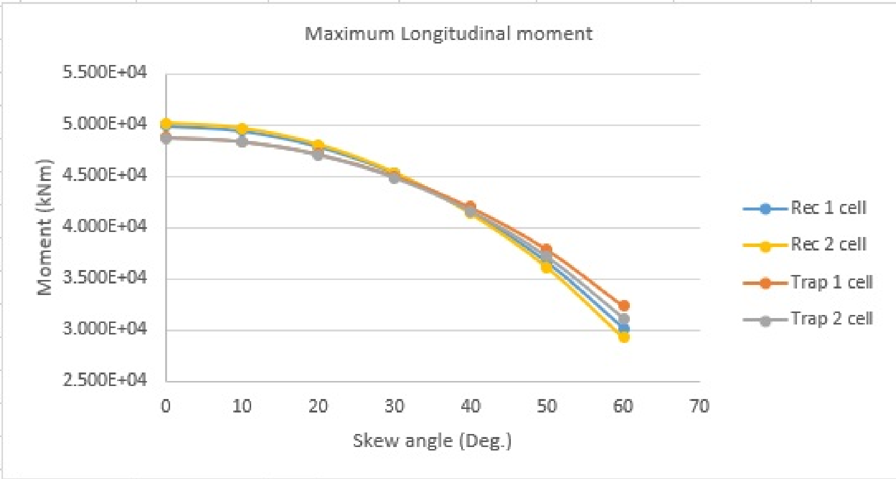

Figure 6.6: Maximum Longitudinal Moment in Nmm

From Figure 6.6 it can be concluded that, with increase in skew angle, longitudinal moment in girder decreases. No considerable difference was observed.

Table 6.7 shows the change in maximum longitudinal moment for increased span, between single cell and double cell cross sections of rectangular and trapezoidal box models for various skew angle.

Table 6.7: Maximum Longitudinal Moment for increased span (N-mm)

Skew angle	**Rectangular w/ single cell**	**Rectangular w/ double cell**	**Trapezoidal w/ single cell**	**Trapezoidal w/ double cell**
0	4.99 x 10^{10}	5.02 x 10^{10}	4.88 x 10^{10}	4.88 x 10^{10}
10	5.09 x 10^{10}	5.11 x 10^{10}	4.99 x 10^{10}	4.98 x 10^{10}
20	5.37 x 10^{10}	5.39 x 10^{10}	5.29 x 10^{10}	5.28 x 10^{10}
30	5.93 x 10^{10}	5.94 x 10^{10}	5.89 x 10^{10}	5.87 x 10^{10}
40	6.82 x 10^{10}	6.81 x 10^{10}	6.88 x 10^{10}	6.81 x 10^{10}
50	8.28 x 10^{10}	8.20 x 10^{10}	8.49 x 10^{10}	8.34 x 10^{10}
60	1.11 x 10^{11}	1.09 x 10^{11}	1.15 x 10^{11}	1.11 x 10^{11}

Figure 6.7: Maximum longitudinal moment for increased span (N-mm)

From the Figure 6.7, it can be concluded that, with increase in skew angle and span, longitudinal moment in girder also increases.

6.6 Stresses

Table 6.8 represents stresses occurring at the top and bottom of the single cell and double cell cross sections of rectangular and trapezoidal box girders under various skew angle. Negative value shows compressive stress and positive values shows tensile stress.

Table 6.8: Stresses At Top And Bottom of Box Section (N/mm^2)

Skew Angle	**Rectangular w/ single cell**		**Rectangular w/ double cell**		**Trapezoidal w/ single cell**		**Trapezoidal w/ double cell**	
	top	**bot**	**top**	**bot**	**top**	**bot**	**top**	**bot**
0	-7.94	12.02	-8	12.1	-8.07	13.46	-8.1	13.5
10	-7.86	11.91	-7.9	12	-8.01	13.36	-8	13.4
20	-7.62	11.54	-7.6	11.6	-7.8	13.02	-7.8	13
30	-7.2	10.91	-7.2	10.9	-7.45	12.43	-7.4	12.4
40	-6.6	10	-6.6	9.97	-6.94	11.58	-6.9	11.5
50	-5.82	8.82	-5.8	8.71	-6.26	10.45	-6.2	10.3
60	-4.79	7.26	-4.9	7.06	-5.36	8.93	-5.2	8.63

