Structural Design Report for Deep Beam Template

Table of Contents

1. Design Conditions

1) General Characteristics

(1) Project Name : Deep Beam Template
(2) Design Code : ASSHTO LRFD
(3) Unit : Kips.in
(4) Strength Reduction Factors
Strut : 0.70
Tie : 0.90
Node : 0.70
(5) Scope of Report

The purpose of this report is to design structural concrete member using strut-tie model. The design is performed according to the ASSHTO LRFD strut-tie model provisions.

This report provides results of calculation for:

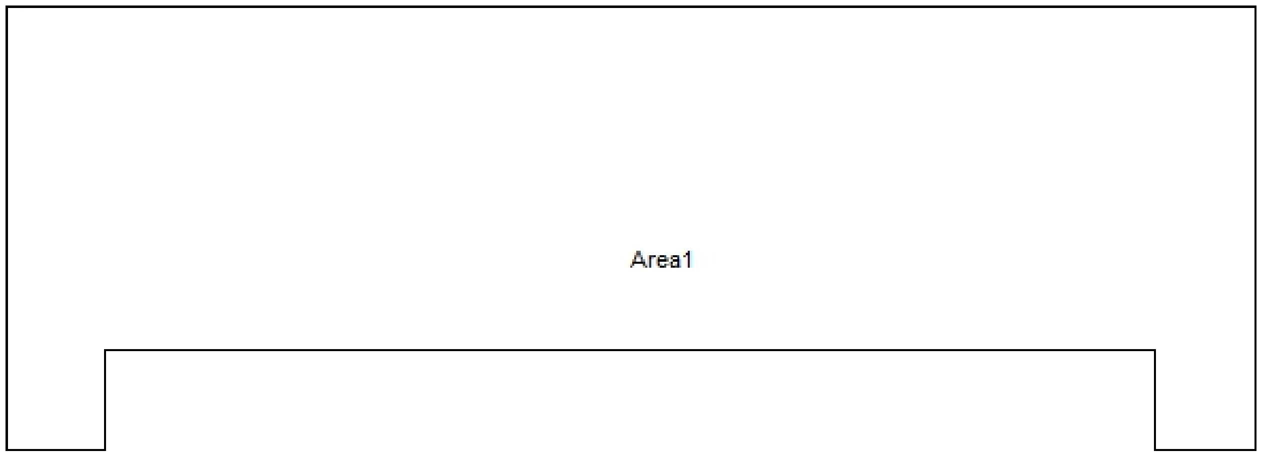
- check capacity of bearing plates
- design tie reinforcement
- check capacity of struts
- check capacity of nodal zones

2) Materials

(1) Concrete
- Mass : 147 lb/ft^3
- Weight : 149.6 lb/ft^3
- Poisson's ratio : 0.15
- Compressive Strength of Concrete, fck : 3480.9 lb/in^2
- Tensile Strength of Concrete, fct : 348.1 lb/in^2
- Elastic modulus of concrete, Ec : 4,039,177 lb/in^2

(2) Steel1
- Mass : 490 lb/ft^3
- Weight : 499.7 lb/ft^3
- Poisson's ratio : 0.15
- Yield strength of steel, fy : 58015.4 lb/in^2
- Elastic modulus of steel, Es : 29,007,699 lb/in^2

3) Geometrical Shape

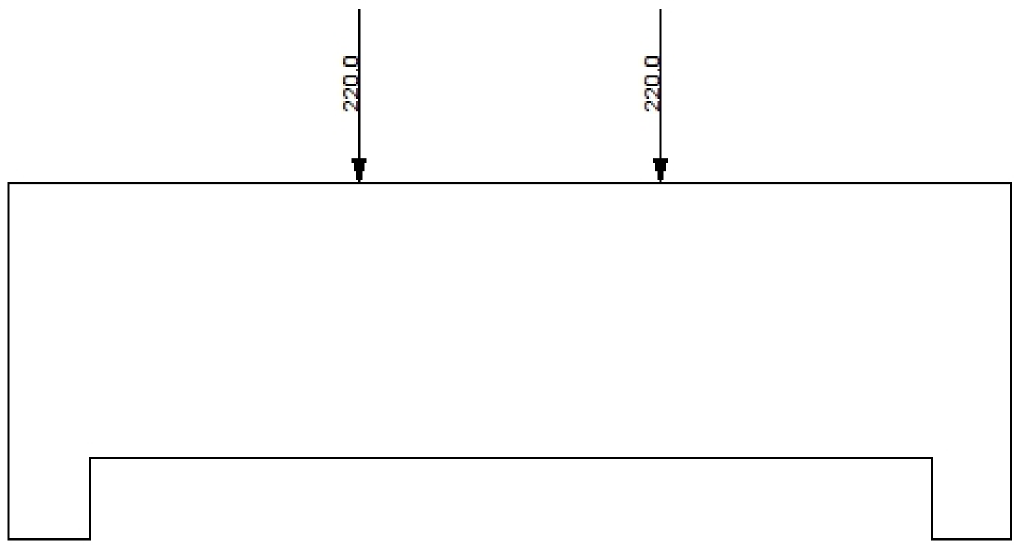


- Thickness : 14.00 in

4) Loads and Load Combinations

(1) Loads

D (Load)



(2) Load Combinations

1) LC01 : 1.00D

5) Reference

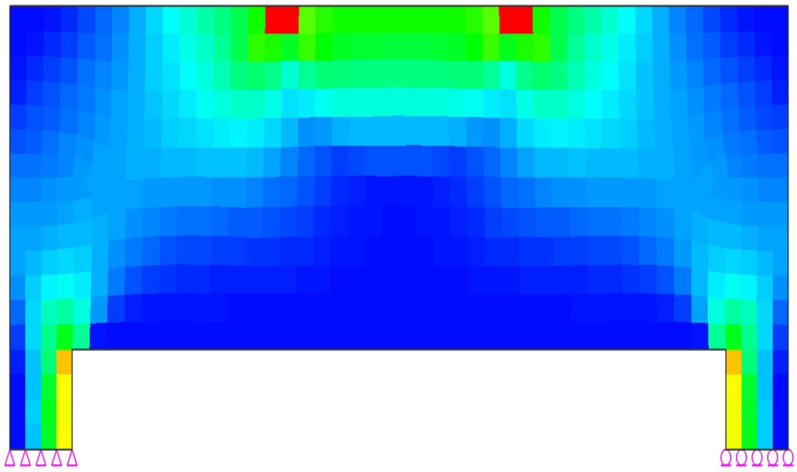
(1) Designer : Hangil IT
(2) Date : 2017-07-15
(3) Note : Design of Deep Beam using Template (AASHTO LRFD)

