midas Civil

Integrated Solution System For Bridge And Civil Engineering

Advanced Application

Box Culvert Design as per AASHTO LRFD

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1. General

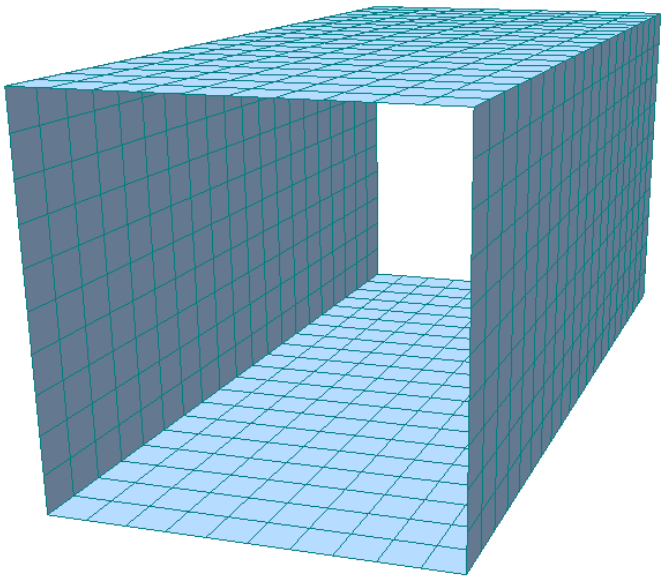
1. Overview

Box culvert is a usually default buried structure type that serves a variety of purposes. It is typically used for conveying water and also frequently used for pedestrian or cattle underpasses. Box culvert can be provided in both 'Precast Concrete Box Culvert' and 'Cast-In-Place Concrete Box Culverts' form. Currently, most box culvert installations are provided in precast form due to the huge reduction of time for place production and construction.

Example: Precast Box Culvert

Image:
CPM. 2016. *CPM, A leading UK manufacturer of precast concrete products*. [ONLINE] Available at: http://www.cpm-group.com/products/drainage/box-culverts/. [Accessed 1 September 2017].

Design new reinforced concrete culverts and extensions to existing culverts subjected to either earth fill and/or highway vehicle loading in accordance with the AASHTO LRFD Bridge Design Specifications. Precast concrete box culvert will be used in this design tutorial.



Simple Box Culvert model

2. Structure Information

Material Properties

➢ Concrete

Material:	:	ASTM (RC) Grade C5000
Compressive Strength f'c	:	5 ksi

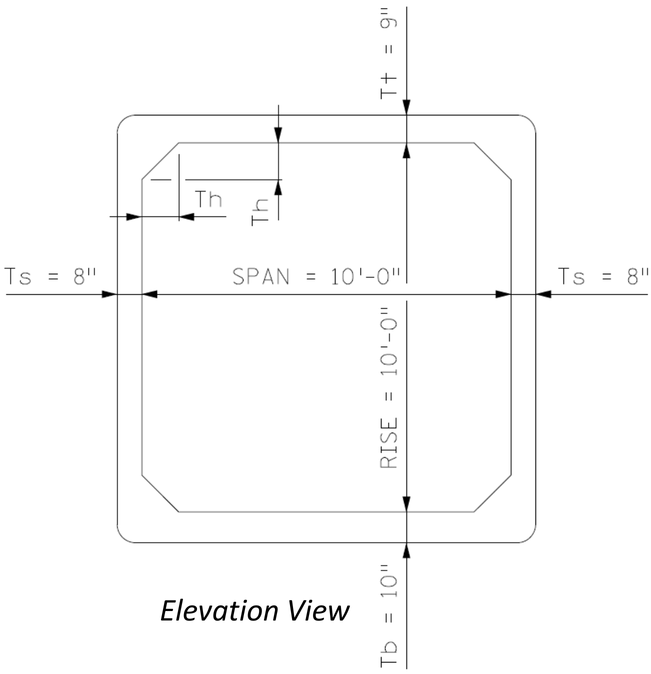
➢ Reinforcement

Material	:	ASTM (RC) Grade 60
Yield Strength fy	:	60 ksi
Reinforced Concrete Unit Weight	:	0.150 kcf

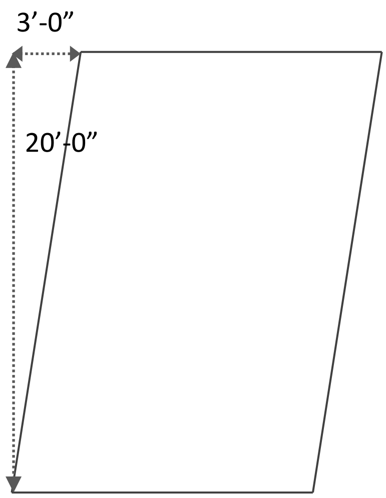
➢ Others

Soil Fill Unit Weight	:	0.120 kcf
Culvert Backfill Angle of Internal Friction	:	30 degrees
Water Unit Weight	:	0.0624 kcf
Coefficient of Subgrade reaction k_1	:	300 lb/in^3 (Dense sand)

Precast Box Culvert Geometry



Elevation View



Plan View (Skewed)

Span	:	10 ft
Top Slab Thickness, Tt	:	9 in
Bottom Slab Thickness, Tb	:	10 in
Wall Thickness, Ts	:	8 in
Haunch Thickness, Th	:	12 in
Reinforcement Clear Cover	:	2 in
Height of earth fill	:	6 ft

Note:
Reference document from MnDOT has been used for this design guide.

LRFD BRIDGE DESIGN. (2013). 1st ed. [ebook] Minnesota: MnDOT, pp.1-54. Available at: http://www.dot.state.mn.us/bridge/pdf/lrfdmanual/section12.pdf [Accessed 16 Aug. 2017].

Note
The minimum wall thickness for all box culverts is 8 inches and it can be increased with the clear span length. The minimum slab thickness for culverts with spans of 6 – 8 feet is 8 inches. The minimum top slab thickness is 9 inches where the minimum bottom slab is 10 inches for all culverts with spans lager than 8 inches.

2. Boundary Condition

1. Boundary Condition

For the boundary condition of the box culvert structure, coefficient of subgrade modulus of the rectangular foundation is calculated and applied as surface spring support feature in midas Civil. The value of the coefficient of subgrade reaction is not a constant for a given soil. It depends on several factors, such as length, L and width, B, of the foundation. Terzaghi equation is used for the calculation of modulus of subgrade reaction.