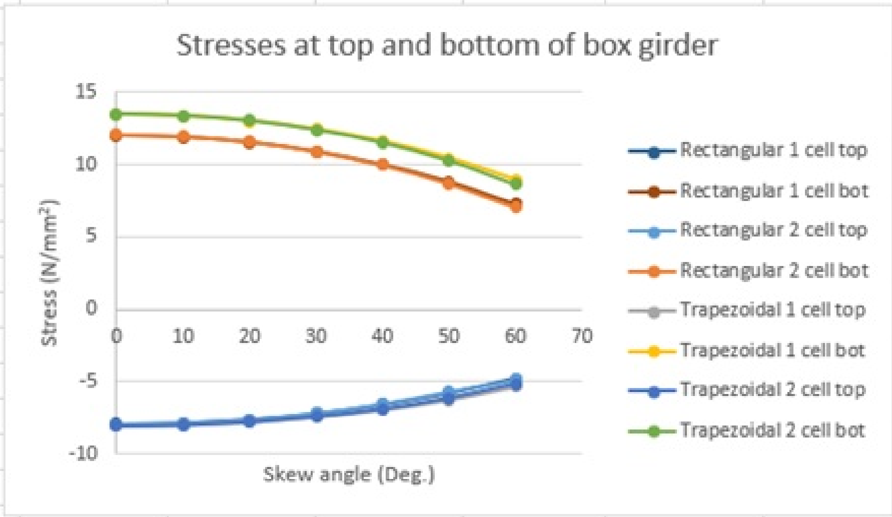

Figure 6.8: Stresses at top and bottom of box girder in N/mm^2

From Figure 6.8, it is observed that, stresses at bottom of single cell rectangular, double cell rectangular, single cell trapezoidal and double cell trapezoidal girder is decreased with increase in skew angle, while change in stresses at the top of both girders are found to be insignificant.

Table 6.9 represents stresses occurring at the top and bottom of the single cell and double cell cross sections of rectangular and trapezoidal box girders under various skew angle and increased span.

Table 6.9: Stresses At Top And Bottom Of Box Section of increased span girder (N/mm^2)

Skew Angle	**Rectangular w/ single cell**		**Rectangular w/ double cell**		**Trapezoidal w/ single cell**		**Trapezoidal w/ double cell**	
	top	**bot**	**top**	**bot**	**top**	**bot**	**top**	**bot**
0	-7.94	12.02	-7.97	12.07	-8.07	13.46	-8.07	13.49
10	-8.09	12.26	-8.12	12.3	-8.24	13.75	-8.24	13.78
20	-8.54	12.94	-8.57	12.98	-8.75	14.59	-8.73	14.61
30	-9.43	14.28	-9.45	14.31	-9.74	16.25	-9.71	16.24
40	-10.85	16.43	-10.82	16.4	-11.38	18.98	-11.27	18.85
50	-13.17	19.95	-13.05	19.76	-14.03	23.41	-13.79	23.07
60	-17.95	26.66	-18.67	26.15	-18.97	31.65	-19.21	30.8

Figure 6.9: Stresses at top and bottom of box girder for increased span N/mm^2

From Figure 6.9, it is observed that, as the span increases, stresses at bottom of single cell rectangular, double cell rectangular, single cell trapezoidal and double cell trapezoidal girder is increased with increase in skew angle.

6.7 Pre-stressing Force

Required Prestressing force is calculated, and checked for the allowable compression and tension stresses at top and bottom. All the stresses were found to be under allowable limit. Table 6.10 shows required pre-stressing force for single cell and double cell cross sections of rectangular and trapezoidal box girders with varying skew angle.

