ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Vol 9, Issue 9, September 2022

Strut-and-Tie Model Approach To Bridge Diaphragm Design

[1] Rounak Kare, [2] Prof. Nisha Naik

[1] P.G. Student Department of Civil Engineering, Goa College of Engineering, Farmagudi, Goa.
[2] Professor, Department of Civil Engineering, Goa College of Engineering, Farmagudi Goa.
Corresponding Author Email: [1] karerounak27@gmail.com, [2] nisha@gec.ac.in

Abstract— ***Beams with large depth in relation to span are known as deep beams. Transfer girders, offshore structures and deep foundations frequently employ deep beams. An established design technique for dealing with D-regions (Discontinuous regions) is the strut-and-tie model. The Strut-and-Tie modeling approach is an analysis and design tool for reinforced concrete elements which assumes that internal stresses in a member are transferred through a truss mechanism. The tensile ties and compressive struts connected by nodal zones form the truss members. The truss idealized by strut-and-tie model indirectly account for distribution of both shear and flexure. A diaphragm in a box girder bridge forms the component in a box girder bridge which strengthens the box girder with respect to torsion and transmits shear to the bearings. Due to the diaphragm having a small span-to-depth ratio and presence of a discontinuity (opening) makes it a D-region. Due to a lack of experience with the design process, the difficulty to validate truss models (using a finite element model), and the length of time it takes to perform strut and tie model design and analysis, bridge architects have yet to fully comprehend the strut and tie model. Consequently, a well defined strut and tie modeling technique will help bridge designers feel more at ease using the design method. This paper presents a uniform design procedure for employing strut-and-tie model for box girder diaphragms that can be practiced by designers***

Index Terms—***Bridge Diaphragm, Deep Beam, D-Region, Strut-and-Tie Model***

I. INTRODUCTION

A deep beam is a type of non-flexural structural member that has a span (L) to depth (D) ratio less than 5. Deep beams have high load and shearing capacity.[6] Deep beams cannot be analyzed as conventional beams using Bernoulli's theory, wherein it assumed that plane sections remain plane after bending and stress is proportional to strain. In areas of construction where we provide openings in webs for accessibility and essential services to pass, the presence of such opening induces geometric discontinuity of the deep beam which further enhances the complexity of non-linear stress distribution along the depth of beam. Regions with concentrated loads within twice the member depth from the face of support are also considered as deep beam.

A diaphragm is a component of the structural system of box-girder Bridge that is used to strengthen the box-girder with respect to torsion and transmit shear stresses and loads to the bearings. The figure 1 below depicts the usual configuration of a pier diaphragm in a single cell box-girder bridge.

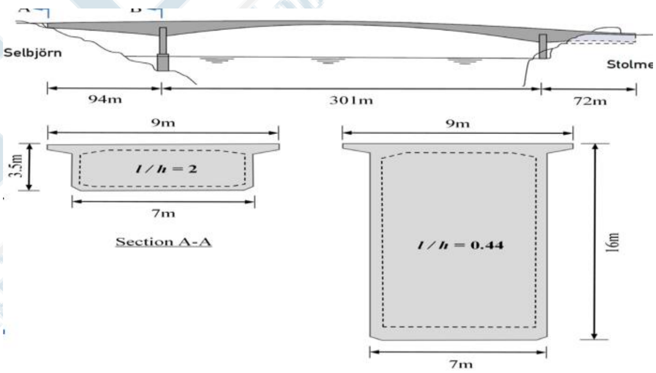


Figure 1: Box Girder Diaphragm Segment

Analysis and design of box-girder bridges are very complex because of its three dimensional behavior consisting of torsion, distortion and bending in longitudinal and transverse directions. The longitudinal bending stress distribution in wide flange girders is distributed non-uniformly throughout the width. It remains maximum at the edge and reduces towards the centre, and cannot be obtained usually from elementary beam theory. Design of concrete box girder diaphragms is a difficult task. The complications that arise during design include:-

a) Wide ranging span-to-depth ratio: The span-to-depth ratio of the diaphragm varies largely in box-girder bridges making the complete structure act as a deep beam.
b) Presence of man-hole: The diaphragms in box-girder bridges are normally provided with openings for accessibility for bridge inspection. The presence of

IFERP
connecting engineers... developing research

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Vol 9, Issue 9, September 2022

this opening in the deep beam induces geometric discontinuity which enhances the non-linear stress distribution along the depth.

c) Side shearing: the diaphragm transmits vertical shear through webs to the bearing, presence of this support further leads to non-linear stress distribution.