2. Foundations on Sandy Soils

$$k = k_1\left(\frac{B+1}{2B}\right)^2$$

$$= 300\left(\frac{10+1}{2\cdot 10}\right)^2 = 90.75\ lb/in^3$$

Where: *k and k_1 = coefficients of subgrade reaction of foundations measuring 1 ft x 1ft and B (ft) x B (ft), respectively (unit is lb/in^3)*

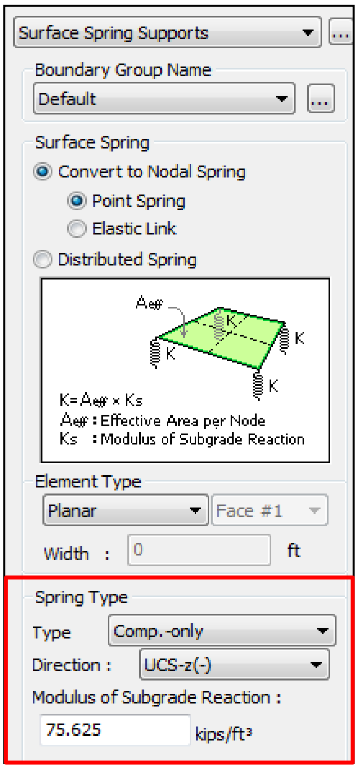
For rectangular foundations having dimensions of *B x L*.

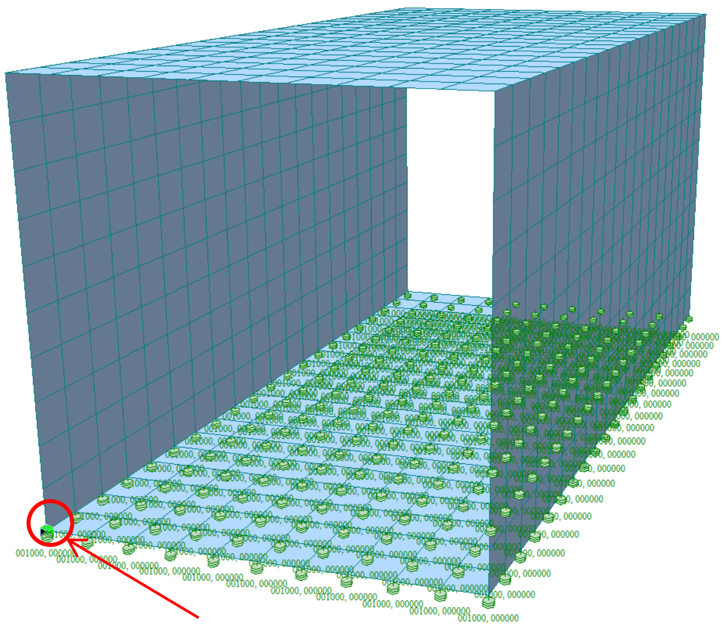
$$k = \frac{k_{(BxB)}\left(1+0.5\frac{B}{L}\right)}{1.5}$$

$$= \frac{90.75\left(1+0.5\frac{10}{20}\right)}{1.5} = 75.625\ lb/in^3$$

Note
Due to the nature of the soil, it cannot resist against tension. Therefore compression-only spring support is applied to the structure as boundary condition. The modulus of subgrade reaction is calculated using Terzaghi equation.

- *Boundary > Spring Supports > Surface Spring*





Support is applied to restrain Dx, Dy and Rz in order to prevent singular error.

Surface Spring Supports applied to the bottom slab of the box culvert

1. Self-Weight

Apply Self-Weight using Self-Weight function .

2. Vertical Earth Pressure (EV)

The weight of fill on top of the culvert produces vertical earth pressure (EV). The fill height is measured from the top surface of the top slab to the top of the pavement or fills. The unit weight of the fill is 0.120 kcf

The weight of earth fill shall be increased for soil-structure interaction. The soil-structure interaction factor, Fe for embankment installations is taken as follows:

$$F_e = 1 + 0.20\frac{H}{B_c} \leq 1.15 = 1 + 0.20 \cdot \left(\frac{6}{2 \cdot 0.67 \cdot 10}\right) = 1.11$$

$$\begin{aligned} EV &= F_e \cdot \gamma_s \cdot H \cdot w \\ &= 1.11 \cdot 0.120 \cdot 6 \cdot 1 = 0.799 \text{ klf} \end{aligned}$$

Where: *H = Design fill depth*
Bc = Total width of culvert normal to centerline
γs = Soil fill unit weight
w = Unit width

3. Horizontal Earth Pressure (EH)

The lateral earth pressure (EH) on the culvert is found using the equivalent fluid method.

Max equivalent fluid unit weight = 0.060 kcf
Min equivalent fluid unit weight = 0.030 kcf

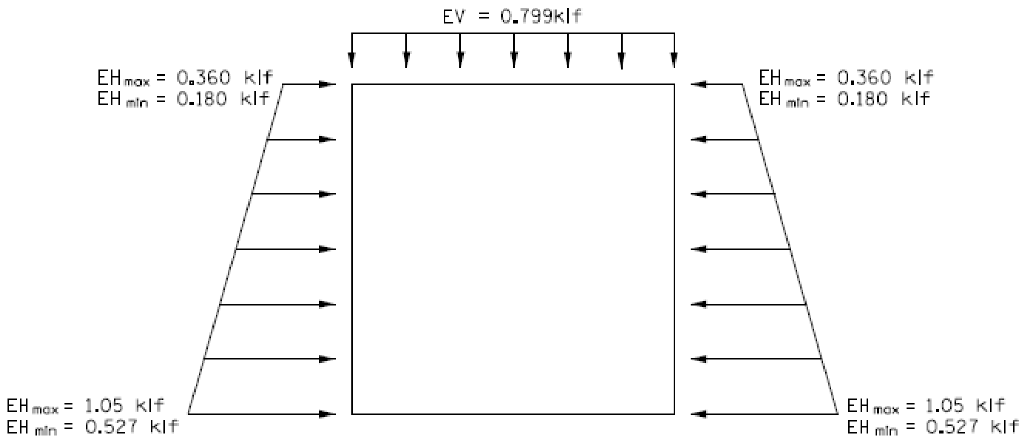
At the top of the culvert, the lateral earth pressure is:

$$\begin{aligned} EH_{max} &= \gamma_{max} \cdot H \cdot w \\ &= 0.060 \cdot 6 \cdot 1 = 0.360 \text{ klf} \\ EH_{min} &= \gamma_{min} \cdot H \cdot w \\ &= 0.030 \cdot 6 \cdot 1 = 0.180 \text{ klf} \end{aligned}$$

At the bottom of the culvert, the lateral earth pressure is:

$$\begin{aligned} EH_{max} &= \gamma_{max} \cdot (H + Tt + Rise + Tb) \cdot w \\ &= 0.060 \cdot (6 + 0.75 + 10 + 0.83) \cdot 1 = 1.05 \text{ klf} \end{aligned}$$

$$\begin{aligned} EH_{min} &= \gamma_{min} \cdot (H + Tt + Rise + Tb) \cdot w \\ &= 0.03 \cdot (6 + 0.75 + 10 + 0.83) \cdot 1 = 0.527 \text{ klf} \end{aligned}$$



Summary of Earth Pressure on the structure

4. Water Pressure (WA)

Designers need to consider load cases where the culvert is full of water as well as cases where the culvert is empty. A simple hydrostatic distribution is used for the water load:

$$WA_{top} = 0.00 \text{ klf}$$
$$WA_{bottom} = \gamma_w \cdot Rise \cdot w$$
$$= 0.064 \cdot 10 \cdot 1 = 0.624 \text{ klf}$$

5. Design Vehicular Live Load (LL): HL-93

All box culverts shall be designed for the axle loads of the HL-93 design vehicular live loading. The approximate strip method is used for design with the 1 foot wide design strip oriented parallel to the span. For box culvert with spans of 15 feet or greater lane loads are also applied to the top slabs of box culverts.