2. Strut-Tie Model Design (Load Combination-1)

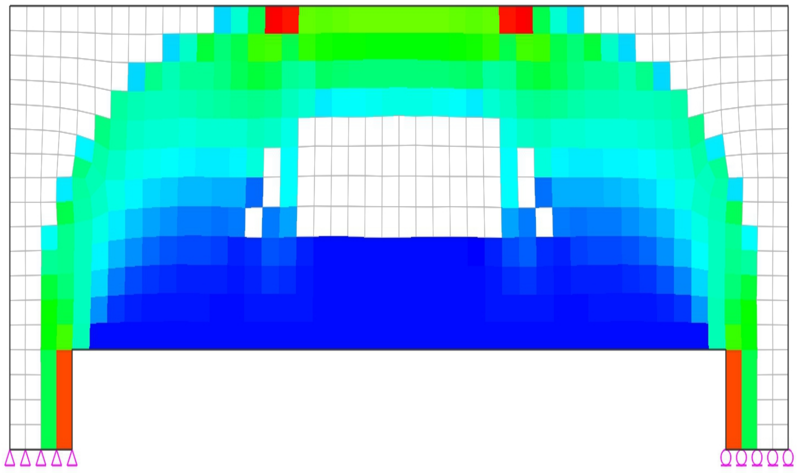
1) Construction of Strut-Tie Model

(1) ESO (Evolutionary Structural Optimization)

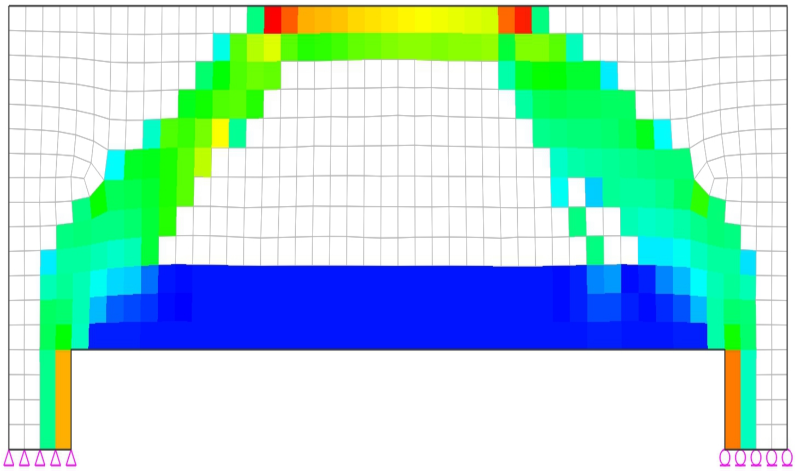
1. STAGE-01 (Initial shape)



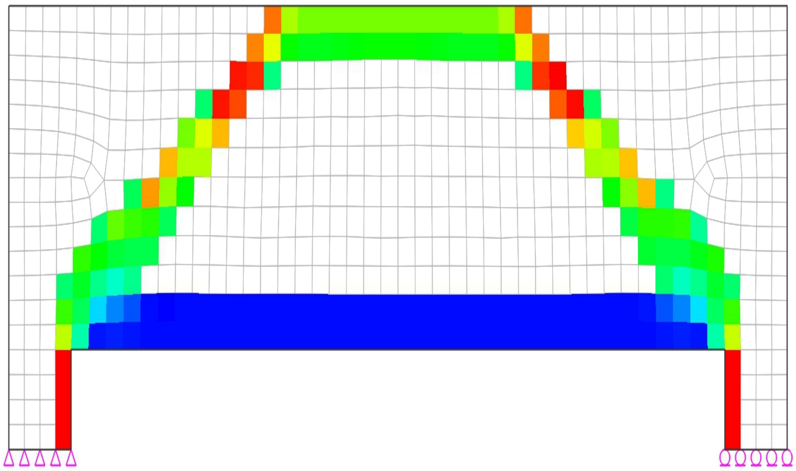
2. STAGE-05 (Elimination ratio = 32%)



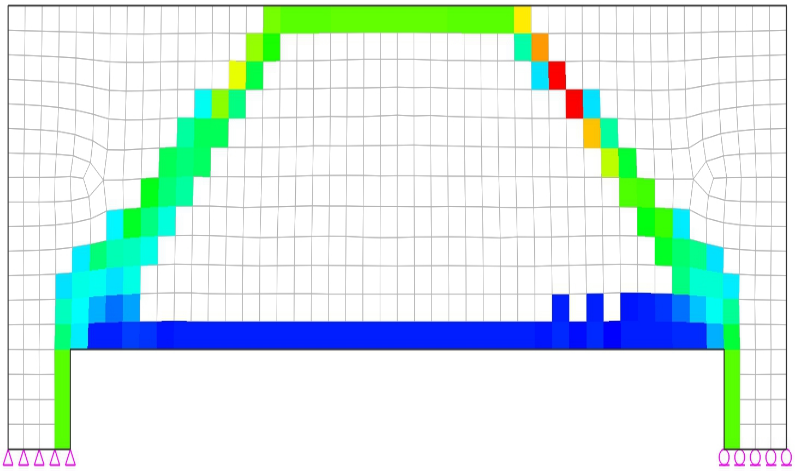
3. STAGE-09 (Elimination ratio = 53%)