Designing areas of structural components affected by a load and/or geometrical discontinuities is where strut-and-tie model is most frequently employed. Within the vicinity, a quadratic distribution of stresses is brought about by loads and architectural imperfections. As a result, it is no longer possible to trust that plane portions will stay that way within of the discontinuity-affected area.

For the past several years designers have been using good engineering judgment and experience in designing and detailing such D-regions. Now, due to implementation of strut-and-tie modeling in several design codes like AASHRO LRFD Bridge Specification, ACI 318-08 and EUROCODE 2 to name a few designers have the tool to accurately design these D-regions. Strut-and-tie modeling is a method of analysis and design for reinforced and prestressed concrete structural members, wherein loads from the loading points are transferred to the supports by a truss system with struts and ties. The flow of compressive forces and tensile stresses from the load path is taken up by the struts ties respectively. The strut-and-tie model was developed to design reinforcement for structural members with disturbed or D-regions where the linear strain distribution across depth is not possible. The successful application of strut-and-tie model depends on the reliable visualization of the flow of forces within a member using the truss elements. A truss in a strut-and-tie model comprises of tensile ties, compressive strut and nodal zones where the struts and ties intersect.

Ritter. (1899), first invented the truss analogy concept that describes the flow of forces after cracking in a concrete member using a truss model [2]. The truss analogy, as it existed in the early 1900's enabled the designer to design the section considering the effects of flexure and shear together. Schlaich and Weischede presented the concept of strut-and-tie model as an extension to the truss analogy [3]. Schlaich et al. [5] generalized the application of concepts of the truss analogy to all parts of reinforced and prestressed concrete structures in the form of the strut-and-tie model. He recommended to visualize the internal flow of forces according to linearly elastic analysis and to orient the strut and ties within 15^{o} of the elastically determined stresses. For a given member there are many truss models and orientations that will satisfy equilibrium. Truss model geometry and reinforcement detailing of the struts, ties and nodal zones is an iterative process. The tension ties represent layers of flexural reinforcement in the structure. On the other hand the struts make up the compressive stress fields having compression acting in the along direction of strut [10] (Kuchma and Tjhin 2001). In the design using strut-and-tie model it is necessary to check that crushing of struts does not occur. Nodal zones are the zones where struts, ties and exterior loads or supports intersect. St. Venant's principle suggests that the localized effect of a disturbance dies out by about one member-depth from the point of the disturbance. On this basis, D-regions are assumed to extend one member-depth each way from the discontinuity.

II. METHODOLOGY

The AASHTO LRFD Bridge Specifications states that strut-and-tie model can be used to design and determine the internal force effects near supports and points of application of loads which is covered in Article 5.6.3.2 to 5.6.3.6 of the same. Figure 2 and 3 below shows the dimension and sectional properties of the design example of the diaphragm that is discussed in the paper. The bridge considered is a single span PSC Box Girder Bridge having a span length of 40m with a total width of 8.5m (7.5m clear carriageway). The Grade of concrete used is M45 and grade of steel is Fe500.