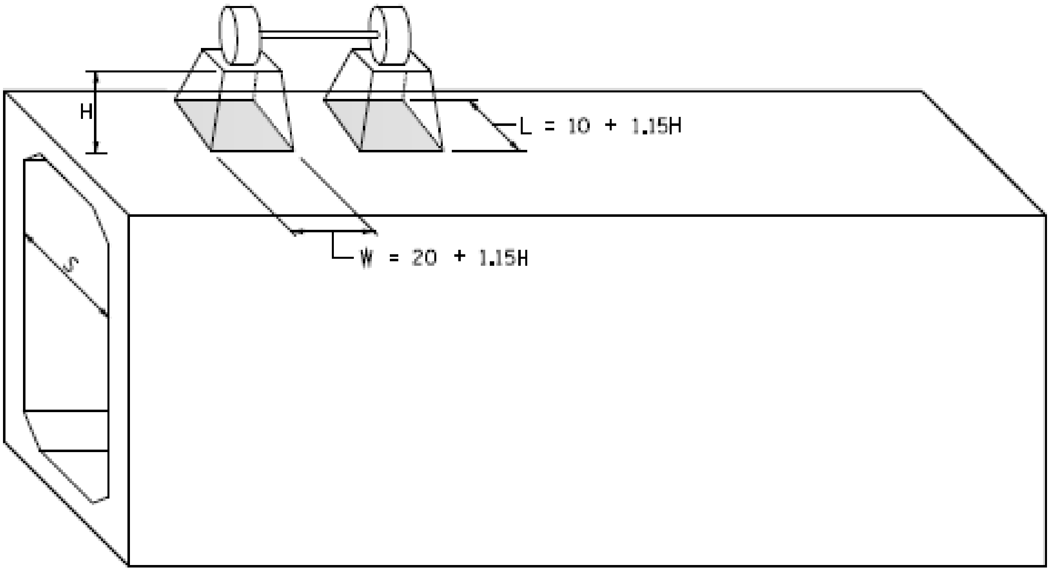
Dynamic Load Allowance (IM) for culverts shall be considered with depth of fill over the culvert lass than 8ft. The equation to calculate the dynamic load allowance is as follows:

$$IM = 33 \cdot (1.0 - 0.125 \cdot D_E) \geq 0\%$$
$$= 33 \cdot (1.0 - 0.125 \cdot 6) = 8.3\%$$

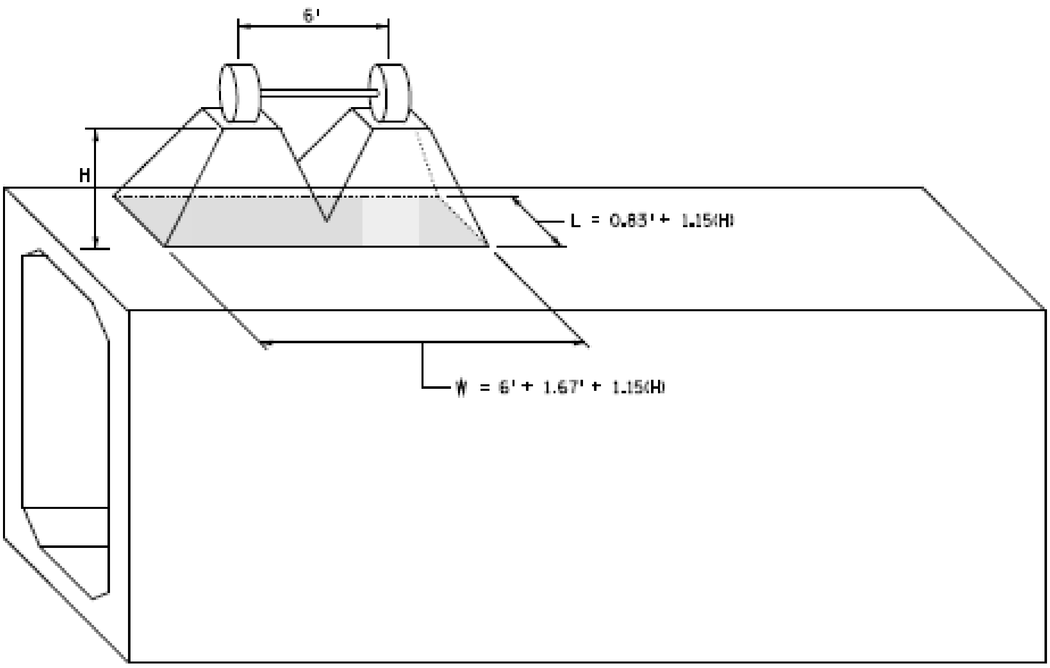
Where: D_E *= the minimum depth of earth fill above the structure (ft)*

The live load distribution varies with different earth fill depths. General cases are divided when the earth fill depth is less or more than 2 ft. When the earth fill depth is more than 2 ft, the cases are divided again whether the load projection overlaps or not as shown below.

3. Load



Traffic Traveling Parallel to Span (≥ 2 ft)



Traffic Traveling Parallel to Span (≥ 2 ft and overlap of load projection)

A single HL-93 truck axle configuration produces a live load intensity of:

$$W_{LL+IM} = \frac{2 \cdot P_W \cdot MPW \cdot (1 + IM)}{W \cdot L}$$

$$= \frac{2 \cdot 16 \cdot 1.20 \cdot (1 + 0.083)}{14.57 \cdot 7.73} = 0.369 \text{ klf}$$

where:

$$W = Axle_{spacing} + W_{tire} + 1.15 \cdot H$$
$$= 6 + 1.67 + 1.15 \cdot 6 = 14.57\ ft$$
$$L = L_{tire} + 1.15 \cdot H = 0.83 + 1.15 \cdot 6 = 7.73\ ft$$

Note
Live load is applied as pressure or plane load on the structure at multiple location to see its effect at different positions of the vehicle.

Note
Live load surcharge should be neglected if the earth fill depth is more than 8′-0″ and exceeds the span length for single span box. For multiple spans, it should be neglected when the earth fill depth exceeds the distance between fill faces of end supports.

