NCHRP Web Document 44 (Project 12-45): Contractor's Final Report

Design Examples for Large-Span Culverts

Supporting Material for *NCHRP Report 473*

Prepared for:

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Examples of Simplified Design Procedures for Metal Culverts

Example of Simplified Design Procedures for Concrete Culverts

Design 9.7 m Span by 3.7 m Rise Low Profile Arch, H = 1.0 m

MathCad Units and Range Variables

$kN := 224.8 \cdot lbf$ $\quad MPa := 145.1379 \cdot \frac{lbf}{in^2}$ $\quad i := 1, 2 .. 4$

Mathcad Terminology:
:= defines a term
= presents result of a calcuation

$kPa := \frac{MPa}{1000}$ $\quad GPa := 1000 \cdot MPa$

Installation Conditions

Depth of burial $H := 1.0 \cdot m$

Width of Structural Backfill $W := 4.85 \cdot m$

Live load

Design Tandem $P := 222 \cdot kN$

Multiple presence factor $mp := 1.2$

Tire length: $L_o := 250 \cdot mm$

Axle plus Wheel Width $W_T := 2300 \cdot mm$

Lane load $Lane := 9.3 \cdot \frac{kN}{m}$

Lane load width $Lane_W := 3 \cdot m$

Culvert Geometry

Span $S := 9.7 \cdot m$

Rise $R := 3.7 \cdot m$

Upper Rise $R_u := 3.2 \cdot m$

Top Radius $R_t := 6.3 \cdot m$

Top Angle $\theta_{top} := 80 \cdot deg$

Span/ Rise Ratio $\frac{S}{R} = 2.62$

$$Topchord := \sin\left(\frac{\theta_{top}}{2}\right) \cdot R_t \cdot 2$$

$$Topchord = 8.10\,m$$

Impact $I_{mp} := if\left(H < 2.44 \cdot m, 1.33 - 0.33 \cdot \frac{H}{2.44 \cdot m}, 1\right)$ $\quad I_{mp} = 1.19$

Live load distribution with depth of fill $LLDF := 1.15$

Culvert Material Properties

$F_y := 227.6 \cdot MPa$ $\quad E_p := 200 \cdot GPa$

Soil Properties:

Structural Backfill (Sn95): Ms selected from table in Specifications based on vertical pressure:

Density $\gamma_s := 18.84 \cdot kN \cdot m^{-3}$

Friction angle (loose) $\phi := 36 \cdot deg$

Poisson's ratio $\nu := 0.3$

$p_{crown} := \gamma_s \cdot H$ $\quad p_{crown} = 19\,kPa$

$p_{side} := \gamma_s \cdot \left(H + \frac{R}{2}\right)$ $\quad p_{side} = 54\,kPa$

$M_{sCrown} := 15.5 \cdot MPa$

$M_{sSide} := 19.4 \cdot MPa$

$M_{sBottom} := 21 \cdot MPa$

Native soil: Soft Clay (See Table C2.3-1)

$M_{sN} := 5 \cdot MPa$

Design factors

Load factors	Earth	Max	$\gamma_{EMax} := 1.3$	Resistance factors	Thrust	$\phi_c := 0.7$
		Min	$\gamma_{EMin} := 0.9$		Bending	$\phi_b := 0.9$
	Live		$\gamma_{LL} := 1.75$		Soil	$\phi_s := 0.9$
					Buckling	$\phi_{bck} := 0.7$

Trial Section Properties

Structural Plate = 150 mm by 50 mm by 6.324 mm,
with circumferential stiffeners (2nd plate of same gage)

Basic plate: $I_u := 2395 \cdot \frac{mm^4}{mm}$ $\quad A := 7.74 \cdot \frac{mm^2}{mm}$

Stiffened plate: $I_p := 4790 \cdot \frac{mm^4}{mm}$ $\quad M_p := 54.92 \cdot \frac{kN \cdot m}{m}$ $\quad M_y := 38.21 \cdot \frac{kN \cdot m}{m}$

MINIMUM STIFFNESS

$$FF_{max} := 0.17 \cdot \frac{mm}{N}$$

$$FF := \frac{(2 \cdot R_t)^2 \cdot (1 - \sin(\phi))^3}{0.07 \cdot E_p \cdot I_p} \qquad FF = 0.17 \frac{mm}{N}$$

$$MinimumStiffness := if(FF < FF_{max}, \text{"OK"}, \text{"Stiffeners Required"})$$

$$MinimumStiffness = \text{"OK"}$$

THRUST CAPACITY

Compute Vertical Arching Factor and Earth Load

1. $F_{W/S}$

$$K_{VAF_i} := \begin{bmatrix} 1.9 - 1.15 \cdot \frac{W}{S} \\ 1.2 \end{bmatrix}$$

$$K_{VAF} := \max(K_{VAF})$$

$$K_{VAF} = 1.33$$

$$SoilRatio := if\left(\frac{M_{sSide}}{M_{sN}} < 100, \frac{M_{sSide}}{M_{sN}}, 100\right)$$

$$F_{WS} := 1.2 + 0.5 \cdot \log(SoilRatio)(K_{VAF} - 1.2)$$

$$F_{WS} = 1.24$$

2. $F_{S/R}$

$$F_{sr_i} := \begin{bmatrix} 1 - \frac{S}{R} \\ 0 \end{bmatrix}$$

$$F_{SR} := \max(F_{sr})$$

$$F_{SR} = 0.00$$

3. $F_{H/S}$

$$hs_{lim_i} := \begin{bmatrix} 0.8 - 0.5 \cdot \frac{S}{R} \\ 0.3 \end{bmatrix}$$

$$HS_{lim} := \max(hs_{lim})$$

$$HS_{lim} = 0.30$$

$$F_{hs_i} := \begin{bmatrix} 2.5 \cdot \left(HS_{lim} - \frac{H}{S}\right) \\ 0 \end{bmatrix}$$

$$F_{HS} := \max(F_{hs})$$

$$F_{HS} = 0.49$$

4. VAF

$$VAF := F_{WS} + F_{SR} + F_{HS}$$

$$VAF = 1.73$$

5. Earth Load

$$K_{sp} := \text{if}\left(0.172 + 0.019 \cdot \frac{S}{R_u} < 0.5, 0.172 + 0.019 \cdot \frac{S}{R_u}, 0.5\right) \qquad K_{sp} = 0.23$$

$$W_{SP} := \gamma_s \cdot S \cdot \left(H + K_{sp} \cdot R_u\right) \qquad W_{SP} = 317 \frac{kN}{m}$$

$$W_E := VAF \cdot W_{SP}$$

$$W_E = 548 \frac{kN}{m}$$

6. Lane Load

$$W_{Lane} := Lane \cdot \left(\frac{Lane_W}{Lane_W + LLDF \cdot H}\right) \qquad W_{Lane} = 6.7 \frac{kN}{m}$$

7. Live Load

$$L_L := L_o + LLDF \cdot H \qquad L_L = 1.40\,m$$

$$L_W := W_T + LLDF \cdot H \qquad L_W = 3.45\,m$$

$$W_{LL} := \frac{0.7 \cdot mp \cdot I_{mp} \cdot P \cdot R_t}{L_L \cdot L_W} \qquad W_{LL} = 291 \frac{kN}{m}$$

Total Factored Thrust

$$T_f := \frac{\gamma_{EMax} \cdot W_E + \gamma_{LL} \cdot W_{LL} + \gamma_{LL} \cdot W_{Lane}}{2} \qquad T_f = 616 \frac{kN}{m}$$