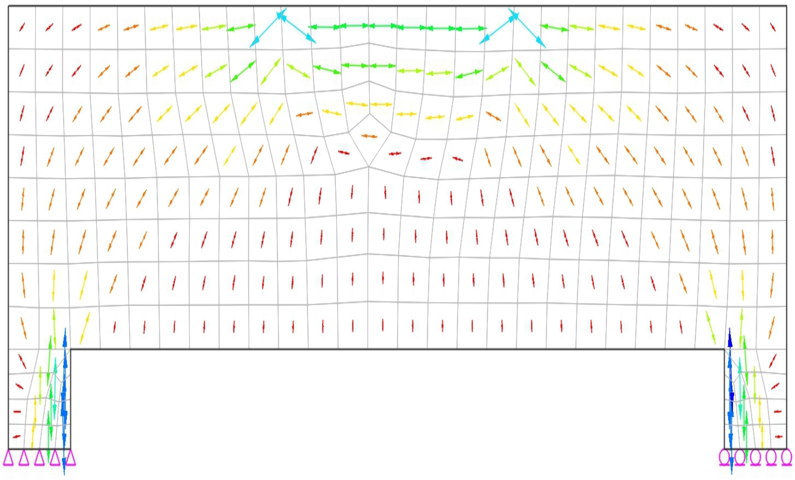
4. STAGE-13 (Elimination ratio = 69%)



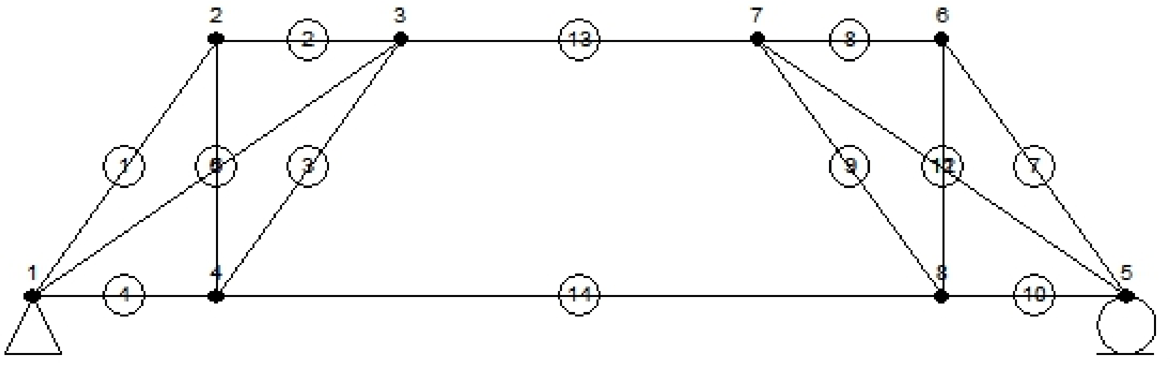
5. STAGE-16 (Elimination ratio = 78%)



(2) Compressive Principal Stress Flow



(3) Constructed Strut-Tie Model



(A) Nodal Coordinates

Node No.	X coordi.	Z coordi.	Node No.	X coordi.	Z coordi.
1	8.000	22.000	2	39.000	65.000
3	70.000	65.000	4	39.000	22.000
5	192.000	22.000	6	161.000	65.000
7	130.000	65.000	8	161.000	22.000

(B) Element Connectivity

Element No.	Start Node	End Node	Element No.	Start Node	End Node
1	1	2	2	2	3
3	3	4	4	4	1
5	2	4	6	1	3
7	5	6	8	6	7
9	7	8	10	8	5
11	6	8	12	5	7
13	3	7	14	4	8

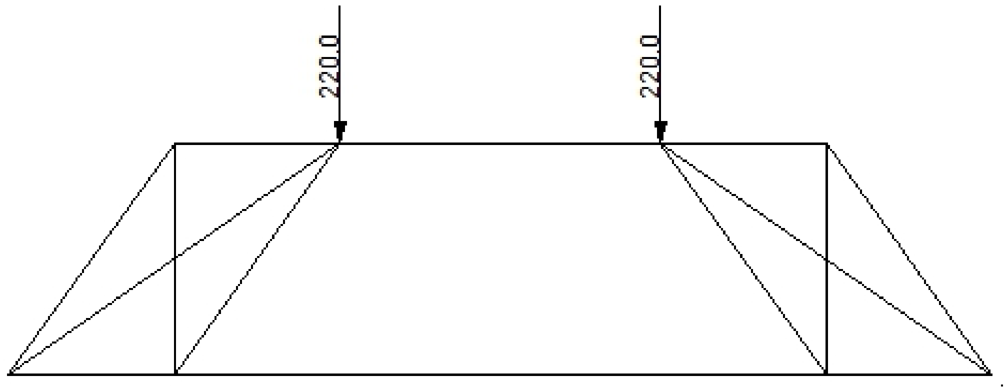
(C) Restraints

Node	Ux	Uy	Uz	Rx	Ry	Rz
1	O	O	O	O	-	O
5	-	-	O	-	-	-

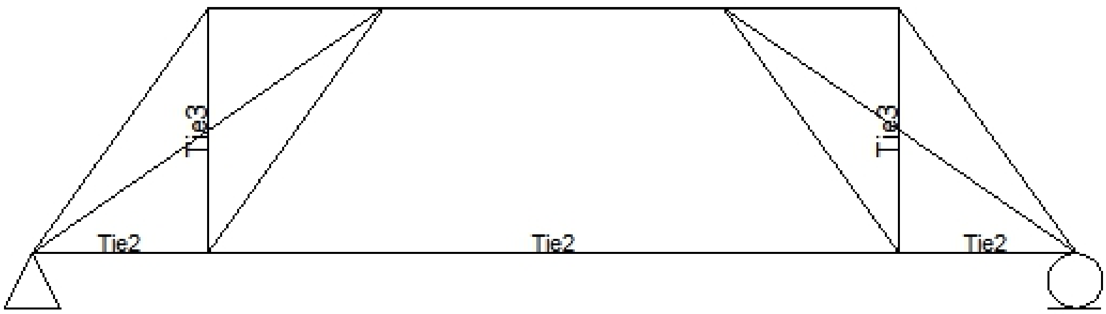
2) Analysis of Strut-Tie Model

(1) Loading Conditions

(1) (D)