6. Live Load Surcharge (LS)

Live load surcharge should be applied where vehicular load is expected to act on the surface of the backfill within a distance equal to one-half the wall height behind the back face of the wall. The increase in horizontal pressure due to live load surcharge may be estimated as:

$$\begin{aligned} \Delta_p &= k_a \cdot \gamma_s \cdot h_{eq} \\ &= 0.33 \cdot 0.120 \cdot 3 \cdot 1 = 0.1188 \text{ klf} \end{aligned}$$

Where:
Δp = constant horizontal earth pressure due to live load surcharge (ksf)
γs = total unit weight of soil (kcf)
k = coefficient of lateral earth pressure
heq = equivalent height of soil for vehicular load (ft)

Abutment Height (ft)	*h_{eq} (ft)*
5.0	4.0
10.0	3.0
≥20.0	2.0

Equivalent Height of Soil for Vehicular Loading on Culvert Walls Perpendicular to Traffic

1. Limit States and Factors & Load Combination

Box culvert design shall consider the Strength I and Service I limit states. Following load combinations and load factors are taken from the Table 3.4.1-1 and 3.4.1-2 of AASHTO LRFD.

Load Description	Load Designation	Strength I		Service I Factor
		Max. Factor	Min. Factor	
Dead Load of Members	DC	1.25	0.9	1
Vertical Earth Pressure	EV	1.3	0.9	1
Horizontal Earth Pressure	EH	1.35	1	1
Water Pressure	WA	1	0	1
Live Load	LL	1.75	0	1
Dynamic Load Allowance	IM	1.75	0	1
Live Load Surcharge	*LS	1.75	1.0/0.0	1

Load factors specified in Table 3.4.1-1 and 3.4.1-2 of AASHTO LRFD

Note
All load modifiers (η) will be 1.0 for box culvert design except EV and EH loads where $\eta_R = 1.05$ is used due to the lack of redundancy. The benefit of axial thrust is not considered for the strength limit state but it may be accounted in the service limit state crack control check.

2. Strength Limit States

Ia. Maximum vertical load and maximum horizontal load:
1.25DC + (1.30)(1.05)EV + 1.75(LL+IM) + (1.35)(1.05)EHmax+ 1.75LS

Ib. Maximum vertical load and minimum horizontal load:
1.25DC + (1.30)(1.05)EV + 1.75(LL+IM) + 1.00WA + (0.9/1.05)EHmin

Ic. Minimum vertical load and maximum horizontal load:
0.90DC + (0.90/1.05)EV + (1.35)(1.05)EHmax + 1.75LS

Note
Following set of load combination is generated for the three moving load cases where each moving load cases represent the vehicle in different positions.

3. Service Limit States

Ia. Maximum vertical load and maximum horizontal load:
1.00DC + 1.00EV + 1.00(LL+IM) + 1.00EHmax + 1.00LS

Ib. Maximum vertical load and minimum horizontal load:
1.00DC + 1.00EV + 1.0(LL+IM) + 1.00WA + 1.00EHmin

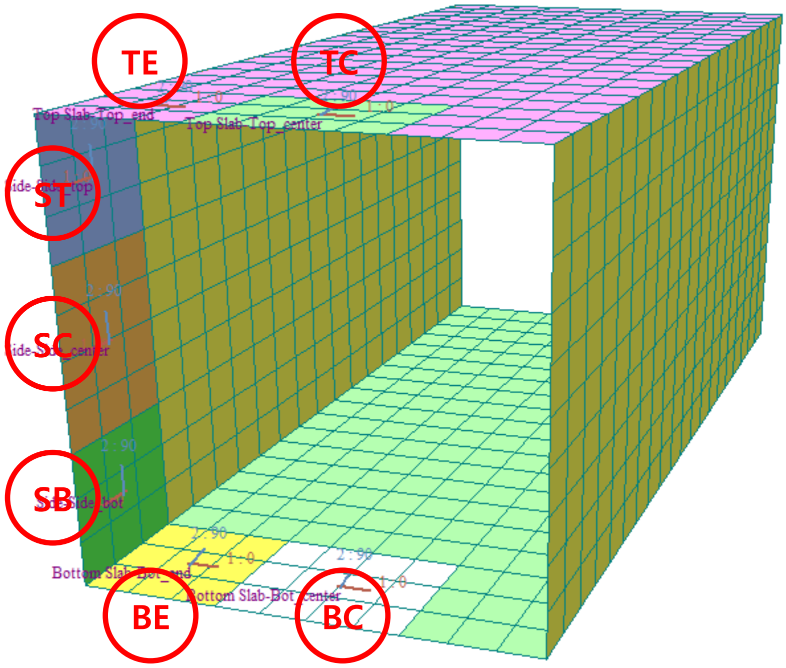
Ic. Minimum vertical load and maximum horizontal load:
1.00DC + 1.00EV + 1.00EHmax + 1.00LS

5. Structure Design

1. Design Locations

Structural analysis is performed and the member forces are checked in the following locations.

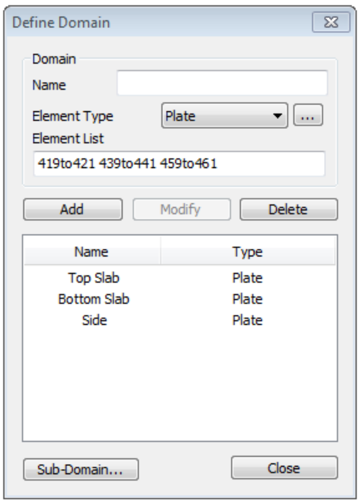
Top slab end	:	TE
Top slab center	:	TC
Bottom slab end	:	BE
Sidewall top	:	ST
Sidewall bottom	:	SB
Sidewall center	:	SC



Box culvert flexure and shear design locations

In order to design the structure in the specific locations, the corresponding locations must be specified as sub-domain in midas Civil.

- *Node/Element > Element > Define Domain*



Pre / Post Processing Input Data for Plate Beam Design should be defined. After creating the plate element, Domain and Sub-Domain of specific elements should be defined and then Plate Member is assigned. Structural design can be performed at these locations using the member forces calculated from the analysis.

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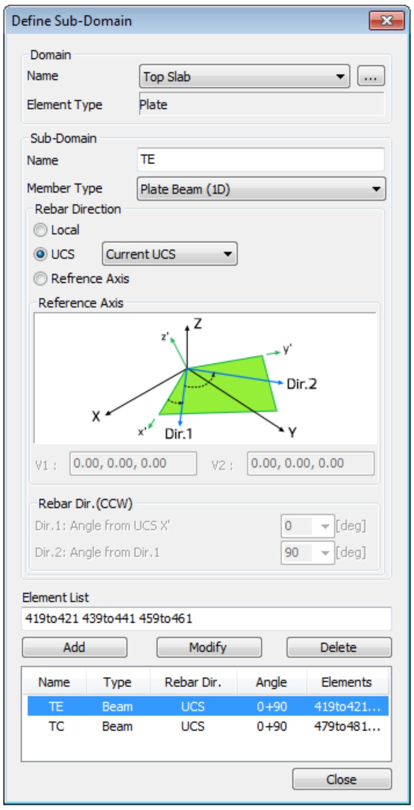
5. Structure Design