Check Capacity for Hoop Thrust

Factored Axial Resistance $R_T := \phi_c \cdot F_y \cdot A$ $\qquad R_T = 1234 \frac{kN}{m}$

$$Status_{Thrust} := \text{if}\left(R_T > T_f, \text{"OK"}, \text{"Redesign"}\right)$$

$$Status_{Thrust} = \text{"OK"}$$

Check Buckling Capacity

Stiffened top arc with live load thrust

$$R_h := \frac{11.4}{\left(11 + \frac{S}{H}\right)} \qquad R_h = 0.55$$

$$C_n := 0.55 \qquad K_b := \frac{(1 - 2 \cdot \nu)}{(1 - \nu)^2} \qquad K_b = 0.82$$

$$R_b := \left[1.2 \cdot \phi_{bck} \cdot C_n \cdot \left(E_p \cdot I_p\right)^{\frac{1}{3}} \cdot \left(\left(\phi_s \cdot M_{sCrown} \cdot K_b\right)\right)^{\frac{2}{3}}\right] \cdot R_h \qquad R_b = 1270 \frac{kN}{m}$$

$$T_f = 616 \frac{kN}{m}$$

$$Status_{Bucklingtop} := if\left(R_b > T_f, "OK", "Redesign"\right)$$

$$Status_{Bucklingtop} = "OK"$$

Unstiffened bottom arc without live load thrust

$$T_E := \frac{\gamma_{EMax} \cdot W_E}{2}$$

$$H_{bot} := H + 0.75 \cdot R$$

$$R_h := \frac{11.4}{\left(11 + \frac{S}{H_{bot}}\right)} \qquad R_h = 0.84$$

$$C_n := 0.55$$

$$R_{bE} := \left[1.2 \cdot \phi_{bck} \cdot C_n \cdot \left(E_p \cdot I_u\right)^{\frac{1}{3}} \cdot \left(\left(\phi_s \cdot M_{sBottom} \cdot K_b\right)\right)^{\frac{2}{3}}\right] \cdot R_h \qquad R_{bE} = 1883 \frac{kN}{m}$$

$$T_E = 356 \frac{kN}{m}$$

$$Status_{Bucklingbottom} := if\left(R_b > T_E, "OK", "Redesign"\right)$$

$$Status_{Bucklingbottom} = "OK"$$

FLEXURAL CAPACITY

Bending stiffness factor $S_B := \dfrac{\phi_s \cdot M_{sSide} \cdot S^3}{E_p \cdot I_p}$ $S_B = 16634$

Earth Load Moment

$$K_{e_i} := \begin{pmatrix} 0.05 \cdot \left(1 - \dfrac{S_B}{S_B + 400}\right) \\ 0.0025 \end{pmatrix}$$

$K_E := \max(K_e)$

$K_E = 0.0025$

$M_E := \gamma_s \cdot S^2 \cdot H \cdot K_E$ $M_E = 4.43 \dfrac{kN \cdot m}{m}$

Live Load Moment

$$K_{ll_i} := \begin{pmatrix} 0.02 \cdot \left(1.05 - \dfrac{S_B}{S_B + 800}\right) \\ 0.001 \end{pmatrix}$$

$K_{LL} := \max(K_{ll})$

$K_{LL} = 0.0019$

$M_{LL} := 2 \cdot W_{LL} \cdot R_t \cdot K_{LL}$ $M_{LL} = 7.02 \dfrac{kN \cdot m}{m}$

Lane Load Moment - Compute with same formula as earth load moment

$$K_{Lane_i} := \begin{pmatrix} 0.05 \cdot \left(1 - \dfrac{S_B}{S_B + 400}\right) \\ 0.0025 \end{pmatrix}$$

$K_{Lane} := \max(K_{Lane})$

$K_{Lane} = 0.0025$

$M_{Lane} := W_{Lane} \cdot S \cdot K_{Lane}$ $M_{Lane} = 0.16 \dfrac{kN \cdot m}{m}$

Check if total live load moment is greater than 15% of plastic moment capacity

$\text{FlexureCheck} := \text{if}\left[\gamma_{LL} \cdot (M_{LL} + M_{Lane}) > 0.15 \cdot (\phi_b \cdot M_p), \text{"Required"}, \text{"Not Required"}\right]$

$\text{FlexureCheck} = \text{"Required"}$

Construction Moment

Maximum allowed extension of top chord

$Topchord_{max} := 1.0$ times original top chord

Select R_{ntrial} to give $\delta_{chord} = 0.0$ $\qquad R_{ntrial} := 6.3 \cdot m$

$CurvMin := 0.005 \cdot m^{-1}$

$$\delta_{chord} := 2 \cdot R_{ntrial} \cdot \sin\left(\frac{\theta_{top} \cdot R_t}{2 \cdot R_{ntrial}}\right) - Topchord_{max} \cdot Topchord \qquad \delta_{chord} = 0.0000\,m$$

$$Curv := if\left(\left|\frac{1}{R_t} - \frac{1}{R_{ntrial}}\right| < CurvMin, CurvMin, \frac{1}{R_t} - \frac{1}{R_{ntrial}}\right) \qquad Curv = 0.005\,m^{-1}$$

$$M_{sidemax} := E_p \cdot I_p \cdot Curv$$

$$M_{sidemax} = 4.79\,kN \cdot \frac{m}{m}$$

Minimum allowed top chord

$Topchord_{min} := 0.98$ times original top chord

Select R_{ntrial} to give $\delta_{chord} = 0.0$ $\qquad R_{ntrial} := 5.66 \cdot m$

$$\delta_{chord} := 2 \cdot R_{ntrial} \cdot \sin\left(\frac{\theta_{top} \cdot R_t}{2 \cdot R_{ntrial}}\right) - Topchord_{min} \cdot Topchord \qquad \delta_{chord} = 0.00\,m$$

$$Curv := if\left(\left|\frac{1}{R_t} - \frac{1}{R_{ntrial}}\right| < CurvMin, CurvMin, \frac{1}{R_t} - \frac{1}{R_{ntrial}}\right) \qquad Curv = -0.018\,m^{-1}$$

$$M_{sidemin} := E_p \cdot I_p \cdot Curv$$

$$M_{sidemin} = -17.21\,\frac{kN \cdot m}{m}$$

$$MaxConstructionM := if\left(\left|M_{sidemax}\right| > \left|M_{sidemin}\right|, \left|M_{sidemax}\right|, \left|M_{sidemin}\right|\right)$$

$$ConstructionControl := if\left(MaxConstructionM < M_y, \text{"OK"}, \text{"Reduce Construction Moment"}\right)$$

$$ConstructionControl = \text{"OK"}$$

Total Moment

$$M_{u_i} :=$$

$$\begin{array}{|c|}\hline \gamma_{EMax} \cdot -M_{sidemin} - \gamma_{EMin} \cdot M_E + \gamma_{LL} \cdot (M_{LL}) \\ \hline \gamma_{EMin} \cdot M_{sidemax} + \gamma_{EMax} \cdot M_E + \gamma_{LL} \cdot (M_{LL} + M_{Lane}) \\ \hline \end{array}$$

$$M_u = \begin{pmatrix} 30.67 \\ 22.65 \\ 0.00 \\ 0.00 \end{pmatrix} \frac{kN \cdot m}{m}$$

$$M_U := \max(M_u)$$

$$M_U = 30.67 \frac{kN \cdot m}{m}$$

Check total moment against total capacity

$$M_n := \phi_b \cdot M_p$$

$$M_n = 49.43 \frac{kN \cdot m}{m}$$

$$Status_{Flexure} := \text{if}(M_n > M_U, \text{"OK"}, \text{"Redesign"})$$

$$Status_{Flexure} = \text{"OK"}$$

COMBINED THRUST AND BENDING

Reduce thrust to reflect that peak thrust and moment do not occur at same location

$$T_{fSh} := \frac{0.67 \cdot \left(\gamma_{EMax} \cdot W_E + \gamma_{LL} \cdot W_{LL} + \gamma_{LL} \cdot W_{Lane}\right)}{2} \qquad T_{fSh} = 413 \frac{kN}{m}$$