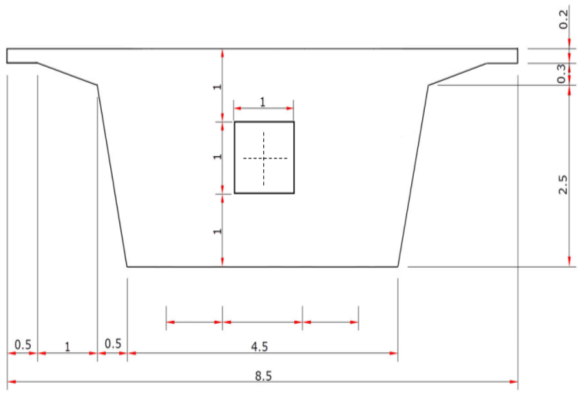
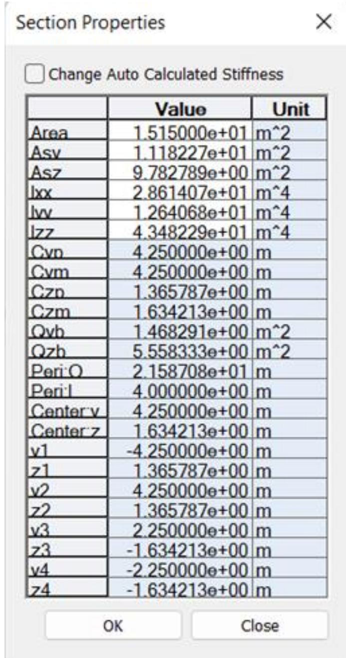


Figure 2: Diaphragm Section



	Value	Unit
Area	1.515000e+01	m^2
Asy	1.118227e+01	m^2
Asz	9.782789e+00	m^2
Ixx	2.861407e+01	m^4
Iyy	1.264068e+01	m^4
Izz	4.348229e+01	m^4
Cyp	4.250000e+00	m
Cym	4.250000e+00	m
Czp	1.365787e+00	m
Czm	1.634213e+00	m
Qyb	1.468291e+00	m^2
Qzb	5.558333e+00	m^2
Peri:O	2.158708e+01	m
Peri:I	4.000000e+00	m
Center:y	4.250000e+00	m
Center:z	1.634213e+00	m
y1	-4.250000e+00	m
z1	1.365787e+00	m
y2	4.250000e+00	m
z2	1.365787e+00	m
y3	2.250000e+00	m
z3	-1.634213e+00	m
y4	-2.250000e+00	m
z4	-1.634213e+00	m

Figure 3: Sectional Properties (Midas Civil)

IFERP connecting engineers... developing research

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Vol 9, Issue 9, September 2022

A. Load Generation

The bridge is modeled and analyzed in Midas Civil software and results obtained from the same have been further used to model and design the diaphragm using the strut-and-tie model approach. The 3D view of the box girder bridge modeled in Midas Civil is shown in Figure 4 below.

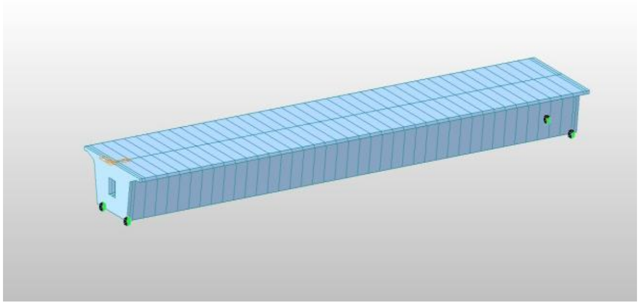


Figure 4: 40m Single Span PSC Box Girder

The loads applied in the model are in accordance with IRC: 6-2017 [10] and the reactions at the bearing location has been obtained for each load case and further corresponding load factor has been applied as per SLS and ULS Load Combination and used in the strut-and-tie model. In SLS condition only quasi-permanent load case is considered for minimum crack control reinforcement. Table 1 below shows the factored reactions for Ultimate Limit State Load conditions as per IRC:6 – 2017

Table 1: ULS Load Combinations

Load Description	Load Factor	Unfactored Load, kN		Factored Load, kN	
Dead Load	1.35	1647	1647	2223	2223
SIDL WC	1.75	165	165	289	289
SIDL CB	1.35	150	150	203	203
LL with IF	1.5	883	883	1324	1324
Total Permanent Load + LL (kN)				4039	4039