- *Node/Element > Element > Define Sub-Domain*

1. *Select Domain.*
2. *Select Member Type (Plate Beam (1D) or Plate Column (1D)).*
3. *Select the method of defining Rebar Direction (Local, UCS or Reference Axis).*
4. *Select elements to be included in the Sub-Domain.*

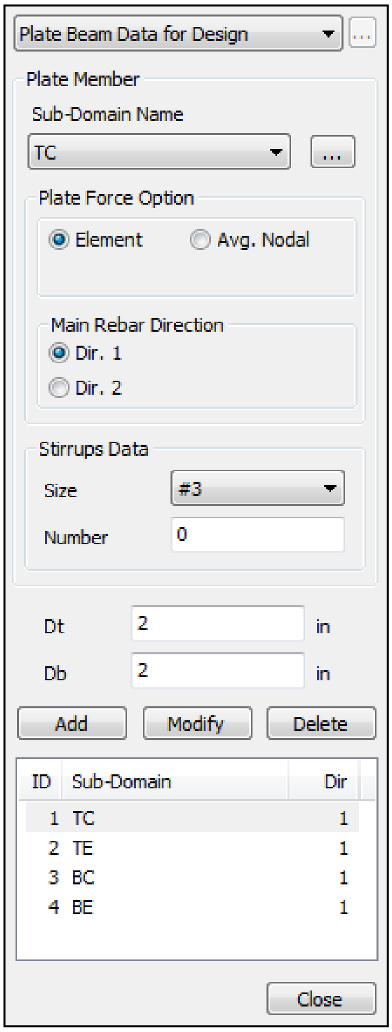
2. Perform Design

- *Design > RC Design (AASHTO-LRFD12(US)) > Plate Beam/Column Data for Design*

1. *Select Sub-Domain.*
2. *Choose Plate Force Option.*
3. *Define Main Rebar Direction.*
4. *Enter the Stirrups Data (optional).*
5. *Enter the cover thickness of top and bottom of the element (Dt and Db).*

Once the structural analysis is performed, the automatic design of the concrete plate beam member will be performed according to AASHTO LRFD using the analysis results and the design input information.

Capacity of cross section is calculated for the elements of each sub-domain considering the load combinations and the maximum area of reinforcement is outputted satisfying the flexural and shear strength criteria.



Note
Plate Beam (1D): Select this if you want Slab Design like 1 way Beam.

Plate Column (1D): Select the Abutment/Side Wall Design like column under only axial force.

Note
Local : Use the local coordinate system of the plate element to define the rebar direction
Dir.1 : Local x-axis
Dir.2 : Local y-axis

UCS : Select a predefined user coordinate system to define the rebar direction. If no user coordinate system is specified, the global coordinate system is used(Current UCS)
Dir.1 : UCS X-axis
Dir.2 : UCS Y-axis

Reference Axis : The user uses the coordinates defined by Reference Axis directly. Select V1 vector to define reference x-axis and select V2 vector to define the plane.
Dir.1 : Reference x-axis
Dir.2 : 90 degree from Reference x-axis (V1)

Note
Rebar Dir. (CCW) feature is used for the calculation of Wood-Armer moment of specific direction. This will be fixed to default for Plate Design
(Dir.1 = 0º, Dir.2 = 90º)

3. Flexure Strength

- *Design > RC Design (AASHTO-LRFD12(US)) > Concrete Code Design > Plate Beam Design (Ctrl + 3)*

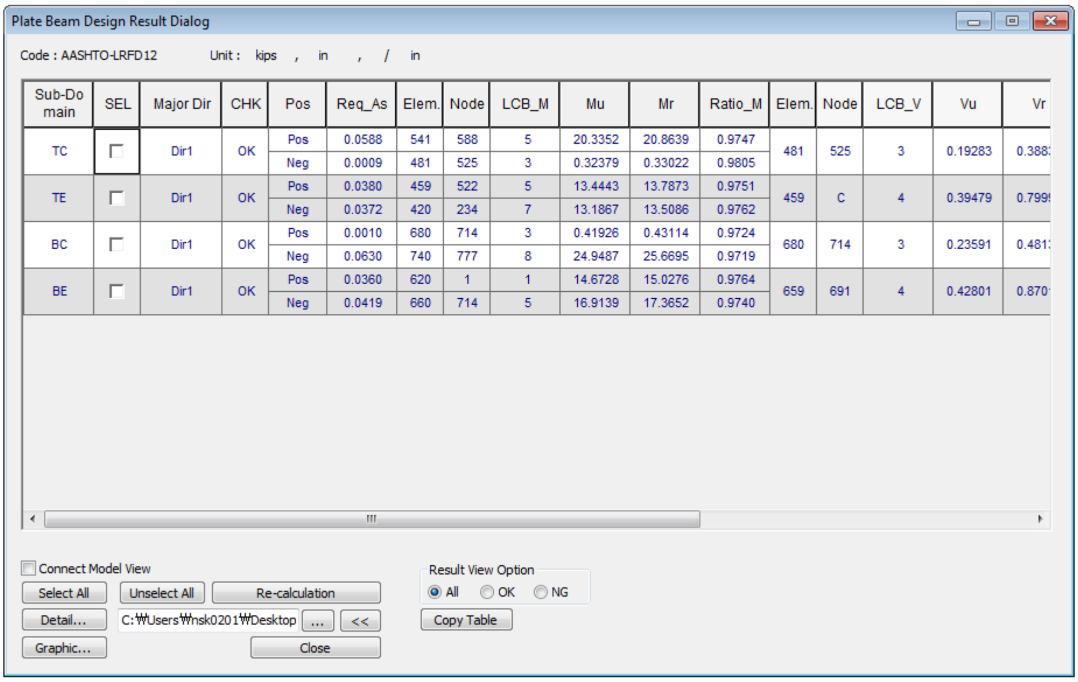


Plate Beam Design Result Dialog

Code : AASHTO-LRFD12 Unit : kips , in , / in

Sub-Domain	SEL	Major Dir	CHK	Pos	Req_As	Elem.	Node	LCB_M	Mu	Mr	Ratio_M	Elem.	Node	LCB_V	Vu	Vr
TC		Dir1	OK	Pos	0.0588	541	588	5	20.3352	20.8639	0.9747	481	525	3	0.19283	0.388
				Neg	0.0009	481	525	3	0.32379	0.33022	0.9805					
TE		Dir1	OK	Pos	0.0380	459	522	5	13.4443	13.7873	0.9751	459	C	4	0.39479	0.799
				Neg	0.0372	420	234	7	13.1867	13.5086	0.9762					
BC		Dir1	OK	Pos	0.0010	680	714	3	0.41926	0.43114	0.9724	680	714	3	0.23591	0.481
				Neg	0.0630	740	777	8	24.9487	25.6695	0.9719					
BE		Dir1	OK	Pos	0.0360	620	1	1	14.6728	15.0276	0.9764	659	691	4	0.42801	0.870
				Neg	0.0419	660	714	5	16.9139	17.3652	0.9740					