$$T_{fCr} := \frac{0.5 \cdot \gamma_{EMax} \cdot W_E + \gamma_{LL} \cdot W_{LL} + 0.5\gamma_{LL} \cdot W_{Lane}}{2} \qquad T_{fCr} = 435 \frac{kN}{m}$$

$$T_{fRed} := \mathrm{if}\left(T_{fCr} > T_{fSh}, T_{fCr}, T_{fSh}\right) \qquad T_{fRed} = 435 \frac{kN}{m}$$

$$\text{Combined}_i := \begin{array}{|c|} \hline \dfrac{T_{fRed}}{R_T} + \dfrac{8}{9} \cdot \dfrac{M_U}{M_n} \\ \hline \dfrac{T_{fRed}}{2 \cdot R_T} + \dfrac{M_U}{M_n} \\ \hline \end{array} \qquad \text{Combined} = \begin{pmatrix} 0.90 \\ 0.80 \\ 0.00 \\ 0.00 \end{pmatrix} \qquad \frac{T_{fRed}}{R_T} = 0.35 \qquad \frac{M_U}{M_n} = 0.62$$

$$\text{Indx} := \mathrm{if}\left(\frac{T_{fRed}}{R_T} \geq 0.2, 1, 2\right) \qquad \text{Indx} = 1.00$$

$$\text{Status}_{Combined} := \mathrm{if}\left(\text{Combined}_{Indx} < 1, \text{"OK"}, \text{"Redesign"}\right)$$

$$\text{Status}_{Combined} = \text{"OK"}$$

DESIGN SUMMARY

$MinimumStiffness = "OK"$

$Status_{Thrust} = "OK"$

$Status_{Bucklingtop} = "OK"$

$Status_{Bucklingbottom} = "OK"$

$FlexureCheck = "Required"$

$Status_{Flexure} = "OK"$

$Status_{Combined} = "OK"$

$Combined_{Indx} = 0.90$

$A = 7.74 \frac{mm^2}{mm}$

$I_u = 2395 \frac{mm^4}{mm}$

$I_p = 4790 \frac{mm^4}{mm}$

$M_p = 54.92 \frac{kN \cdot m}{m}$

$T_f = 616 \frac{kN}{m}$

$M_U = 30.67 \frac{kN \cdot m}{m}$

$ConstructionControl = "OK"$

$Topchord_{max} = 1.00$

$Topchord_{min} = 0.98$

Notes

- Circumferential stiffeners are used to meet minimum stiffness requirement

- Seam strength must also be checked and must be greater than $T_{f.}$

Design 31.2 ft Span by 19 ft Rise Elliptical Culvert, H = 2 ft

MathCad Units and Range Variables

$ksi := 1000 \cdot psi$

$k := 1000 \cdot lbf$

$i := 1, 2 .. 4$

Mathcad Terminology:
:= defines a term
= presents result of a calcuation

Installation Conditions

Depth of burial $H := 2.0 \cdot ft$

Width of Structural Backfill $W := 30 \cdot ft$

Live load

Design Tandem $P := 50 \cdot k$

Multiple presence factor $mp := 1.2$

Tire length: $L_o := 10 \cdot in$

Axle plus Wheel Width $W_T := 7.67 \cdot ft$

Lane load $Lane := 640 \cdot \frac{lbf}{ft}$

Lane load width $Lane_W := 10 \cdot ft$

Impact $I_{mp} := if\left(H < 8 \cdot ft, 1.33 - 0.33 \cdot \frac{H}{8 \cdot ft}, 1\right)$ $I_{mp} = 1.25$

Live load distribution with depth of fill $LLDF := 1.15$

Culvert Geometry

Span $S := 31.2 \cdot ft$

Rise $R := 19.0 \cdot ft$

Upper Rise $R_u := 9.5 \cdot ft$

Top Radius $R_t := 21.0 \cdot ft$

Top Angle $\theta_{top} := 80 \cdot deg$

Span/ Rise Ratio $\frac{S}{R} = 1.64$

$Topchord := \sin\left(\frac{\theta_{top}}{2}\right) \cdot R_t \cdot 2$

$Topchord = 27.00\,ft$

Culvert Material Properties

$F_y := 33 \cdot ksi$ $E_p := 29000 \cdot ksi$

Soil Properties:

Structural Backfill (Sn95): Ms selected from table in Specifications based on vertical pressure:

Density $\gamma_s := 120 \cdot lbf \cdot ft^{-3}$

Friction angle (loose) $\phi := 36 \cdot deg$

Poisson's ratio $\nu := 0.3$

$p_{crown} := \gamma_s \cdot H$ $p_{crown} = 1.67\,psi$

$p_{side} := \gamma_s \cdot \left(H + \frac{R}{2}\right)$ $p_{side} = 9.58\,psi$

$M_{sCrown} := 2100 \cdot psi$

$M_{sSide} := 2950 \cdot psi$

$M_{sBottom} := 3050 \cdot psi$

Native soil: Soft Clay (See Table C2.3-1)

$M_{sN} := 750 \cdot MPa$

Design factors

Load factors	Earth	Max	$\gamma_{EMax} := 1.3$	Resistance factors	Thrust	$\phi_c := 0.7$
		Min	$\gamma_{EMin} := 0.9$		Bending	$\phi_b := 0.9$
	Live		$\gamma_{LL} := 1.75$		Soil	$\phi_s := 0.9$
					Buckling	$\phi_{bck} := 0.7$

Trial Section Properties

Structural Plate = 6 in. by 2 in. by 0.276 in.,
with circumferential stiffeners (2nd plate of same gage)

Basic plate: $I_u := 0.166 \cdot \frac{in^4}{in}$ $A := 4.119 \cdot \frac{in^2}{ft}$

Stiffened plate: $I_p := 0.332 \cdot \frac{in^4}{in}$ $M_p := 167 \cdot \frac{in \cdot k}{ft}$ $M_y := 115 \cdot \frac{in \cdot k}{ft}$

MINIMUM STIFFNESS

$$FF_{max} := 30 \cdot \frac{in}{k}$$

$$FF := \frac{(2 \cdot R_t)^2 \cdot (1 - \sin(\phi))^3}{0.07 \cdot E_p \cdot I_p} \qquad FF = 26.40 \frac{in}{k}$$

MinimumStiffness := if(FF < FF_{max}, "OK" , "Stiffeners Required")

MinimumStiffness = "OK"

THRUST CAPACITY

Compute Vertical Arching Factor and Earth Load

1. $F_{W/S}$

$$K_{VAF_i} := \begin{pmatrix} 1.9 - 1.15 \cdot \frac{W}{S} \\ 1.2 \end{pmatrix}$$

$$K_{VAF} := \max(K_{VAF})$$

$$K_{VAF} = 1.20$$

$$SoilRatio := if\left(\frac{M_{sSide}}{M_{sN}} < 100, \frac{M_{sSide}}{M_{sN}}, 100\right)$$

$$F_{WS} := 1.2 + 0.5 \cdot \log(SoilRatio)(K_{VAF} - 1.2)$$

$$F_{WS} = 1.20$$

2. $F_{S/R}$

$$F_{sr_i} := \begin{pmatrix} 1 - \frac{S}{R} \\ 0 \end{pmatrix}$$

$$F_{SR} := \max(F_{sr})$$

$$F_{SR} = 0.00$$

3. $F_{H/S}$

$$hs_{lim_i} := \begin{pmatrix} 0.8 - 0.5 \cdot \frac{S}{R} \\ 0.3 \end{pmatrix}$$

$$HS_{lim} := \max(hs_{lim})$$

$$HS_{lim} = 0.30$$

$$F_{hs_i} := \begin{pmatrix} 2.5 \cdot \left(HS_{lim} - \frac{H}{S}\right) \\ 0 \end{pmatrix}$$

$$F_{HS} := \max(F_{hs})$$

$$F_{HS} = 0.59$$

4. VAF

$$VAF := F_{WS} + F_{SR} + F_{HS}$$

$$VAF = 1.79$$

5. Earth Load

$$K_{sp} := \text{if}\left(0.172 + 0.019\cdot\frac{S}{R_u} < 0.5, 0.172 + 0.019\cdot\frac{S}{R_u}, 0.5\right) \qquad K_{sp} = 0.23$$

$$W_{SP} := \gamma_s\cdot S\cdot\left(H + K_{sp}\cdot R_u\right) \qquad W_{SP} = 16\frac{k}{ft}$$

$$W_E := VAF\cdot W_{SP}$$

$$W_E = 28\frac{k}{ft}$$

6. Lane Load

$$W_{Lane} := Lane\cdot\left(\frac{Lane_W}{Lane_W + LLDF\cdot H}\right) \qquad W_{Lane} = 0.5\frac{k}{ft}$$