B. Defining Truss Model

Schlaich et al. (1987) [5] proposed simple criteria for optimizing a model derived from the principle of minimum strain energy for linear elastic energy for linear elastic behavior of struts and ties following the event of cracking. The contribution of the concrete struts can usually be ignored because the strains of the struts are usually much smaller than that of steel ties. The minimum number of ties required for a model can be found using the equation.

$$\Sigma F_i l_i \epsilon_{mi} = Minimum \quad (1)$$

Where, Fi = force in strut or tie, li = length of member I, $\epsilon mi = mean\ strain\ of\ member\ i$

First step in defining the truss is figuring the nodal locations. Since the diaphragm defined in the example is supported at two locations by bearings, the nodal zones are defined and shown in Figure 5. The tension ties should be modeled at the predicted location while the compressive struts are modeled to represent the primary compressive stress and defined accordingly. (Shown in Figure 5)

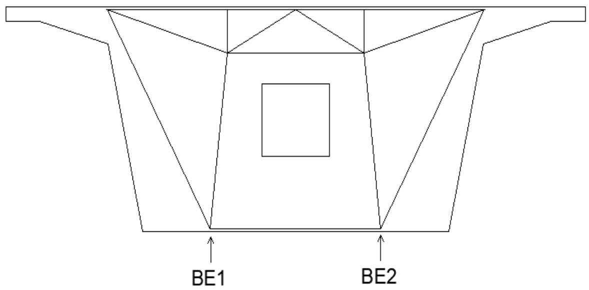
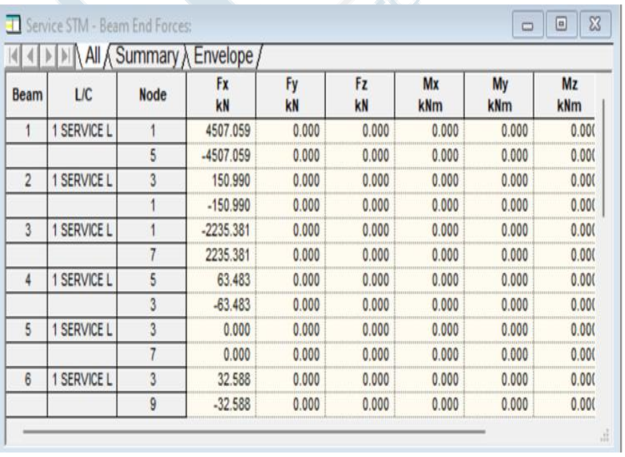


Figure 5: Truss Model for Diaphragm

C. Generating Member Forces

After performing several iterations, the truss model shown in figure 5 above was considered optimal and was used for the diaphragm analysis. Figure 6 also shows the resulting forces obtained after truss analysis. The truss analysis was performed using Staad.Pro software and the results obtained for each member was used for the design of truss elements.



Service STM - Beam End Forces:

All / Summary / Envelope

Beam	L/C	Node	Fx kN	Fy kN	Fz kN	Mx kNm	My kNm	Mz kNm
1	1 SERVICE L	1	4507.059	0.000	0.000	0.000	0.000	0.00
		5	-4507.059	0.000	0.000	0.000	0.000	0.00
2	1 SERVICE L	3	150.990	0.000	0.000	0.000	0.000	0.00
		1	-150.990	0.000	0.000	0.000	0.000	0.00
3	1 SERVICE L	1	-2235.381	0.000	0.000	0.000	0.000	0.00
		7	2235.381	0.000	0.000	0.000	0.000	0.00
4	1 SERVICE L	5	63.483	0.000	0.000	0.000	0.000	0.00
		3	-63.483	0.000	0.000	0.000	0.000	0.00
5	1 SERVICE L	3	0.000	0.000	0.000	0.000	0.000	0.00
		7	0.000	0.000	0.000	0.000	0.000	0.00
6	1 SERVICE L	3	32.588	0.000	0.000	0.000	0.000	0.00
		9	-32.588	0.000	0.000	0.000	0.000	0.00

Figure 6: Truss Analysis Results (Staad.Pro)

The results obtained in the truss elements after analyzing the truss model are given in table 3 below and figure 7 shows the member numbers.