Positive/Negative Moment

Design Position		*Load Combination*	*Mu (kip-in/in)*	*Mr (kip-in/in)*	*Ratio Mu/Mr*	*Required As (in^2/in)*
TC	*+*	*5*	*20.15*	*20.71*	*0.97*	*0.0583*
	-	*3*	*0.44*	*0.45*	*0.97*	*0.0012*
TE	*+*	*5*	*13.28*	*13.63*	*0.97*	*0.0375*
	-	*7*	*13.37*	*13.67*	*0.98*	*0.0378*
BC	*+*	*3*	*0.91*	*0.93*	*0.97*	*0.0022*
	-	*8*	*22.70*	*23.30*	*0.97*	*0.0568*
BE	*+*	*1*	*13.83*	*14.14*	*0.98*	*0.0339*
	-	*5*	*15.78*	*16.12*	*0.98*	*0.0388*
ST	*+*	*3*	*5.32*	*5.43*	*0.98*	*0.0172*
	-	*1*	*13.68*	*13.97*	*0.98*	*0.0456*
SC	*+*	*3*	*7.02*	*7.21*	*0.97*	*0.0230*
	-	*5*	*6.27*	*6.46*	*0.97*	*0.0205*
SB	*+*	*3*	*4.04*	*4.14*	*0.98*	*0.0130*
	-	*7*	*13.24*	*13.53*	*0.98*	*0.0443*

Summary of flexure design and required area of reinforcement

Note
Required area of reinforcement is calculated by iteration between minimum and maximum area of reinforcement (AASHTO LRFD 5.7.3.3.2). Obtained required area of reinforcement is used as reference for the reinforcement input data for design checking.

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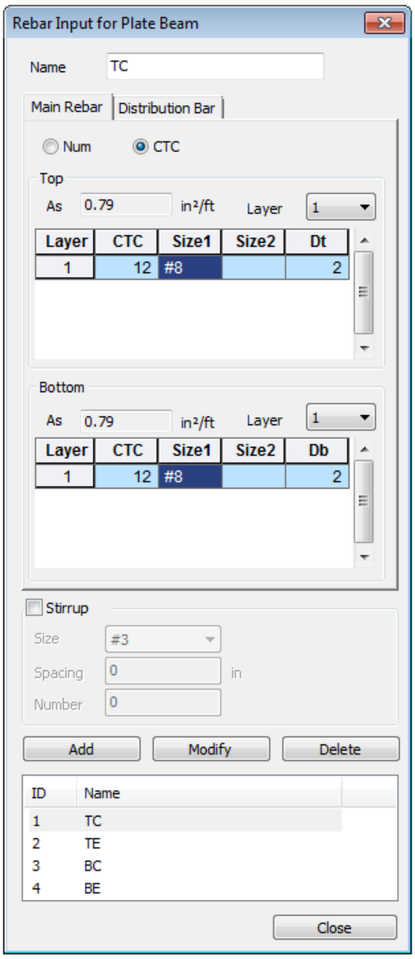
5. Structure Design

Note
Rebar can be inputted either defining the number (Num) or spacing (CTC) between the rebar.



- *Design > RC Design (AASHTO-LRFD12(US)) > Rebar Input for Plate Beam...*

Required area or reinforcement information is used as a guide to define the rebar input for the plate beam.

Following reinforcement arrangement is used to suffice flexure requirement of the beam:

TC	Top	#6	12 inch spacing
	Bot	#8	12 inch spacing
TE	Top	#7	12 inch spacing
	Bot	#7	12 inch spacing
BC	Top	#8	12 inch spacing
	Bot	#6	12 inch spacing
BE	Top	#7	12 inch spacing
	Bot	#6	12 inch spacing
ST	Top	#7	12 inch spacing
	Bot	#6	12 inch spacing
SC	Top	#6	12 inch spacing
	Bot	#6	12 inch spacing
SB	Top	#7	12 inch spacing
	Bot	#6	12 inch spacing

Design Position		*Required As (in^2/in)*	*Rebar Layout*	*Used As (in^2/in)*	*Mu (kip-in/in)*	*Mr (kip-in/in)*	*CHK*
TC	+	*0.0583*	*#8 @12*	*0.0658*	*20.15*	*23.14*	✓
	-	*0.0012*	*#6 @12*	*0.0367*	*0.44*	*13.35*	✓
TE	+	*0.0375*	*#7 @12*	*0.0500*	*13.28*	*17.91*	✓
	-	*0.0378*	*#7 @12*	*0.0500*	*13.37*	*17.91*	✓
BC	+	*0.0022*	*#6 @12*	*0.0367*	*0.91*	*15.24*	✓
	-	*0.0568*	*#8 @12*	*0.0658*	*22.70*	*26.72*	✓
BE	+	*0.0339*	*#6 @12*	*0.0367*	*13.83*	*15.24*	✓
	-	*0.0388*	*#7 @12*	*0.0500*	*15.78*	*20.55*	✓
ST	+	*0.0172*	*#6 @12*	*0.0367*	*5.32*	*11.33*	✓
	-	*0.0456*	*#7 @12*	*0.0500*	*13.68*	*15.17*	✓
SC	+	*0.0230*	*#6 @12*	*0.0367*	*7.02*	*11.33*	✓
	-	*0.0205*	*#6 @12*	*0.0367*	*6.27*	*11.33*	✓
SB	+	*0.0130*	*#6 @12*	*0.0367*	*4.04*	*11.33*	✓
	-	*0.0443*	*#7 @12*	*0.0500*	*13.24*	*15.17*	✓

Summary of flexure design check

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5. Structure Design

Note
Displays the procedure for calculating the minimum area of reinforcement. The ρ_{min} given in the standard is compared and examined. (AASHTO-LRFD12, 5.7.3.3.2)

Note
The required area of reinforcement is found using iteration method which outputs the ratio of Mu/Mr closest to 1.

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===================================================================================
MIDAS/Civil - RC-Plate Beam Design  [ AASHTO-LRFD12 ]                   Civil 2018
===================================================================================

     *.MIDAS/Civil - RC- PLATE BEAM Analysis/Design Program.

     *.PROJECT        :
     *.DESIGN CODE    : AASHTO-LRFD12,    *.UNIT SYSTEM : kips, ft, /ft
     *.SUB-DOMAIN        : TC      Member Type = PLATE BEAM(1D),   Dir  = 1  )

     *.DESCRIPTION OF PLATE BEAM DATA :
       Thickness                =          0.750 ft.
       Unit Width               =              1 ft.
       Concrete Strength (fc)            =       720.000 ksf.
       Main Rebar Strength (fy)          =      8640.000 ksf.
       Stirrups Strength (fys)           =      8640.000 ksf.
       Modulus of Elasticity (Es)        =   4176000.000 ksf.