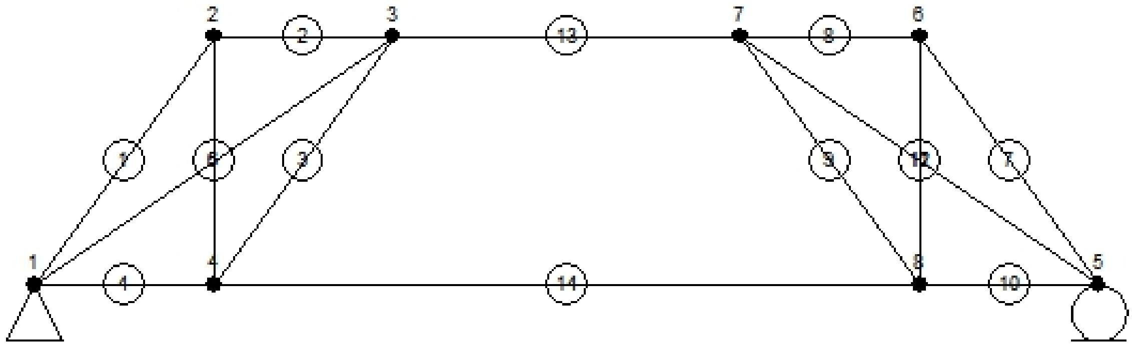


(2) Strut and Tie Types



- Tie1 : Tie for top rebars
- Tie2 : Tie for bottom rebars
- Tie3 : Tie for intermediate vertical/horizontal rebars

(3) Strut and Tie Forces



Elem. No.	Force (kip)	Elem. No.	Force (kip)	Elem. No.	Force (kip)	Elem. No.	Force (kip)
1	-68.1	2	-39.8	3	-68.1	4	277.4
5	55.2	6	-289.1	7	-68.1	8	-39.8
9	-68.1	10	277.4	11	55.2	12	-289.1
13	-317.2	14	317.2				

3) Strength Verification and Required Rebars

(1) Strength under Bearing/Loading Plates

phi fce = phi·0.65·fck > Fu / A
A = Area of bearing plates (= BxW)

Node	phi	fce(lb/in²)	Fu (kip)	B (in)	W (in)	Fu/A (lb/in²)	Note
1	0.70	1583.82	220.0	14.0	16.0	982.143	O.K
5	0.70	1583.82	220.0	14.0	16.0	982.143	O.K
3	0.70	1583.82	220.0	14.0	16.0	982.143	O.K
7	0.70	1583.82	220.0	14.0	16.0	982.143	O.K

(2) Required Area of Rebars

1) Main Rebars

(A) Horizontal Rebars

As.req = Fu / phi·fy·cos theta < As.used
where,
Fu = member force of steel tie
phi = strength reduction factor of steel tie : 0.90
fy = yield strength of steel : 58015.4 lb/in²
theta = angle of steel tie measured from positive horizontal axis
(+: counterclockwise)

Tie No.	Types	Fu (kip)	theta (deg.)	Rebars	As.req (in²)	As.used (in²)	Note
4	Bottom	62.36	0.0	8-#9	5	8	O.K
14	Bottom	71.31	0.0	8-#9	6	8	O.K

2) Transverse Rebars

(A) Horizontal-Vertical Rebars

Tie No.	Fu (kip)	theta (deg.)	Rebars	Weff,tie (in)	Sprov (in)	phi Fn (kip)	Note
5	12.42	90.0	4-#9 4-#9	1.2 1.2	0.5 0.5	123.2	O.K

phi·Fn = (phi·Avh·fy·Weff,tie·cos theta / Sh) + (phi·Av·fy·Weff,tie·sin theta / Sv) > Fu
where,
Fu = member force of steel tie
phi = strength reduction factor of steel tie : 0.90
fy = yield strength of steel : 58015.4 lb/in²

```
      theta = angle of steel tie measured from positive horizontal axis
                (+: counterclockwise)
      Sprov = spacing of vertical and horizontal rebars
   Weff,tie = effective width of tie
```

(3) Available Widths of Struts and Nodal Zones

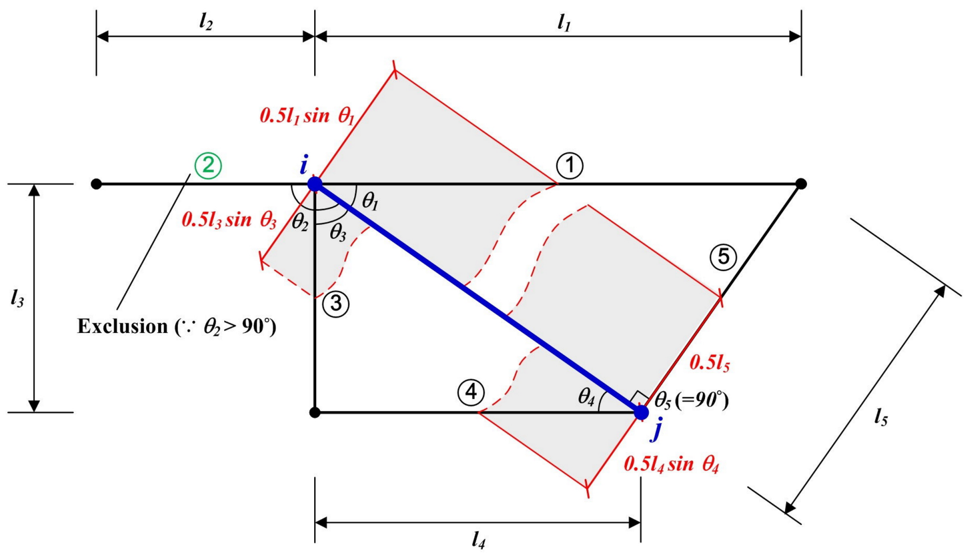
1) Node without bearing plate

The available widths of a strut at both ends and nodal zone faces are determined by taking the minimum ones from the values calculated below for case 1 and case 2.

2) Node with bearing plate

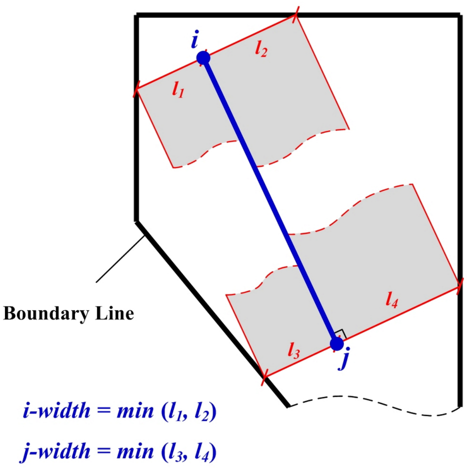
The available widths of a strut at both ends and nodal zone faces are determined by taking the values calculated below for case 3.