7. Live Load

$$L_L := L_o + LLDF\cdot H \qquad L_L = 3.13\,ft$$

$$L_W := W_T + LLDF\cdot H \qquad L_W = 9.97\,ft$$

$$W_{LL} := \frac{0.7\cdot mp\cdot I_{mp}\cdot P\cdot R_t}{L_L\cdot L_W} \qquad W_{LL} = 35\frac{k}{ft}$$

Total Factored Thrust

$$T_f := \frac{\gamma_{EMax}\cdot W_E + \gamma_{LL}\cdot W_{LL} + \gamma_{LL}\cdot W_{Lane}}{2} \qquad T_f = 50\frac{k}{ft}$$

Check Capacity for Hoop Thrust

Factored Axial Resistance $\quad R_T := \phi_c\cdot F_y\cdot A \qquad R_T = 95\frac{k}{ft}$

$$Status_{Thrust} := \text{if}\left(R_T > T_f, \text{"OK"}, \text{"Redesign"}\right)$$

$$Status_{Thrust} = \text{"OK"}$$

Check Buckling Capacity

Stiffened top arc with live load thrust

$$R_h := \frac{11.4}{\left(11 + \frac{S}{H}\right)} \qquad R_h = 0.43$$

$$C_n := 0.55 \qquad K_b := \frac{(1 - 2\cdot\nu)}{(1 - \nu)^2} \qquad K_b = 0.82$$

$$R_b := \left[1.2\cdot\phi_{bck}\cdot C_n\cdot(E_p\cdot I_p)^{\frac{1}{3}}\cdot\left(\left(\phi_s\cdot M_{sCrown}\cdot K_b\right)\right)^{\frac{2}{3}}\right]\cdot R_h \qquad R_b = 67\frac{k}{ft}$$

$$T_f = 50\frac{k}{ft}$$

$$Status_{Bucklingtop} := if\left(R_b > T_f, \text{"OK"}, \text{"Redesign"}\right)$$

$$Status_{Bucklingtop} = \text{"OK"}$$

Unstiffened bottom arc without live load thrust

$$T_E := \frac{\gamma_{EMax}\cdot W_E}{2}$$

$$H_{bot} := H + 0.75\cdot R$$

$$R_h := \frac{11.4}{\left(11 + \frac{S}{H_{bot}}\right)} \qquad R_h = 0.88$$

$$C_n := 0.55$$

$$R_{bE} := \left[1.2\cdot\phi_{bck}\cdot C_n\cdot(E_p\cdot I_u)^{\frac{1}{3}}\cdot\left(\left(\phi_s\cdot M_{sBottom}\cdot K_b\right)\right)^{\frac{2}{3}}\right]\cdot R_h \qquad R_{bE} = 141\frac{k}{ft}$$

$$T_E = 18\frac{k}{ft}$$

$$Status_{Bucklingbottom} := if\left(R_b > T_E, \text{"OK"}, \text{"Redesign"}\right)$$

$$Status_{Bucklingbottom} = \text{"OK"}$$

FLEXURAL CAPACITY

Bending stiffness factor $S_B := \dfrac{\phi_s \cdot M_{sSide} \cdot S^3}{E_p \cdot I_p}$ $\quad S_B = 14472$

Earth Load Moment

$$K_{e_i} := \begin{bmatrix} 0.05 \cdot \left(1 - \dfrac{S_B}{S_B + 400}\right) \\ 0.0025 \end{bmatrix}$$

$K_E := \max(K_e)$

$K_E = 0.0025$

$M_E := \gamma_s \cdot S^2 \cdot H \cdot K_E$ $\quad M_E = 7.01 \dfrac{in \cdot k}{ft}$

Live Load Moment

$$K_{ll_i} := \begin{bmatrix} 0.02 \cdot \left(1.05 - \dfrac{S_B}{S_B + 800}\right) \\ 0.001 \end{bmatrix}$$

$K_{LL} := \max(K_{ll})$

$K_{LL} = 0.0020$

$M_{LL} := 2 \cdot W_{LL} \cdot R_t \cdot K_{LL}$ $\quad M_{LL} = 36.35 \dfrac{in \cdot k}{ft}$

Lane Load Moment - Compute with same formula as earth load moment

$$K_{Lane_i} := \begin{bmatrix} 0.05 \cdot \left(1 - \dfrac{S_B}{S_B + 400}\right) \\ 0.0025 \end{bmatrix}$$

$K_{Lane} := \max(K_{Lane})$

$K_{Lane} = 0.0025$

$M_{Lane} := W_{Lane} \cdot S \cdot K_{Lane}$ $\quad M_{Lane} = 0.49 \dfrac{in \cdot k}{ft}$

Check if total live load moment is greater than 15% of plastic moment capacity

$FlexureCheck := \text{if}\left[\gamma_{LL} \cdot (M_{LL} + M_{Lane}) > 0.15 \cdot (\phi_b \cdot M_p), \text{"Required"}, \text{"Not Required"}\right]$

$FlexureCheck = \text{"Required"}$

Construction Moment

Maximum allowed extension of top chord

$Topchord_{max} := 1.002$ times original top chord

Select R_{ntrial} to give $\delta_{chord} = 0.0$ $\quad R_{ntrial} := 21.254 \cdot ft$

$CurvMin := 0.0015 \cdot ft^{-1}$

$$\delta_{chord} := 2 \cdot R_{ntrial} \cdot \sin\left(\frac{\theta_{top} \cdot R_t}{2 \cdot R_{ntrial}}\right) - Topchord_{max} \cdot Topchord \qquad \delta_{chord} = -0.0001\,ft$$

$$Curv := if\left(\left|\frac{1}{R_t} - \frac{1}{R_{ntrial}}\right| < CurvMin, CurvMin, \frac{1}{R_t} - \frac{1}{R_{ntrial}}\right) \qquad Curv = 0.0015\,ft^{-1}$$

$$M_{sidemax} := E_p \cdot I_p \cdot Curv$$

$$M_{sidemax} = 14.44\,\frac{in \cdot k}{ft}$$

Minimum allowed top chord

$Topchord_{min} := 0.995$ times original top chord

Select R_{ntrial} to give $\delta_{chord} = 0.0$ $\quad R_{ntrial} := 20.40 \cdot ft$

$$\delta_{chord} := 2 \cdot R_{ntrial} \cdot \sin\left(\frac{\theta_{top} \cdot R_t}{2 \cdot R_{ntrial}}\right) - Topchord_{min} \cdot Topchord \qquad \delta_{chord} = -0.0002\,ft$$

$$Curv := if\left(\left|\frac{1}{R_t} - \frac{1}{R_{ntrial}}\right| < CurvMin, CurvMin, \frac{1}{R_t} - \frac{1}{R_{ntrial}}\right) \qquad Curv = 0.0015\,ft^{-1}$$