      < Selected Elements >
        All Elements
      < Positive Bending Moment >
          P-Mu =        20.15 ft-kips/ft., ELEM =    541,   LCB =   5,   NODE =     588
      < Negative Bending Moment >
          N-Mu =         0.44 ft-kips/ft., ELEM =    481,   LCB =   3,   NODE =     525
      < Shear Force >
          Vu   =        -4.66 kips/ft.   , ELEM =    481,   LCB =   7,   NODE =     525

     *.REINFORCEMENT PATTERN :
          Dt   =        0.167  (  ft. )
          Db   =        0.167  (  ft. )
       ----------------------------------------------------------
          Stirrups :  No BarNum

 ===============================================================================
    [[[*]]]   ANALYZE POSITIVE BENDING MOMENT CAPACITY.
 ===============================================================================

     ( ). Compute parameter.
          -. phi    =   0.90
          -. Alpha  =   0.85
          -. Beta   =   0.80
          -. d      =     0.5833 ft.
          -. ecu    =  0.0030

     ( ). Compute maximum and minimum reinforcement.
          -. Rhomin1 = (1.2)*Mcr/[ phi*fy*b*d*(d-a/2) ]       =  0.0034
          -. Rhomin2 = 1.33*Mu/[ phi*fy*b*d*(d-a/2) ]         =  0.0110
          -. Rhomin  = MIN[ Rhomin1, Rhomin2 ]                =  0.0034
          -. As_min =  Rhomin * Ag   =     0.0096 ft^2/ft.
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     ( ). Search for required reinforcement......  Unit :  kips.,  ft.
          ------------------------------------------------------------------------
            Trial    Assumed As(Top & Bottom)        Mr         Ratio     Status
          ------------------------------------------------------------------------
              1         0.0025                        5.64        3.574      N.G
              2         0.0139                       28.77        0.700      O.K
              3         0.0082                       17.64        1.142      N.G
              4         0.0110                       23.35        0.863      O.K
              5         0.0096                       20.48        0.984      O.K
              6         0.0103                       21.92        0.919      O.K
              7         0.0100                       21.24        0.948      O.K
              8         0.0098                       20.86        0.966      O.K
              9         0.0097                       20.71        0.973      O.K
          ------------------------------------------------------------------------

     ( ). Check moment capacity.
          -. c           =     0.0855 ft.
          -. Cc          =      41.88 kips/ft.
          -. Ts          =      41.96 kips/ft.
          -. Mr          =      20.71 ft-kips/ft.
          -. Mu/Mr       =      0.973  ---> O.K !
```

Example of flexure strength check from detail report

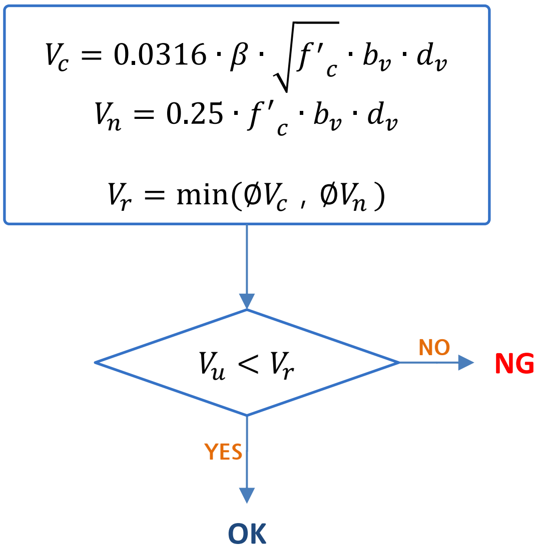
4. Shear Strength

Maximum design shear should be checked at the effective shear depth of section, dv. Factored shear resistance Vr should not be taken less than factored shear Vu at every locations for all load combination. Shear strength is checked at the same positions of flexure design positions.

$$d_v = \max(dv, 0.9d, 0.72 \cdot H_c) \qquad \textit{(AASHTO LRFD 5.8.2.9)}$$

$$\varepsilon_s = \frac{\left(\left|\frac{M_u}{d_v}\right| + 0.5N_u + |V_u|\right)}{E_s \cdot A_s} \qquad \textit{(AASHTO LRFD 5.8.3.4.2−4)}$$

$$\beta = \frac{4.8}{1 + 750\varepsilon_s} \qquad \textit{(AASHTO LRFD 5.8.3.4.2)}$$



Basic algorithm of shear strength check as per AASHTO LRFD

Design Position	*Load Combination*	*Vu (kip/ft)*	*Vr (kip/ft)*	*Ratio Vu/Vr*	*CHK*
TC	*7*	*4.66*	*9.70*	*0.48*	✓
TE	*1*	*4.45*	*8.93*	*0.50*	✓
BC	*4*	*4.79*	*12.05*	*0.40*	✓
BE	*4*	*5.27*	*11.01*	*0.48*	✓
ST	*7*	*4.59*	*9.24*	*0.50*	✓
SC	*1*	*2.70*	*8.47*	*0.32*	✓
SB	*3*	*4.10*	*8.32*	*0.49*	✓

Summary of applied shear force and shear strength

Note
Indicates the basis for calculating the effective shear depth (dv) and the coefficient used to calculate the shear strength. (AASHTO-LRFD12,5.8.2.9)

Note
Calculate the shear strength of concrete. (AASHTO-LRFD12,5.8.3.3)

Note
Determine the maximum spacing of stirrup reinforcement according to the conditions. (AASHTO-LRFD12,5.8.2.4)

Note
Determine whether the tensile force generated by the shear can be resisted by the longitudinal reinforcement or not. (AASHTO-LRFD12,5.8.3.5)

```
=============================================================================
   [[[*]]]   ANALYZE SHEAR CAPACITY.
=============================================================================

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     ( ). Compute shear parameter.
          -. phi    =   0.90
          -. Av     =   0.0000 ft^2/ft.
          -. bv     =   0.08 ft.
          -. dv     =   0.5447 ft.  (for Beta Calculation)
          -. theta =   0.582 Deg.
          -. Epsilon_s = MIN[ (|Mu|/dv + 0.5*Nu + |Vu|)/(Es*As), 0.006 ] =  0.0012
          -. beta  =  4.8/(1+750*Epsilon_s) =  2.4863

     ( ). Compute shear strength of concrete.
          -. dv      =  MAX[ dv, 0.9*d, 0.72*Hc ]  =     0.54 ft.
          -. Vu      =   6.80 kips/ft.
          -. Vc      = 0.0316*beta*SQRT[fc']*bv*dv =  13.78 kips/ft.
          -. phiVc   = phi * Vc =  12.40 kips/ft.
          -. Vn_lim = 0.25*fc'*bv*dv =  98.04 kips/ft.

     ( ). Compute stirrup spacing.
          -. Maximum spacing smax   = MIN[ 0.8*dv, 24 in ] =    0.436 ft.
          -. phiVc/2 < Vu < phiVc  --->  Required minimum shear reinforcement.
          -.                 smax   = MIN[ smax, Av/(0.0316*SQRT(fc')*bv/fys) ] =    0.000 ft.
          -. Applied spacing s    =    0.000 ft.

     ( ). Compute shear strength of reinforcement.
          -. Vs_lim  = 0.25*fc'*bv*dv - Vc =    84.26 kips/ft.
          -. Vs      = Vs_lim =    84.26 kips/ft.
          -. phiVs   = phi*Vs =    75.83 kips/ft.