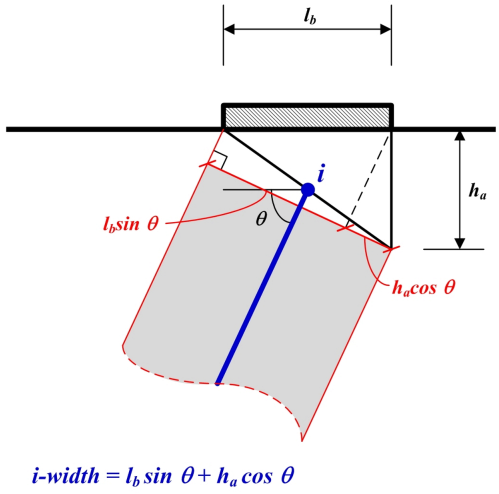
[CASE 1]



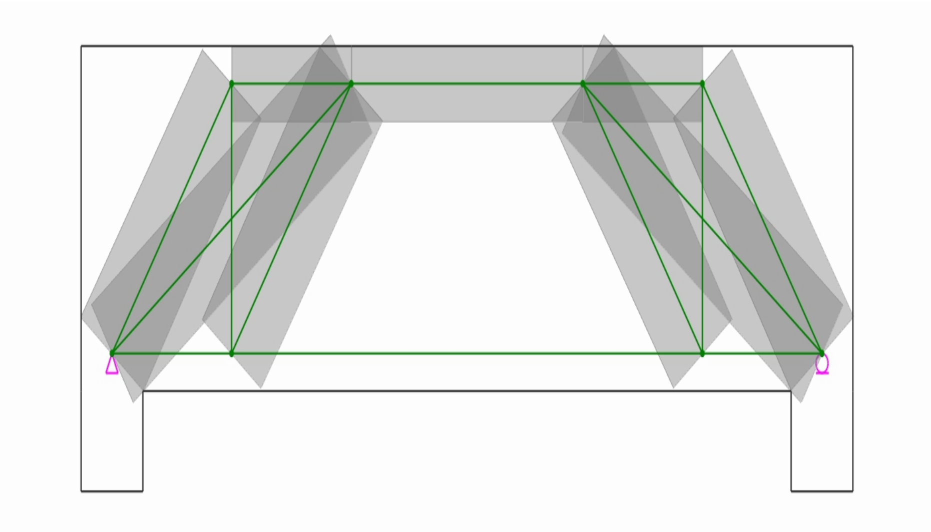
$i\text{-width} = \min\,(l_1 \sin\theta_1,\ l_3 \sin\theta_3)$

$j\text{-width} = \min\,(l_4 \sin\theta_4,\ l_5)$





The available widths of struts and ties determined by the methods introduced above are shown below



Elem. No.	i-width	j-width	Available Width	Elem. No.	i-width	j-width	Available Width
1	19.9	18.7	18.7	2	11.9	11.9	11.9
3	19.9	18.7	18.7	6	18.9	18.9	18.9
7	19.9	18.7	18.7	8	11.9	11.9	11.9
9	19.9	18.7	18.7	12	18.9	18.9	18.9
13	11.9	11.9	11.9				