$$M_{sidemin} := E_p \cdot I_p \cdot Curv$$

$$M_{sidemin} = 14.44\,\frac{in \cdot k}{ft}$$

$$MaxConstructionM := if\left(\left|M_{sidemax}\right| > \left|M_{sidemin}\right|, \left|M_{sidemax}\right|, \left|M_{sidemin}\right|\right)$$

$$ConstructionControl := if\left(MaxConstructionM < M_y, \text{"OK"}, \text{"Reduce Construction Moment"}\right)$$

$$ConstructionControl = \text{"OK"}$$

Total Moment

$$M_{u_i} := \begin{pmatrix} \gamma_{EMax} \cdot -M_{sidemin} - \gamma_{EMin} \cdot M_E + \gamma_{LL} \cdot (M_{LL}) \\ \gamma_{EMin} \cdot M_{sidemax} + \gamma_{EMax} \cdot M_E + \gamma_{LL} \cdot (M_{LL} + M_{Lane}) \end{pmatrix}$$

$$M_u = \begin{pmatrix} 38.53 \\ 86.57 \\ 0.00 \\ 0.00 \end{pmatrix} \frac{in \cdot k}{ft}$$

$$M_U := max(M_u)$$

$$M_U = 86.57 \frac{in \cdot k}{ft}$$

Check total moment against total capacity

$$M_n := \phi_b \cdot M_p$$

$$M_n = 150.30 \frac{in \cdot k}{ft}$$

$$Status_{Flexure} := if(M_n > M_U, \text{"OK"}, \text{"Redesign"})$$

$$Status_{Flexure} = \text{"OK"}$$

COMBINED THRUST AND BENDING

Reduce thrust to reflect that peak thrust and moment do not occur at same location

$$T_{fSh} := \frac{0.67\cdot\left(\gamma_{EMax}\cdot W_E + \gamma_{LL}\cdot W_{LL} + \gamma_{LL}\cdot W_{Lane}\right)}{2} \qquad T_{fSh} = 33\,\frac{k}{ft}$$

$$T_{fCr} := \frac{0.5\cdot\gamma_{EMax}\cdot W_E + \gamma_{LL}\cdot W_{LL} + 0.5\gamma_{LL}\cdot W_{Lane}}{2} \qquad T_{fCr} = 40\,\frac{k}{ft}$$

$$T_{fRed} := \text{if}\left(T_{fCr} > T_{fSh}, T_{fCr}, T_{fSh}\right) \qquad T_{fRed} = 40\,\frac{k}{ft}$$

$$\text{Combined}_i := \begin{pmatrix} \frac{T_{fRed}}{R_T} + \frac{8}{9}\cdot\frac{M_U}{M_n} \\ \frac{T_{fRed}}{2\cdot R_T} + \frac{M_U}{M_n} \end{pmatrix} \qquad \text{Combined} = \begin{pmatrix} 0.94 \\ 0.79 \\ 0.00 \\ 0.00 \end{pmatrix} \qquad \frac{T_{fRed}}{R_T} = 0.42 \qquad \frac{M_U}{M_n} = 0.58$$

$$\text{Indx} := \text{if}\left(\frac{T_{fRed}}{R_T} \ge 0.2, 1, 2\right) \qquad \text{Indx} = 1.00$$

$$\text{Status}_{Combined} := \text{if}\left(\text{Combined}_{Indx} < 1, \text{"OK"}, \text{"Redesign"}\right)$$

$$\text{Status}_{Combined} = \text{"OK"}$$

DESIGN SUMMARY

$\text{MinimumStiffness} = \text{"OK"}$

$\text{Status}_{\text{Thrust}} = \text{"OK"}$

$\text{Status}_{\text{Bucklingtop}} = \text{"OK"}$

$\text{Status}_{\text{Bucklingbottom}} = \text{"OK"}$

$\text{FlexureCheck} = \text{"Required"}$

$\text{Status}_{\text{Flexure}} = \text{"OK"}$

$\text{Status}_{\text{Combined}} = \text{"OK"}$

$\text{Combined}_{\text{Indx}} = 0.94$

$A = 4.12\,\frac{in^2}{ft}$

$I_u = 0.1660\,\frac{in^4}{in}$

$I_p = 0.3320\,\frac{in^4}{in}$

$M_p = 167.00\,\frac{in \cdot k}{ft}$

$T_f = 50\,\frac{k}{ft}$

$M_U = 86.57\,\frac{in \cdot k}{ft}$

$\text{ConstructionControl} = \text{"OK"}$

$\text{Topchord}_{\text{max}} = 1.00$

$\text{Topchord}_{\text{min}} = 1.00$

Notes

- Circumferential stiffeners are used to meet minimum stiffness requirement

- Seam strength must also be checked and must be greater than $T_{f.}$

Design 14.3 m Span by 8.6 m Elliptical Culvert, H = 2 m

MathCad Units and Range Variables

$kN := 224.8 \cdot lbf$ $\quad MPa := 145.1379 \cdot \frac{lbf}{in^2}$ $\quad i := 1, 2..4$

Mathcad Terminology:
:= defines a term
= presents result of a calcuation

$kPa := \frac{MPa}{1000}$ $\quad GPa := 1000 \cdot MPa$

Installation Conditions

Depth of burial $H := 2.0 \cdot m$

Width of Structural Backfill $W := 14.3 \cdot m$

Live load

Design Tandem $P := 222 \cdot kN$

Multiple presence factor $mp := 1.2$

Tire length: $L_o := 250 \cdot mm$

Axle + Wheel Width $W_T := 2300 \cdot mm$

Lane load $Lane := 9.3 \cdot \frac{kN}{m}$

Lane load width $Lane_W := 3 \cdot m$

Culvert Geometry

Span $S := 14.3 \cdot m$

Rise $R := 8.6 \cdot m$

Upper Rise $R_u := 4.3 \cdot m$

Top Radius $R_t := 9.6 \cdot m$

Top Angle $\theta_{top} := 80 \cdot deg$

Span/ Rise Ratio $\frac{S}{R} = 1.66$

$$Topchord := \sin\left(\frac{\theta_{top}}{2}\right) \cdot R_t \cdot 2$$

$Topchord = 12.34\,m$

Impact $I_{mp} := if\left(H < 2.44 \cdot m, 1.33 - 0.33 \cdot \frac{H}{2.44 \cdot m}, 1\right)$ $\quad I_{mp} = 1.06$

Live load distribution with depth of fill $\quad LLDF := 1.15$

Culvert Material Properties

$F_y := 227.6 \cdot MPa$ $\quad E_p := 200 \cdot GPa$

Soil Properties:

Structural Backfill (Sn95): Ms selected from table in Specifications based on vertical pressure:

Density $\gamma_s := 18.84 \cdot kN \cdot m^{-3}$

Friction angle (loose) $\phi := 36 \cdot deg$

Poisson's ratio $\nu := 0.3$

$p_{crown} := \gamma_s \cdot H$ $\quad p_{crown} = 38\,kPa$ $\quad M_{sCrown} := 18.1 \cdot MPa$

$p_{side} := \gamma_s \cdot \left(H + \frac{R}{2}\right)$ $\quad p_{side} = 119\,kPa$ $\quad M_{sSide} := 23.1 \cdot MPa$

$M_{sBottom} := 24 \cdot MPa$

Native soil: Soft Clay (See Table C2.3-1)

$M_{sN} := 5 \cdot MPa$

Design factors

Load factors	Earth	Max	$\gamma_{EMax} := 1.3$	Resistance factors	Thrust	$\phi_c := 0.7$
		Min	$\gamma_{EMin} := 0.9$		Bending	$\phi_b := 0.9$
	Live		$\gamma_{LL} := 1.75$		Soil	$\phi_s := 0.9$
					Buckling	$\phi_{bck} := 0.7$