          -. phiVs > (Vu-phiVc)  --->  O.K !
          -. Using Av  =  Vs / (fys*d)  =   0.0010 ft^2/ft.

     ( ). Check tension force in the longitudinal reinforcement caused by shear.
          -. phib    =   0.90
          -. phiv    =   0.90
          -. Vs1     =  MIN[ Vs, Vu/phiv ] =     7.56 kips/ft.
          -. As_req  =  [ Mu/(phib*dv) + (Vu/phiv - 0.5*Vs1)*cot(theta) ] / fy =   0.0035 ft^2/ft.
          -. As      =   0.0055 ft^2/ft.
          -. As_req < As  --->  O.K !
```

Example of shear strength check from detail report

5. Check Thrust

The largest thrust should be acting on the sidewall so the axial capacity of the culvert should be checked at the sidewall where the axial force will be large compared to the top/bottom slabs to satisfy the provisions of AASHTO LRFD 5.7.4.

$$P_u < P_r = \emptyset P_n$$

Note
The axial capacity of the side wall is adequate. Thus the benefit of axial force is not included in the calculation of flexural strength.

Design Position	*Load Combination*	*Pu (kip/ft)*	*Pr (kip/ft)*	*Ratio Pu/Pr*	*CHK*
ST	*2*	*1.07*	*29.12*	*0.04*	✓
SC	*1*	*0.89*	*28.57*	*0.03*	✓
SB	*1*	*0.85*	*29.12*	*0.03*	✓

Summary of applied axial force and factored axial strength

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5. Structure Design

6. Crack Control

Crack control is checked for all concrete members of box culvert. The spacing of steel reinforcement (s) is checked with the allowable crack spacing (sa)

$$s < s_a \qquad \text{(AASHTO LRFD 5.7.3.4)}$$

where:

$$s_a = \frac{700 \cdot \gamma_e}{\beta_e \cdot f_{ss}} - 2d_c$$

$$\beta_e = 1 + \frac{d_c}{0.7(h - d_c)}$$

$\gamma_e = exposure\ factor$

$d_c = thickness\ of\ concrete\ cover\ from\ extreme\ tension\ fiber\ to\ center\ of\ the\ flexural\ reinforcement\ (in.)$

$f_{ss} = tensile\ stress\ in\ steel\ reinforcement\ at\ the\ SLS\ (ksi)$

$h = overall\ thickness\ or\ depth\ of\ the\ component\ (in.)$

Design Position		Load Combination	S (in)	Sa (in)	CHK
TC	Top	10	0	0	✓
	Bot	11	12	11.63	NG
TE	Top	10	12	13.742	✓
	Bot	11	12	13.878	✓
BC	Top	11	12	12.077	✓
	Bot	10	0	0	✓
BE	Top	11	12	13.469	✓
	Bot	10	12	10.552	NG
ST	Top	10	12	9.5189	NG
	Bot	16	12	34.379	✓
SC	Top	11	12	19.779	✓
	Bot	16	12	21.733	✓
SB	Top	10	12	10.623	NG
	Bot	16	12	56.343	✓

Summary of applied axial force and factored axial strength

5. Structure Design

Note
Calculate the allowable crack reinforcement spacing as specified in the standard and compare it with the spacing of main rebar.
(AASHTO-LRFD12,5.7.3.4)

Note
Calculate the minimum rebar of Deck as specified in the standard, and review the results by using the spacing of required area of rebar and spacing of main reinforcement.
(AASHTO-LRFD12,9.7.2.5)

Note
The required area of reinforcement for the shrinkage / temperature rebar is compared with the area of used rebar.
(AASHTO-LRFD12,5.10.8).

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  [[[*]]]   ANALYZE CRACK.
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     ( ). Check crack control of Bottom reinforcement. ( LCB =   11 )
         -. Mu       =      13.1725 in-kips/in.
         -. h        =       9.0000 in.
         -. dc       =       2.0000 in.
         -. Beta_s   = 1+dc/(0.7*(h-dc)) = 1.41
         -. Gamma_e  = 1.00
         -. c_cr     =       2.1248 in.
         -. Icr      =      14.3882 in^4/in.
         -. fss      =        31.805 ksi.
         -. s        =       12.0000 in.
         -. sa       = 700*Gamma_e/(Beta_s*fss)-2*dc =     11.6295 in.
         -. s > sa ---> Not Acceptable !!

     ( ). Check crack control of Bottom reinforcement requirements.
         -. As_req              =      0.0225 in^2/in.
         -. As(Outermost layer) =      0.0658 in^2/in.
         -. As_req < As ---> O.K !
         -. Max. spacing smax    =     18.0000 in.
         -. s(Outermost layer)   =     12.0000 in.
         -. s < smax ---> O.K !

     ( ). Check crack control of Top reinforcement. ( LCB =   10 )
         -. Mu       =       0.0000 in-kips/in.
         -. h        =       9.0000 in.
         -. dc       =       2.0000 in.
         -. Beta_s   = 1+dc/(0.7*(h-dc)) = 1.41
         -. Gamma_e  = 1.00
         -. c_cr     =       1.7325 in.
         -. Icr      =       9.0551 in^4/in.
         -. fss      =          0.000 ksi.
         -. s        =        0.0000 in.
         -. sa       = 700*Gamma_e/(Beta_s*fss)-2*dc =      0.0000 in.
         -. fss = 0 ---> Crack check is not required.(Mu=0)

     ( ). Check crack control of Top reinforcement requirements.
         -. As_req              =      0.0150 in^2/in.
         -. As(Outermost layer) =      0.0367 in^2/in.
         -. As_req < As ---> O.K !
         -. Max. spacing smax    =     18.0000 in.
         -. s(Outermost layer)   =     12.0000 in.
         -. s < smax ---> O.K !

==============================================================================
  [[[*]]]   SHRINKAGE AND TEMPERATURE REINFORCEMENT.
==============================================================================

     ( ). Check Bottom Shrinkage and Temperature Reinforcement.
         -. As_Req    = 1.3*b*h/(2*(b+h)*fys) =      0.0098 in^2/in.
         -. As        =        0.0092 in^2/in.
         -. As_Req > As ---> N.G !
         -. 0.0092 <  As  < 0.0500  ---> O.K !

     ( ). Check Top Shrinkage and Temperature Reinforcement.
         -. As_Req    = 1.3*b*h/(2*(b+h)*fys) =      0.0098 in^2/in.
         -. As        =        0.0092 in^2/in.
         -. As_Req > As ---> N.G !
         -. 0.0092 <  As  < 0.0500  ---> O.K !
```

Example of crack control check from detail report

Plate beam/column design feature provides convenient solution for the structural design involved with plate elements such as box culvert, slab bridge or abutment design. Intuitive design result can be obtained for particular locations and engineers need to go over with the verification of result using the graphic/detail report in order to convince themselves with the results.