(4) Strength of Struts

The verification of the strut strength should be done through comparing the available strut area with that required. In this report, because the thickness of the structural concrete is consistent, the verification will be done by comparing the available strut width, Wprov, with that required, Wreq.

```
      Wreq = Fu / phi·fcu·b < Wprov  (See AASHTO LRFD Article 5.6.3.3)
       fcu = fck / 0.8 + 170epsilon_l < 0.85
 epsilon_l = epsilon_s + ( epsilon_s + 0.002 )cot2 alpha
     alpha = The smallest angle between the compressive strut and adjoining tension ties
 epsilon_s = The tensile strain in the concrete in the direction of the tension tie
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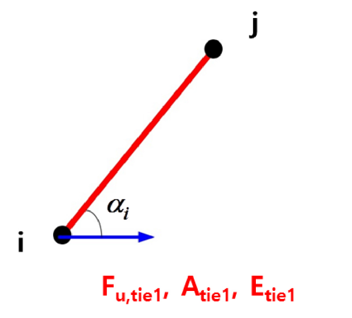
The principal tensile strain is determined by taking the maximum ones from the values calculated below for six cases.

- Case 1



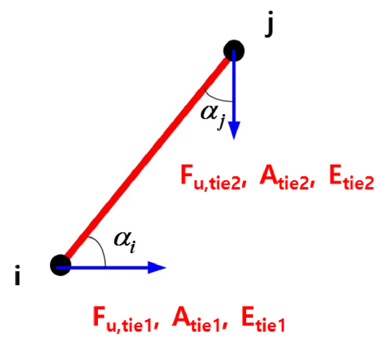
$$\varepsilon_{s,inode} = F_{u,tie1} \Big/ A_{tie1} E_{tie1}$$

$$\varepsilon_{s,inode,adjust} = \frac{1}{2}\varepsilon_{s,inode}$$

$$\varepsilon_{1,inode} = \varepsilon_{s,inode,adjust} + (\varepsilon_{s,inode,adjust} + 0.002)\cot^2 a_i$$

$$\varepsilon_1 = \varepsilon_{1,inode}$$

- Case 2



$$\varepsilon_{s,inode} = F_{u,tie1} \Big/ A_{tie1} E_{tie1}$$

$$\varepsilon_{s,jnode} = F_{u,tie2} \Big/ A_{tie2} E_{tie2}$$

$$\varepsilon_{s,inode,adjust} = \frac{1}{2}\varepsilon_{s,inode}$$

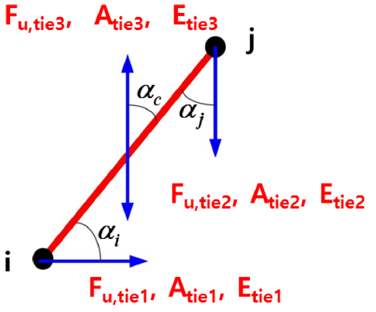
$$\varepsilon_{s,jnode,adjust} = \frac{1}{2}\varepsilon_{s,jnode}$$

$$\varepsilon_{1,inode} = \varepsilon_{s,inode,adjust} + (\varepsilon_{s,inode,adjust} + 0.002)\cot^2 a_i$$

$$\varepsilon_{1,jnode} = \varepsilon_{s,jnode,adjust} + (\varepsilon_{s,jnode,adjust} + 0.002)\cot^2 a_j$$

$$\varepsilon_1 = \max.\left[\varepsilon_{1,inode},\ \ \varepsilon_{1,jnode}\right]$$

- Case 3



$$\varepsilon_{s,inode} = \frac{F_{u,tie1}}{A_{tie1}E_{tie1}} \qquad \varepsilon_{s,jnode} = \frac{F_{u,tie2}}{A_{tie2}E_{tie2}} \qquad \varepsilon_{s,center} = \frac{F_{u,tie3}}{A_{tie3}E_{tie3}}$$

$$\varepsilon_{s,inode,adjust} = \frac{1}{2}\varepsilon_{s,inode} \qquad \varepsilon_{s,jnode,adjust} = \frac{1}{2}\varepsilon_{s,jnode}$$

$$\varepsilon_{s,center,adjust} = \varepsilon_{s,cener}$$

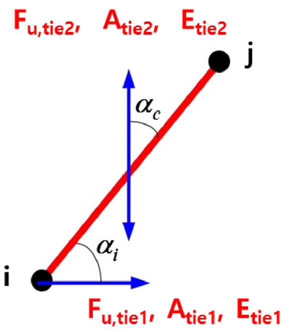
$$\varepsilon_{1,inode} = \varepsilon_{s,inode,adjust} + (\varepsilon_{s,inode,adjust} + 0.002)\cot^2 \boldsymbol{a}_i$$

$$\varepsilon_{1,jnode} = \varepsilon_{s,jnode,adjust} + (\varepsilon_{s,jnode,adjust} + 0.002)\cot^2 \boldsymbol{a}_j$$

$$\varepsilon_{1,center} = \varepsilon_{s,center,adjust} + (\varepsilon_{s,center,adjust} + 0.002)\cot^2 \boldsymbol{a}_c$$

$$\varepsilon_1 = \max.\left[\varepsilon_{1,inode},\ \ \varepsilon_{1,jnode},\ \ \varepsilon_{1,center}\right]$$

- Case 4



$$\varepsilon_{s,inode} = \frac{F_{u,tie1}}{A_{tie1}E_{tie1}} \qquad \varepsilon_{s,center} = \frac{F_{u,tie2}}{A_{tie2}E_{tie2}}$$

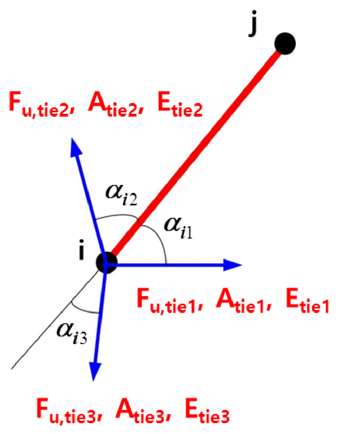
$$\varepsilon_{s,inode,adjust} = \frac{1}{2}\varepsilon_{s,inode} \qquad \varepsilon_{s,center,adjust} = \varepsilon_{s,cener}$$

$$\varepsilon_{1,inode} = \varepsilon_{s,inode,adjust} + (\varepsilon_{s,inode,adjust} + 0.002)\cot^2 \boldsymbol{a}_i$$

$$\varepsilon_{1,center} = \varepsilon_{s,center,adjust} + (\varepsilon_{s,center,adjust} + 0.002)\cot^2 \boldsymbol{a}_c$$