Table 6.10: Required Pre-Stressing Force (kN)

Skew angle	**Rectangular w/ single cell**	**Rectangular w/ double cell**	**Trapezoidal w/ single cell**	**Trapezoidal w/ double cell**
0	4.11 x 10^4	4.13 x 10^7	4.16 x 10^4	4.16 x 10^4
10	4.07 x 10^4	4.09 x 10^7	4.13 x 10^4	4.12 x 10^4
20	3.95 x 10^4	3.96 x 10^7	4.03 x 10^4	4.01 x 10^4
30	3.73 x 10^4	3.73 x 10^7	3.84 x 10^4	3.82 x 10^4
40	3.43 x 10^4	3.41 x 10^7	3.58 x 10^4	3.54 x 10^4
50	3.01 x 10^4	2.98 x 10^7	3.23 x 10^4	3.17 x 10^4
60	2.48 x 10^4	2.41 x 10^7	2.76 x 10^4	2.66 x 10^4

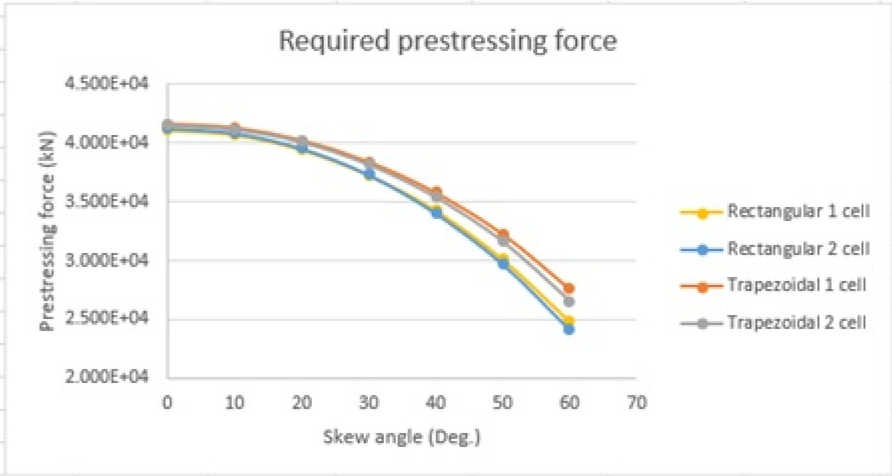

Figure 6.10: Required Pre-stressing Force in kN

Figure 6.10 shows required pre-stressing force in kN. In the case of single cell and double cell rectangular box girder 39.6% and 41.54% decrease in required pre-stressing force is observed respectively, while for single cell trapezoidal box girder required prestressing force is decreased by 33.67% and for the double cell trapezoidal box girder 36.1% decrease was observed.

Table 6.11 shows required pre-stressing force for increased span of girder, for single cell and double cell cross sections of rectangular and trapezoidal box girders with varying skew angle.

Table 6.11: Required Pre-Stressing Force for increased span (kN)

Skew angle	Rectangular w/ single cell	Rectangular w/ double cell	Trapezoidal w/ single cell	Trapezoidal w/ double cell
0	4.11 x 10^4	4.13 x 10^4	4.16 x 10^4	4.16 x 10^4
10	4.19 x 10^4	4.21 x 10^4	4.25 x 10^4	4.24 x 10^4
20	4.42 x 10^4	4.44 x 10^4	4.51 x 10^4	4.50 x 10^4
30	4.88 x 10^4	4.89 x 10^4	5.02 x 10^4	5.00 x 10^4
40	5.62 x 10^4	5.60 x 10^4	5.86 x 10^4	5.80 x 10^4
50	6.82 x 10^4	6.75 x 10^4	7.23 x 10^4	7.10 x 10^4
60	9.11 x 10^4	8.94 x 10^4	9.78 x 10^4	9.48 x 10^4