Trial Section Properties

Structural Plate = 150 mm by 50 mm by 7.112 mm,
with circumferential stiffeners of same structural plate

Basic plate: $I_u := 2717 \cdot \frac{mm^4}{mm}$ $\quad A := 8.72 \cdot \frac{mm^2}{mm}$

Stiffened plate: $I_p := 5434 \cdot \frac{mm^4}{mm}$ $\quad M_p := 62.08 \cdot \frac{kN \cdot m}{m}$ $\quad M_y := 42.79 \cdot \frac{kN \cdot m}{m}$

MINIMUM STIFFNESS

$$FF_{max} := 0.17 \cdot \frac{mm}{N}$$

$$FF := \frac{(2 \cdot R_t)^2 \cdot (1 - \sin(\phi))^3}{0.07 \cdot E_p \cdot I_p} \qquad FF = 0.34 \frac{mm}{N}$$

MinimumStiffness := if(FF < FF_{max}, "OK" , "Stiffeners Required")

MinimumStiffness = "Stiffeners Required"

NOTE: Use longitudinal stiffeners in addition to circumferential stiffeners (Longitudinal stiffeners not designed in this example)

THRUST CAPACITY

Compute Vertical Arching Factor and Earth Load

1. $F_{W/S}$

$$K_{VAF_i} := \begin{pmatrix} 1.9 - 1.15\cdot\frac{W}{S} \\ 1.2 \end{pmatrix}$$

$$K_{VAF} := \max(K_{VAF})$$

$$K_{VAF} = 1.20$$

$$SoilRatio := if\left(\frac{M_{sSide}}{M_{sN}} < 100, \frac{M_{sSide}}{M_{sN}}, 100\right)$$

$$F_{WS} := 1.2 + 0.5\cdot\log(SoilRatio)(K_{VAF} - 1.2)$$

$$F_{WS} = 1.20$$

2. $F_{S/R}$

$$F_{sr_i} := \begin{pmatrix} 1 - \frac{S}{R} \\ 0 \end{pmatrix}$$

$$F_{SR} := \max(F_{sr})$$

$$F_{SR} = 0.00$$

3. $F_{H/S}$

$$hs_{lim_i} := \begin{pmatrix} 0.8 - 0.5\cdot\frac{S}{R} \\ 0.3 \end{pmatrix}$$

$$HS_{lim} := \max(hs_{lim})$$

$$HS_{lim} = 0.30$$

$$F_{hs_i} := \begin{pmatrix} 2.5\cdot\left(HS_{lim} - \frac{H}{S}\right) \\ 0 \end{pmatrix}$$

$$F_{HS} := \max(F_{hs})$$

$$F_{HS} = 0.40$$

4. VAF

$$VAF := F_{WS} + F_{SR} + F_{HS}$$

$$VAF = 1.60$$

5. Earth Load

$$K_{sp} := \text{if}\left(0.172 + 0.019 \cdot \frac{S}{R_u} < 0.5, 0.172 + 0.019 \cdot \frac{S}{R_u}, 0.5\right) \qquad K_{sp} = 0.24$$

$$W_{SP} := \gamma_s \cdot S \cdot \left(H + K_{sp} \cdot R_u\right) \qquad W_{SP} = 811 \frac{kN}{m}$$

$$W_E := VAF \cdot W_{SP}$$

$$W_E = 1298 \frac{kN}{m}$$

6. Lane Load

$$W_{Lane} := Lane \cdot \left(\frac{Lane_W}{Lane_W + LLDF \cdot H}\right) \qquad W_{Lane} = 5.3 \frac{kN}{m}$$

7. Live Load

$$L_L := L_o + LLDF \cdot H \qquad L_L = 2.55\,m$$

$$L_W := W_T + LLDF \cdot H \qquad L_W = 4.60\,m$$

$$W_{LL} := \frac{0.7 \cdot mp \cdot I_{mp} \cdot P \cdot R_t}{L_L \cdot L_W} \qquad W_{LL} = 162 \frac{kN}{m}$$

Total Factored Thrust

$$T_f := \frac{\gamma_{EMax} \cdot W_E + \gamma_{LL} \cdot W_{LL} + \gamma_{LL} \cdot W_{Lane}}{2} \qquad T_f = 990 \frac{kN}{m}$$

Check Capacity for Hoop Thrust

Factored Axial Resistance $\quad R_T := \phi_c \cdot F_y \cdot A \qquad R_T = 1390 \frac{kN}{m}$

$$Status_{Thrust} := \text{if}\left(R_T > T_f, \text{"OK"}, \text{"Redesign"}\right)$$

$$Status_{Thrust} = \text{"OK"}$$

Check Buckling Capacity

Stiffened top arc with live load thrust

$$R_h := \frac{11.4}{\left(11 + \frac{S}{H}\right)} \qquad R_h = 0.63$$

$$C_n := 0.55 \qquad K_b := \frac{(1 - 2 \cdot \nu)}{(1 - \nu)^2} \qquad K_b = 0.82$$

$$R_b := \left[1.2 \cdot \phi_{bck} \cdot C_n \cdot (E_p \cdot I_p)^{\frac{1}{3}} \cdot ((\phi_s \cdot M_{sCrown} \cdot K_b))^{\frac{2}{3}}\right] \cdot R_h \qquad R_b = 1676 \frac{kN}{m}$$

$$T_f = 990 \frac{kN}{m}$$

$$Status_{Bucklingtop} := \text{if}(R_b > T_f, \text{"OK"}, \text{"Redesign"})$$

$$Status_{Bucklingtop} = \text{"OK"}$$

Unstiffened bottom arc without live load thrust

$$T_E := \frac{\gamma_{EMax} \cdot W_E}{2}$$

$$H_{bot} := H + 0.75 \cdot R$$

$$R_h := \frac{11.4}{\left(11 + \frac{S}{H_{bot}}\right)} \qquad R_h = 0.90$$

$$C_n := 0.55$$

$$R_{bE} := \left[1.2 \cdot \phi_{bck} \cdot C_n \cdot (E_p \cdot I_u)^{\frac{1}{3}} \cdot ((\phi_s \cdot M_{sBottom} \cdot K_b))^{\frac{2}{3}}\right] \cdot R_h \qquad R_{bE} = 2296 \frac{kN}{m}$$

$$T_E = 844 \frac{kN}{m}$$

$$Status_{Bucklingbottom} := \text{if}(R_b > T_E, \text{"OK"}, \text{"Redesign"})$$

$$Status_{Bucklingbottom} = \text{"OK"}$$

FLEXURAL CAPACITY

Bending stiffness factor $S_B := \dfrac{\phi_s \cdot M_{sSide} \cdot S^3}{E_p \cdot I_p}$ $S_B = 55939$

Earth Load Moment

$K_{e_i} :=$

$0.05 \cdot \left(1 - \dfrac{S_B}{S_B + 400}\right)$
0.0025

$K_E := \max(K_e)$

$K_E = 0.0025$

$M_E := \gamma_s \cdot S^2 \cdot H \cdot K_E$ $M_E = 19.26 \dfrac{kN \cdot m}{m}$

Live Load Moment

$K_{ll_i} :=$

$0.02 \cdot \left(1.05 - \dfrac{S_B}{S_B + 800}\right)$
0.001

$K_{LL} := \max(K_{ll})$

$K_{LL} = 0.0013$

$M_{LL} := 2 \cdot W_{LL} \cdot R_t \cdot K_{LL}$ $M_{LL} = 3.98 \dfrac{kN \cdot m}{m}$

Lane Load Moment - Compute with same formula as earth load moment

$K_{Lane_i} :=$

$0.05 \cdot \left(1 - \dfrac{S_B}{S_B + 400}\right)$
0.0025

$K_{Lane} := \max(K_{Lane})$

$K_{Lane} = 0.0025$

$M_{Lane} := W_{Lane} \cdot S \cdot K_{Lane}$ $M_{Lane} = 0.19 \dfrac{kN \cdot m}{m}$