$$\varepsilon_1 = \max.\left[\varepsilon_{1,inode},\ \ \varepsilon_{1,center}\right]$$

- Case 5



$$\varepsilon_{s,inode,tie1} = \frac{F_{u,tie1}}{A_{tie1}E_{tie1}} \quad \varepsilon_{s,inode,tie2} = \frac{F_{u,tie2}}{A_{tie2}E_{tie2}} \quad \varepsilon_{s,inode,tie3} = \frac{F_{u,tie3}}{A_{tie2}E_{tie3}}$$

$$\varepsilon_{s,inode,tie1,adjust} = \frac{1}{2}\varepsilon_{s,inode,tie1} \quad \varepsilon_{s,inode,tie2,adjust} = \frac{1}{2}\varepsilon_{s,inode,tie2}$$

$$\varepsilon_{s,inode,tie3,adjust} = \frac{1}{2}\varepsilon_{s,inode,tie3}$$

$$\varepsilon_{1,inode,tie1} = \varepsilon_{s,inode,tie1,adjust} + (\varepsilon_{s,inode,tie1,adjust} + 0.002)\cot^2 a_{i1}$$

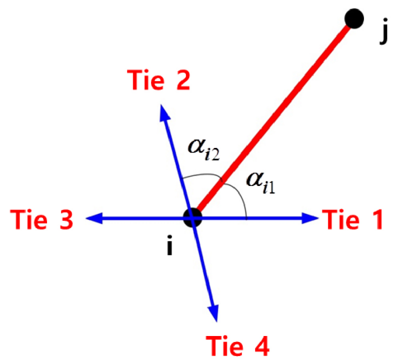
$$\varepsilon_{1,inode,tie2} = \varepsilon_{s,inode,tie2,adjust} + (\varepsilon_{s,inode,tie2,adjust} + 0.002)\cot^2 a_{i2}$$

$$\varepsilon_{1,inode,tie3} = \varepsilon_{s,inode,tie3,adjust} + (\varepsilon_{s,inode,tie3,adjust} + 0.002)\cot^2 a_{i3}$$

$$\varepsilon_{1,inode} = \max.\left[\varepsilon_{1,inode,tie1},\ \varepsilon_{1,inode,tie2},\ \varepsilon_{1,inode,tie3}\right]$$

$$\varepsilon_1 = \varepsilon_{1,inode}$$

- Case 6



$$\varepsilon_{s,inode,tie1} = \frac{F_{u,tie1}}{A_{tie1}E_{tie1}} \quad \varepsilon_{s,inode,tie2} = \frac{F_{u,tie2}}{A_{tie2}E_{tie2}}$$

$$\varepsilon_{s,inode,tie3} = \frac{F_{u,tie3}}{A_{tie2}E_{tie3}} \quad \varepsilon_{s,inode,tie4} = \frac{F_{u,tie4}}{A_{tie4}E_{tie4}}$$

$$\varepsilon_{s,inode,tie1,adjust} = \frac{1}{2}\varepsilon_{s,inode,tie1} \quad \varepsilon_{s,inode,tie2,adjust} = \frac{1}{2}\varepsilon_{s,inode,tie2}$$

$$\varepsilon_{s,inode,tie3,adjust} = \frac{1}{2}\varepsilon_{s,inode,tie3} \quad \varepsilon_{s,inode,tie4,adjust} = \frac{1}{2}\varepsilon_{s,inode,tie4}$$

$$\varepsilon_{s,inode,tie1\&3} = \varepsilon_{s,inode,tie1,adjust} + \varepsilon_{s,inode,tie3,adjust}$$

$$\varepsilon_{s,inode,tie2\&4} = \varepsilon_{s,inode,tie2,adjust} + \varepsilon_{s,inode,tie4,adjust}$$

$$\varepsilon_{1,inode,tie1\&3} = \varepsilon_{s,inode,tie1\&3} + (\varepsilon_{s,inode,tie1\&3} + 0.002)\cot^2 a_{i1}$$

$$\varepsilon_{1,inode,tie2\&4} = \varepsilon_{s,inode,tie2\&4} + (\varepsilon_{s,inode,tie2\&4} + 0.002)\cot^2 a_{i2}$$

$$\varepsilon_{1,inode} = \max.\left[\varepsilon_{1,inode,tie1\&3},\ \varepsilon_{1,inode,tie2\&4}\right]$$

$$\varepsilon_1 = \varepsilon_{1,inode}$$

- Effective strength of concrete struts

Strut No.	Tie No.	Tie Force (kip)	epsilon_s	alpha (deg.)	epsilon_l	epsilon_l,max	nu (=fcu/fck)
1	4	277.40	0.00120	54.2	0.00195	0.00411	0.66700
	5	55.25	0.00018	35.8	0.00411		
2	5	55.25	0.00018	90.0	0.00009	0.00009	0.85000
3	4	277.40	0.00120	54.2	0.00299	0.00411	0.66700
	14	317.20	0.00137	54.2	0.00299		
	5	55.25	0.00018	35.8	0.00411		
6	4	277.40	0.00120	34.7	0.00600	0.00600	0.54900
	5	55.25	0.00018	55.3	0.00123		
7	10	277.40	0.00120	54.2	0.00195	0.00411	0.66700
	11	55.25	0.00018	35.8	0.00411		
8	11	55.25	0.00018	90.0	0.00009	0.00009	0.85000
9	10	277.40	0.00120	54.2	0.00299	0.00411	0.66700
	14	317.20	0.00137	54.2	0.00299		
	11	55.25	0.00018	35.8	0.00411		
12	10	277.40	0.00120	34.7	0.00600	0.00600	0.54900
	11	55.25	0.00018	55.3	0.00123		
13		0.00	0.00000	0.0	0.00000	0.00000	0.85000

- Check strength of concrete struts

Strut No.	nu	theta	Fu (kip)	phi	Wreq (in)	Wprov (in)	Note