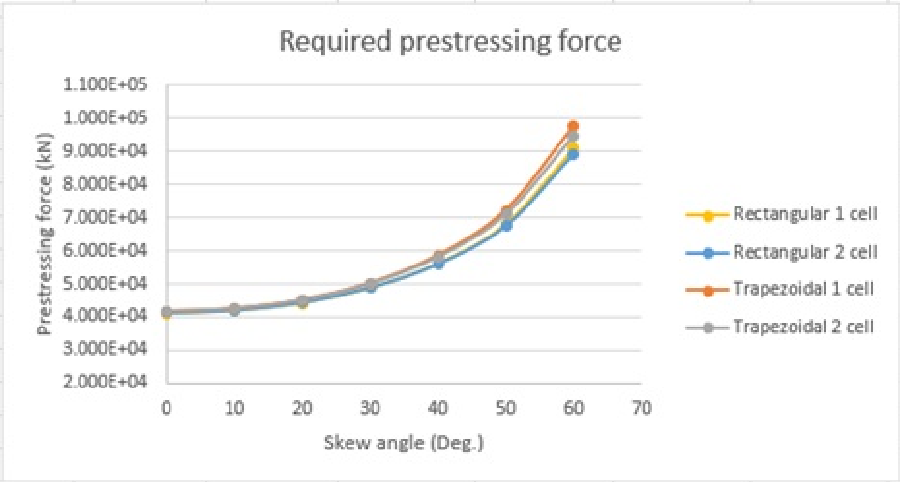

Figure 6.11: Required prestressing force for increased span (kN)

From Figure 6.11 it can be concluded that, as the span of the girder increase, the value of prestressing force also increases, though the skew angle is also increased.

6.8 Closure

In above chapter, results obtained after analysis of single cell rectangular, double cell rectangular, single cell trapezoidal and double cell trapezoidal box girder in terms of torsion, moment, stresses, deflection and required pre-stressing force are discussed. Also, this chapter focus on comparative study among four type of box girder under skew effect.

Chapter 7

Conclusion and Future Scope

7.1 Introduction

In this research, analysis was carried out for single cell rectangular, double cell rectangular, single cell trapezoidal and double cell trapezoidal using CSi Bridge software. Conclusions are drawn from above study and given in this chapter. Future scope of this work is also mentioned at the end of this chapter.

7.2 Conclusion

From all the analysis and results obtained for rectangular and trapezoidal box girder with varying skew angles, conclusions drawn are as follows:

1. Increasing length of box girders to avoid skew angle induces high stresses in the girder. The longitudinal moment for increased span girder was observed to increase by 197% for 60^0 skew angle, as compared with 40m span girder.

2. With increase in skew angle, it can be concluded that responses such as stresses at top and bottom, longitudinal moment and required pre stressing force decrease by 39.6% and 41.5% for single and double cell rectangular box girder respectively. While the same responses were observed to be decreased by 33.6% in single cell trapezoidal box girder and 36% in case of double cell trapezoidal box girder.

3. With increase in skew angle, high torsional moments are generated in both single cell and double cell rectangular and trapezoidal box girder. But single

cell trapezoidal box girder section shows least i.e. 880% increase as compared to other cross sections.

4. Along with increase in skew angle, deflection in single cell and double cell rectangular box girder is reduced by 49.3% and 51% respectively. Whereas deflection in single cell and double cell trapezoidal box girder is decreased by 42.1% and 44.55% respectively.

5. Rapid growth in the length of girder was observed, while maintaining 40m road width below the girder. Swift growth in all parameters viz. stresses at top and bottom, longitudinal moment, torsional moment, deflection and required prestressing force was observed.

6. Considering parameters like stresses at top and bottom, longitudinal moment, deflection and required prestressing force, it is observed that double cell box girder shows better results as compared to single cell box girder when skew angle effects are induced.

7. It can also be concluded that rectangular box girders show greater resistance to deflection and stresses as compared to trapezoidal girders. But to resist torsional stresses generated due to skewness, trapezoidal girder could be preferred.

7.3 Future scope

The following are the recommendations for the future study,

1. Effect of skewness of bridge by considering span to depth ratio can be studied further.

2. Study of skew bridge by considering width to span ratio can be done further.

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[1] Pranav M. Kulkarni, P. M. Mohite , “Parametric Study on Behaviour of Rectangular Box Girder Bridges with Varying Skew Angle”, International Research Journal of Engineering and Technology (IRJET), Vol 6, Issue 8,174-176 August 2019.

[2] Pranav M. Kulkarni, P. M. Mohite , “Parametric Study of Structural Response of Post Tensioned Box Girder Skewed Bridge ” International Journal on Advanced Science, Engineering and Information Technology (In Review)

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