Check if total live load moment is greater than 15% of plastic moment capacity

$FlexureCheck := \text{if}\left[\gamma_{LL} \cdot (M_{LL} + M_{Lane}) > 0.15 \cdot (\phi_b \cdot M_p), \text{"Required"}, \text{"Not Required"}\right]$

$FlexureCheck = \text{"Not Required"}$

Construction Moment

Maximum allowed extension of top chord

$Topchord_{max} := 1.005$ times original top chord

Select R_{ntrial} to give $\delta_{chord} = 0.0$ $R_{ntrial} := 9.9 \cdot m$

$CurvMin := 0.005 \cdot m^{-1}$

$$\delta_{chord} := 2 \cdot R_{ntrial} \cdot \sin\left(\frac{\theta_{top} \cdot R_t}{2 \cdot R_{ntrial}}\right) - Topchord_{max} \cdot Topchord \qquad \delta_{chord} = 0.0003\,m$$

$$Curv := if\left(\left|\frac{1}{R_t} - \frac{1}{R_{ntrial}}\right| < CurvMin, CurvMin, \frac{1}{R_t} - \frac{1}{R_{ntrial}}\right) \qquad Curv = 0.005\,m^{-1}$$

$$M_{sidemax} := E_p \cdot I_p \cdot Curv$$

$$M_{sidemax} = 5.44\,kN \cdot \frac{m}{m}$$

Minimum allowed top chord

$Topchord_{min} := 1.00$ times original top chord

Select R_{ntrial} to give $\delta_{chord} = 0.0$ $R_{ntrial} := 9.6 \cdot m$

$$\delta_{chord} := 2 \cdot R_{ntrial} \cdot \sin\left(\frac{\theta_{top} \cdot R_t}{2 \cdot R_{ntrial}}\right) - Topchord_{min} \cdot Topchord \qquad \delta_{chord} = 0.00\,m$$

$$Curv := if\left(\left|\frac{1}{R_t} - \frac{1}{R_{ntrial}}\right| < CurvMin, CurvMin, \frac{1}{R_t} - \frac{1}{R_{ntrial}}\right) \qquad Curv = 0.005\,m^{-1}$$

$$M_{sidemin} := E_p \cdot I_p \cdot Curv$$

$$M_{sidemin} = 5.44\,\frac{kN \cdot m}{m}$$

$$MaxConstructionM := if\left(\left|M_{sidemax}\right| > \left|M_{sidemin}\right|, \left|M_{sidemax}\right|, \left|M_{sidemin}\right|\right)$$

$$ConstructionControl := if\left(MaxConstructionM < M_y, \text{"OK"}, \text{"Reduce Construction Moment"}\right)$$

$$ConstructionControl = \text{"OK"}$$

Total Moment

$$M_{u_i} :=$$

$$\begin{bmatrix} \gamma_{EMax} \cdot -M_{sidemin} - \gamma_{EMin} \cdot M_E + \gamma_{LL} \cdot (M_{LL}) \\ \gamma_{EMin} \cdot M_{sidemax} + \gamma_{EMax} \cdot M_E + \gamma_{LL} \cdot (M_{LL} + M_{Lane}) \end{bmatrix}$$

$$M_u = \begin{pmatrix} -17.44 \\ 37.23 \\ 0.00 \\ 0.00 \end{pmatrix} \frac{kN \cdot m}{m} \qquad M_U := \max(M_u)$$

$$M_U = 37.23 \frac{kN \cdot m}{m}$$

Check total moment against total capacity

$$M_n := \phi_b \cdot M_p \qquad M_n = 55.87 \frac{kN \cdot m}{m}$$

$$Status_{Flexure} := \text{if}(M_n > M_U, \text{"OK"}, \text{"Redesign"})$$

$$Status_{Flexure} = \text{"OK"}$$

COMBINED THRUST AND BENDING

Reduce thrust to reflect that peak thrust and moment do not occur at same location

$$T_{fSh} := \frac{0.67\cdot\left(\gamma_{EMax}\cdot W_E + \gamma_{LL}\cdot W_{LL} + \gamma_{LL}\cdot W_{Lane}\right)}{2} \qquad T_{fSh} = 663\,\frac{kN}{m}$$

$$T_{fCr} := \frac{0.5\cdot\gamma_{EMax}\cdot W_E + \gamma_{LL}\cdot W_{LL} + 0.5\gamma_{LL}\cdot W_{Lane}}{2} \qquad T_{fCr} = 566\,\frac{kN}{m}$$

$$T_{fRed} := \text{if}\left(T_{fCr} > T_{fSh}, T_{fCr}, T_{fSh}\right) \qquad T_{fRed} = 663\,\frac{kN}{m}$$

$$\text{Combined}_i := \begin{pmatrix} \frac{T_{fRed}}{R_T} + \frac{8}{9}\cdot\frac{M_U}{M_n} \\ \frac{T_{fRed}}{2\cdot R_T} + \frac{M_U}{M_n} \end{pmatrix} \qquad \text{Combined} = \begin{pmatrix} 1.07 \\ 0.90 \\ 0.00 \\ 0.00 \end{pmatrix}$$

$$\frac{T_{fRed}}{R_T} = 0.48 \qquad \frac{M_U}{M_n} = 0.67$$

$$\text{Indx} := \text{if}\left(\frac{T_{fRed}}{R_T} \geq 0.2, 1, 2\right) \qquad \text{Indx} = 1.00$$

$$\text{Status}_{Combined} := \text{if}\left(\text{Combined}_{Indx} < 1, \text{"OK"}, \text{"Redesign"}\right)$$

$$\text{Status}_{Combined} = \text{"Redesign"}$$

DESIGN SUMMARY

MinimumStiffness = "Stiffeners Required"

$Status_{Thrust}$ = "OK"

$Status_{Bucklingtop}$ = "OK"

$Status_{Bucklingbottom}$ = "OK"

FlexureCheck = "Not Required"

$Status_{Flexure}$ = "OK"

$Status_{Combined}$ = "Redesign"

$Combined_{Indx} = 1.07$

$A = 8.72 \frac{mm^2}{mm}$

$I_u = 2717 \frac{mm^4}{mm}$

$I_p = 5434 \frac{mm^4}{mm}$

$M_p = 62.08 \frac{kN \cdot m}{m}$

$T_f = 990 \frac{kN}{m}$

$M_U = 37.23 \frac{kN \cdot m}{m}$

ConstructionControl = "OK"

$Topchord_{max} = 1.00$

$Topchord_{min} = 1.00$

Notes

- Circumferential stiffeners are used to meet minimum stiffness requirement

- Seam strength must also be checked and must be greater than $T_{f.}$

Design 9.2 m Span by 9.0 m Rise Pear Shaped Culvert, H = 8 m

MathCad Units and Range Variables

$kN := 224.8 \cdot lbf$ $\quad MPa := 145.1379 \cdot \frac{lbf}{in^2}$ $\quad i := 1, 2 .. 4$

Mathcad Terminology:
:= defines a term
= presents result of a calcuation

$kPa := \frac{MPa}{1000}$ $\quad GPa := 1000 \cdot MPa$

Installation Conditions

Depth of burial $H := 8.0 \cdot m$

Width of Structural Backfill $W := 4.6 \cdot m$

Live load

Design Tandem $P := 222 \cdot kN$

Multiple presence factor $mp := 1.2$

Tire width: $W_o := 500 \cdot mm$

Tire length: $L_o := 250 \cdot mm$

Wheel Spacing $W_T := 1800 \cdot mm$

Lane load $Lane := 9.3 \cdot \frac{kN}{m}$

Lane load width $Lane_W := 3 \cdot m$

Impact $I_{mp} := if\left(H < 2.44 \cdot m, 1.33 - 0.33 \cdot \frac{H}{2.44 \cdot m}, 1\right)$ $\quad I_{mp} = 1.00$