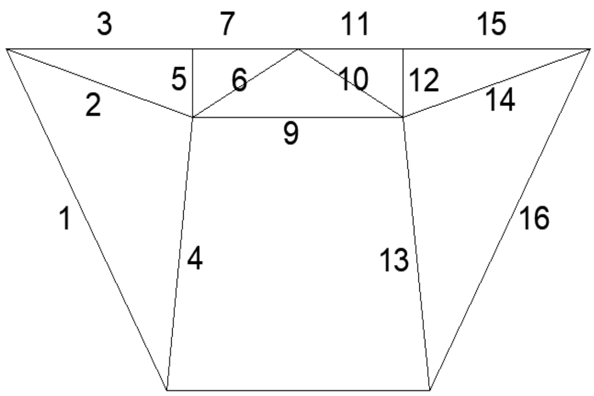


Figure 7: Member Numbers

Table 3: Truss Analysis Results

Member No.	Forces (kN)	Tension/ Compression Members	Tie/Strut
1	4507	Compression	Strut
2	151	Compression	Strut
3	-2235	Tension	Tie
4	63.5	Compression	Strut
5	0	-	-
6	32.6	Compression	Strut
7	-2235.4	Tension	Tie
8	0	-	-
9	122.1	Compression	Strut
10	-32.6	Tension	Tie
11	-2179	Tension	Tie
12	0	-	-
13	14	Compression	Strut
14	97.3	Compression	Strut
15	-2179	Tension	Tie
16	4519.2	Compression	Strut

D. Dimensioning of truss elements

The dimensioning of the compression strut, tensile ties and nodes are to be done in accordance with Article 5.6.3.2 to 5.6.3.3 of AASHTO LRDF Bridge Specifications. The axial members of the truss model must satisfy the following equation:

$$Pu \leq \emptyset Pn \quad (2)$$

Where, Pn = nominal resistance of strut and tie, ϕ = resistance factor for tension and compression given in Article 5.5.4.2.

The nominal resistance of a tensile tie must be calculated using the following equation:

$$Pn = fyAst \quad (3)$$

Where, Ast = Total area of longitudinal mild steel reinforcement in the tie, fy = yield strength of mild steel longitudinal reinforcement.

Using Pn≥ Pu/ϕ and solving the equation for Ast, the area of steel required to resist tensile load can be found, from which the area of reinforcement can be suggested based on AASHTO LRFD Specifications.

For finding the capacity of a strut the first step is to calculate the limiting compressive stress, fcu. This can be found from the equation below:

$$fcu = \frac{fc'}{0.8+170\varepsilon 1} \leq 0.85f'c \quad (4)$$

Where $\varepsilon 1 = \ \varepsilon s + (\varepsilon s + 0.002)\cot^2 \alpha s$

$\propto s$ = smallest angle between the compressive strut and adjoining tensile tie (deg), εs = tensile strain in the concrete in the direction of tensile tie, f'c = concrete compressive strength.

Based on the value of f'cu the nominal resistance can be calculated for the reinforcing pattern used in the diaphragm. AASHTO gives the following equations for the nominal resistance of a compressive strut.

$$Pn = fcu\ Acs \quad (5)$$

Where, Pn = nominal resistance of a compressive strut, fcu = limiting compressive stress as specified in Article 5.6.3.3.3, Acs = effective cross-sectional area of strut specified in Article 5.6.3.3.2

The value of Acs must determined both available concrete area and anchorage conditions at the ends of the strut as shown in figure 8 below.