1	0.67	54.2	68.1	0.70	3.0	18.7	O.K
2	0.85	0.0	39.8	0.70	1.4	12.0	O.K
3	0.67	54.2	68.1	0.70	3.0	18.7	O.K
6	0.55	34.7	289.1	0.70	15.4	19.0	O.K
7	0.67	54.2	68.1	0.70	3.0	18.7	O.K
8	0.85	0.0	39.8	0.70	1.4	12.0	O.K
9	0.67	54.2	68.1	0.70	3.0	18.7	O.K
12	0.55	34.7	289.1	0.70	15.4	19.0	O.K
13	0.85	0.0	317.2	0.70	10.9	12.0	O.K

(5) Strength of Nodal Zones

The verification of the nodal zone strength should be done through comparing the available nodal zone area with that required. In this report, if the thickness of the structural concrete is consistent, the verification will be done by comparing the available nodal zone width, Wprov, with that required, Wreq

Wreq = Fu / phi·nu·fck·b < Wprov (See AASHTO LRFD Article 5.6.3.5)

nu = 0.85 (for node regions bounded by compressive struts and bearing areas)
0.75 (for node regions anchoring a one-direction tension tie)
0.65 (for node regions anchoring tension ties in more than one direction)

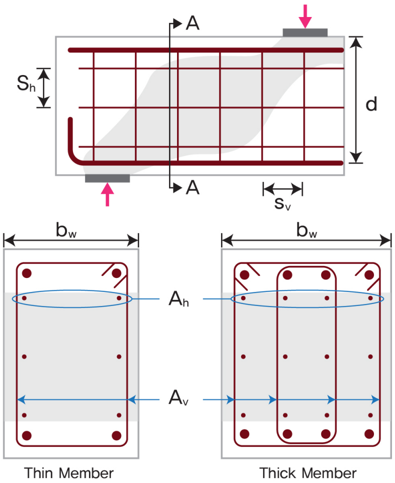
Node No.	nu	Type	Element	Fu (kip)	Wreq (in)	Wprov (in)	Note
1	0.75	CCT	R	220.0	8.6	16.0	O.K
			C-1	68.1	2.7	20.0	O.K
			T-4	277.4	10.8	12.0	O.K
			C-6	289.1	11.3	19.0	O.K
2	0.75	CCT	C-1	68.1	2.7	18.7	O.K
			C-2	39.8	1.6	12.0	O.K
			T-5	55.2	2.2	31.0	O.K
3	0.85	CCC	V	49.5	1.7	16.0	O.K
			C-2	39.8	1.4	12.0	O.K
			C-3	68.1	2.3	20.0	O.K
			C-6	289.1	10.0	19.0	O.K
			C-13	317.2	10.9	12.0	O.K
4	0.65	CTT	C-3	68.1	3.1	18.7	O.K
			T-4	-	-	-	-
			T-5	55.2	2.5	31.0	O.K
			T-14	39.8	1.8	12.0	O.K
5	0.75	CCT	R	220.0	8.6	16.0	O.K
			C-7	68.1	2.7	20.0	O.K
			T-10	277.4	10.8	12.0	O.K
			C-12	289.1	11.3	19.0	O.K
6	0.75	CCT	C-7	68.1	2.7	18.7	O.K
			C-8	39.8	1.6	12.0	O.K
			T-11	55.2	2.2	31.0	O.K
7	0.85	CCC	V	49.5	1.7	16.0	O.K
			C-8	39.8	1.4	12.0	O.K
			C-9	68.1	2.3	20.0	O.K
			C-12	289.1	10.0	19.0	O.K
			C-13	317.2	10.9	12.0	O.K
8	0.65	CTT	C-9	68.1	3.1	18.7	O.K
			T-10	-	-	-	-
			T-11	55.2	2.5	31.0	O.K
			T-14	39.8	1.8	12.0	O.K

C: compression; T: tension; V: vertical force; H: horizontal force

4) Detailed design

(1) Calculate the minimum reinforcement for crack control

Structures and components or regions thereof, except for slabs and footings, which have been designed in accordance with the provisions of Article 5.6.3, shall contain orthogonal grids of reinforcing bars. The spacing of the bars in these grid shall not exceed the smaller of d/4 and 300 mm.
The reinforcement in the vertical and horizontal direction shall satisfy the following:



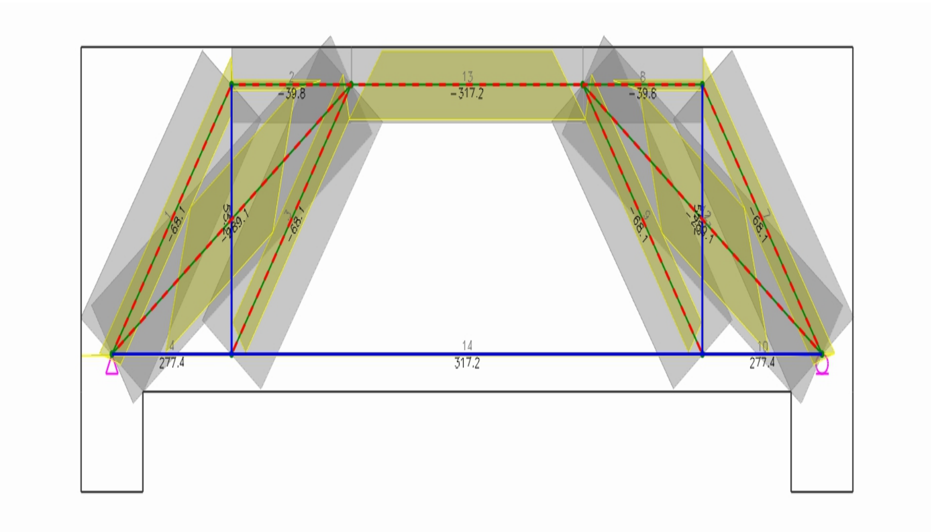
$(A_v / b_w S_v) > 0.003$
$(A_h / b_w S_h) > 0.003$

Elem. No.	Av (in²)	Sv (in)	Ah (in²)	Sh (in)	Av/(bw·Sv)	Ah/(bw·Sh)	Note
1	4.0	11.8	4.0	11.8	0.0242	0.0242	O.K
3	4.0	11.8	4.0	11.8	0.0242	0.0242	O.K
6	4.0	11.8	4.0	11.8	0.0242	0.0242	O.K
7	4.0	11.8	4.0	11.8	0.0242	0.0242	O.K
9	4.0	11.8	4.0	11.8	0.0242	0.0242	O.K
12	4.0	11.8	4.0	11.8	0.0242	0.0242	O.K

3. Summary

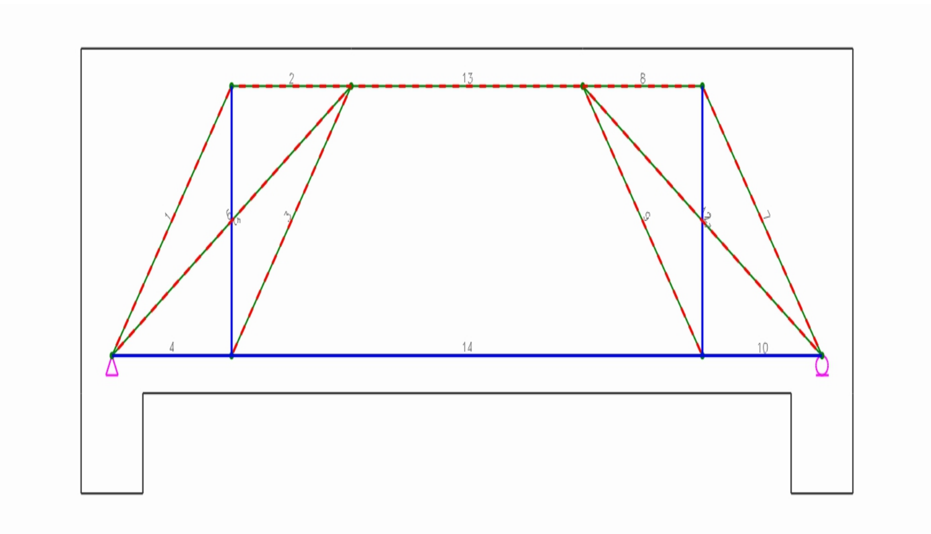
1) Dimensioned Shape

1) Load Combination - 1



2) Required and Used Areas of Rebars

1) Load Combination - 1



(A) Main Rebars

Tie No.	Types	Fu (kip)	theta (deg.)	Rebars	As.req (in^2)	As.used (in^2)	Note
4	Bottom	62.36	0.0	8-#9	5	8	O.K

14	Bottom	71.31	0.0	8-#9	6	8	O.K

(B) Transverse Rebars

- Horizontal-Vertical Rebars

Tie No.	Fu (kip)	theta (deg.)	Rebars	Weff,tie (in)	Sprov (in)	phi Fn (kip)	Note
5	12.42	90.0	4-#9 4-#9	1.2 1.2	0.5 0.5	123.2	O.K