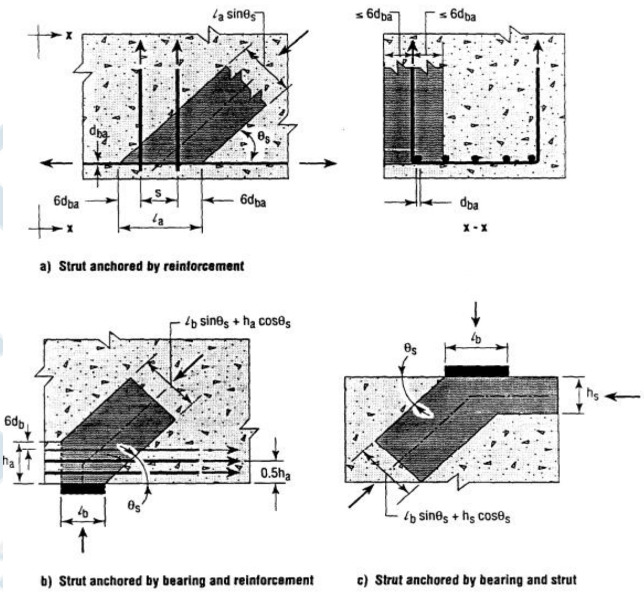


Figure 8: Anchorage conditions on effective cross-sectional area of strut (AASHTO LRFD)

Using Pn≥ Pu/ϕ and solving the equation for Acs, the area of concrete required to resist compressive load can be found.

The width of strut la, can be determined using the equations below:

i) For strut anchored by reinforcement,

$$width\ of\ strut = la sin\theta \quad (6)$$

Where, $la = 6dba + s + 6dba$

$dba = dia\ of\ bar$

$s = spacing\ between\ reinforcement\ bars\ provided$

ii) For strut anchored by bearing and reinforcement,

$$width\ of\ strut = lb\ sin\theta + hs\ cos\theta \quad (7)$$

Where, $lb = width\ of\ support$

$hs = lb/tan\theta$

iii) For strut anchored by bearing and another strut,

$$Width\ of\ strut\ = \ lb\ sin\theta + hs\ cos\theta \quad (8)$$

When compressive strut contains reinforcement parallel to the strut the following equation must be used to find the nominal resistance of the strut.

ISSN (Online) 2456-1290
International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 9, Issue 9, September 2022

$$Pn = fcuAcs + fyAss \quad (9)$$

Where, Ass = area fo reinforcement in the strut, Acs = effective cross sectional area of strut as defined in Article 5.6.3.3.2, fy = yield strength of steel.

Again in a similar manner using Pn≥ Pu/ϕ and solving for Acs, the area of concrete required to resist compressive load can be found. The value of provided Acs must be greater than Acs required.

After dimensioning the tension ties and compression struts, the levels in the nodal zones must be checked to be within limit. AASHTO LRFD specifies the stress in the nodal regions of the struts to not exceed the following:

For node regions bounded by compressive struts and bearing areas (CCC): $0.85\emptyset f'c$

For node regions anchoring a one direction tie (CCT): $0.75\emptyset f'c$

For node regions anchoring tension ties in more than one direction (CTT/TTT): $0.65\emptyset f'c$

However, it would be imprudent not to provide shear stirrups in the design of reinforced concrete. The shear design should be accomplished using a sectional approach provided by AASHTO LRFD Article 5.8.3.3. Additionally, distributed steel should be provided in accordance with relevant codal provisions and AASHTO LRFD Specifications.

III. RESULTS

Table 4: Tensile reinforcement

Tie	Pu (kN)	Φ	Fy (Mpa)	As Reqd	Dia of Bars (mm)	Spacing (mm)	Nos.	As Prov
Top	2235.4	0.9	500	4968	25	180	6	5890

Tensile reinforcement provided is 6 Nos. of 25mm Dia bars at 180 mm c/c in 2 layers within 1m width of diaphragm

As per AASHTO LRFD Article 5.6.3.3.3 the stresses in the struts are limited to fcu

As per Eq. 4 above fcu = 29.87 Mpa < 30.6

Where fc' = 36Mpa, αs = 60 Degrees, ε1 = $2.38x10^{-3}$

The required width of struts as per are given in Table 5 below

Table 5: Concrete Compression requirements

Members	Reqd. Width (mm)	Dia of Main Bars	Stirrups Spacing	Width provided
2 & 14	5	16	150	106
9	6	16	150	342
1 & 16	216	16	150	625
4 & 3	3	16	150	538

Table 6 below shows the Classification of Nodal Zones and Table 7 shows the nodal zone checks.

Table 6: Classification of Nodal Zones

Node No.	Nodal Zone Type
1	CCC
2	TT
3	CTTT
4	TT
5	TCC
6	CCCC
7	CCCT
8	CC
9	CC

Table 7: Nodal Zone Checks

Node No.	Type	Max comp. force	Acs (MM)	Stress (Mpa)	Allowable Stress	Check
1	CCC	4507	374741	12	21.42	OK
5	TCC	4519.2	374741	12.1	18.9	OK
6	CCC	151	322816	0.5	21.42	OK
7	CCCT	4519.2	374741	12.1	18.9	OK
8	CC	4507	322816	14	21.42	OK
9	CC	4519.2	374741	12.1	21.42	OK

IV. CONCLUSION

The main objective of this study was to find the reinforcing requirements for shear and flexure with the strut-and-tie model and to develop a simplified procedure for modeling bridge diaphragms for box girder bridges using the strut-and-tie model. The results from the strut-and-tie model approach were found to be satisfying and suitable for designing bridge diaphragms. The design procedure demonstrated the process for defining truss elements i.e. tensile ties, compression strut and nodal zones.

To summarize the following steps were used for designing the diaphragm by strut-and-tie model:

- Determine the reactions from the box girder superstructure which are transferred to the substructure through bearings.
- Define nodal zones.
- Define tension ties and compression struts for respective nodal zones and at depths nearly equal to the reinforcing pattern.
- Check truss continuity at every nodal zone
- Solve internal truss forces for tension ties and check compressive strut regions

- Design Tensile Ties and
- Check stresses at nodal zones.
- Revise truss as and if required
- Provide shear stirrups and distributed steel.

Although just one example is presented for service stage of bridge diaphragm but the diaphragm has to be analyzed and checked for various conditions it is exposed to, which include jacking stage which is done during maintenance and replacement of bearings and stacking condition when diaphragms and girders are stacked at the construction yard.

REFERENCES

[1] AASHTO LRFD (1998) Bridge design specifications, 2nd edn. American Association of State Highway and Transportation Officials, Washington DC
[2] Ritter, W.: The hennebique design method (Die NauweiseHennebique) (1899)
[3] Schlaich. J.; Weischede,D detailing of reinforced concrete structures. Canadian Structural Concrete Conference, Department of civil engineering, University of Toronto.
[4] Liang QQ, Xie YM, Steven GP (2002) Performance-based optimisation for strut-tie modeling of structural concrete. J StructEng
[5] schlaich J, Scha¨fer K, Jennewein M (1987) Toward a consistent design of structural concrete. J PrestressConcrInst 32(3):74–150
[6] Ahmed S, Ahmed E-S (2016) Experimental verification of strut-and-tie model for HSC deep beams without shear reinforcement. ENgStruct 117:71 85
[7] Yun YM, Ramirez JA (1996) Strength of struts and nodes in strut-tie model. J StructEng 122:20–29
[8] A Review on Strut and Tie Methods Kannan C Bhanu1* , N Ganesan2 and P V Indira3
[9] Analysis and Design of Simply Supported Deep Beams Using Strut and Tie Method Praveen Nagarajan* and T. M. Madhavan Pillai
[10] IRC: 6-2017 : Standard Specifications and code of practice for road bridges Section II: Loads and Load Combinations
[11] IRC 112-2011 : Code of practice for Concrete Road Bridges.