Live load distribution with depth of fill $\quad LLDF := 1.15$

Culvert Geometry

Span $S := 9.2 \cdot m$

Rise $R := 9.0 \cdot m$

Upper Rise $R_u := 3.0 \cdot m$

Top Radius $R_t := 6.7 \cdot m$

Top Angle $\theta_{top} := 67 \cdot deg$

Span/ Rise Ratio $\frac{S}{R} = 1.02$

Side Radius $R_{side} := 7.4 \cdot m$

$$Topchord := \sin\left(\frac{\theta_{top}}{2}\right) \cdot R_t \cdot 2$$

$Topchord = 7.40\,m$

Culvert Material Properties

$F_y := 227.6 \cdot MPa$ $\quad E_p := 200 \cdot GPa$

Soil Properties:

Structural Backfill (Sn95): Ms selected from table in Specifications based on vertical pressure:

Density $\gamma_s := 18.84 \cdot kN \cdot m^{-3}$

Friction angle (loose) $\phi := 36 \cdot deg$

Poisson's ratio $\nu := 0.3$

$p_{crown} := \gamma_s \cdot H$ $\quad p_{crown} = 151\,kPa$ $\quad M_{sCrown} := 24.6 \cdot MPa$

$p_{side} := \gamma_s \cdot \left(H + \frac{R}{2}\right)$ $\quad p_{side} = 235\,kPa$ $\quad M_{sSide} := 28.8 \cdot MPa$

$M_{sBottom} := 30 \cdot MPa$

Native soil: Soft Clay (See Table C2.3-1)

$M_{sN} := 5 \cdot MPa$

Design factors

Load factors	Earth	Max	$\gamma_{EMax} := 1.3$	Resistance factors	Thrust	$\phi_c := 0.7$
		Min	$\gamma_{EMin} := 0.9$		Bending	$\phi_b := 0.9$
	Live		$\gamma_{LL} := 1.75$		Soil	$\phi_s := 0.9$
					Buckling	$\phi_{bck} := 0.7$

Trial Section Properties

Structural Plate = 150 mm by 50 mm by 6.324 mm,
without circumferential stiffeners

Basic plate: $I_u := 2395 \cdot \frac{mm^4}{mm}$ $\quad A := 7.74 \cdot \frac{mm^2}{mm}$

Stiffened plate: $I_p := 2395 \cdot \frac{mm^4}{mm}$ $\quad M_p := 27.46 \cdot \frac{kN \cdot m}{m}$ $\quad M_y := 19.11 \cdot \frac{kN \cdot m}{m}$

MINIMUM STIFFNESS

Top Plates

$$FF_{max} := 0.17 \cdot \frac{mm}{N}$$

$$FF := \frac{(2 \cdot R_t)^2 \cdot (1 - \sin(\phi))^3}{0.07 \cdot E_p \cdot I_p} \qquad FF = 0.37 \frac{mm}{N}$$

$$MinimumStiffness := if(FF < FF_{max}, \text{"OK"}, \text{"Stiffeners Required"})$$

$$MinimumStiffness = \text{"Stiffeners Required"}$$

Side Plates

$$FF_{side} := \frac{(2 \cdot R_{side})^2 \cdot (1 - \sin(\phi))^3}{0.07 \cdot E_p \cdot I_p} \qquad FF_{max} := 0.17 \cdot \frac{mm}{N} \qquad FF_{side} = 0.46 \frac{mm}{N}$$

$$MinimumStiffness_{side} := if(FF < FF_{max}, \text{"OK"}, \text{"Increase Side Stiffness"})$$

$$MinimumStiffness_{side} = \text{"Increase Side Stiffness"}$$

NOTE: Use heavier gage for side plates
or adjust flexibility requirement, or increase control
of side compaction

THRUST CAPACITY

Compute Vertical Arching Factor and Earth Load

1. $F_{W/S}$

$$K_{ws_i} := \begin{bmatrix} 1.9 - 1.15 \cdot \frac{W}{S} \\ 1.2 \end{bmatrix}$$

$$K_{WS} := \max(K_{ws})$$

$$K_{WS} = 1.33$$

$$SoilRatio := \mathrm{if}\left(\frac{M_{sSide}}{M_{sN}} < 100, \frac{M_{sSide}}{M_{sN}}, 100\right)$$

$$F_{WS} := 1.2 + 0.5 \cdot \log(SoilRatio)\left(K_{WS} - 1.2\right)$$

$$F_{WS} = 1.25$$

2. $F_{S/R}$

$$F_{sr_i} := \begin{bmatrix} 1 - \frac{S}{R} \\ 0 \end{bmatrix}$$

$$F_{SR} := \max(F_{sr})$$

$$F_{SR} = 0.00$$

3. $F_{H/S}$

$$hs_{lim_i} := \begin{bmatrix} 0.8 - 0.5 \cdot \frac{S}{R} \\ 0.3 \end{bmatrix}$$

$$HS_{lim} := \max(hs_{lim})$$

$$HS_{lim} = 0.30$$

$$F_{hs_i} := \begin{bmatrix} 2.5 \cdot \left(HS_{lim} - \frac{H}{S}\right) \\ 0 \end{bmatrix}$$

$$F_{HS} := \max(F_{hs})$$

$$F_{HS} = 0.00$$

4. VAF

$$VAF := F_{WS} + F_{SR} + F_{HS}$$

$$VAF = 1.25$$

5. Earth Load

$$K_{sp} := \mathrm{if}\left(0.172 + 0.019 \cdot \frac{S}{R_u} < 0.5, 0.172 + 0.019 \cdot \frac{S}{R_u}, 0.5\right) \qquad K_{sp} = 0.23$$

$$W_{SP} := \gamma_s \cdot S \cdot (H + K_{sp} \cdot R_u) \qquad W_{SP} = 1506 \frac{kN}{m}$$

$$W_E := VAF \cdot W_{SP}$$

$$W_E = 1879 \frac{kN}{m}$$

6. Lane Load

$$W_{Lane} := Lane \cdot \left(\frac{Lane_W}{Lane_W + LLDF \cdot H}\right) \qquad W_{Lane} = 2.3 \frac{kN}{m}$$

7. Live Load

$$L_L := L_o + LLDF \cdot H \qquad L_L = 9.45\,m$$

$$L_W := W_o + W_T + LLDF \cdot H \qquad L_W = 11.50\,m$$

$$W_{LL} := \frac{0.7 \cdot mp \cdot I_{mp} \cdot P \cdot R_t}{L_L \cdot L_W} \qquad W_{LL} = 11 \frac{kN}{m}$$

Total Factored Thrust

$$T_f := \frac{\gamma_{EMax} \cdot W_E + \gamma_{LL} \cdot W_{LL} + \gamma_{LL} \cdot W_{Lane}}{2} \qquad T_f = 1234 \frac{kN}{m}$$

Check Capacity for Hoop Thrust

Factored Axial Resistance $\quad R_T := \phi_c \cdot F_y \cdot A \qquad R_T = 1234 \frac{kN}{m}$

$$Status_{Thrust} := \mathrm{if}\left(R_T > T_f, \text{"OK"}, \text{"Redesign"}\right)$$

$$Status_{Thrust} = \text{"OK"}$$

Check Buckling Capacity

Stiffened top arc with live load thrust

$$R_h := \frac{11.4}{\left(11 + \frac{S}{H}\right)} \qquad R_h = 0.94$$

$$C_n := 0.55 \qquad K_b := \frac{(1 - 2\cdot\nu)}{(1 - \nu)^2} \qquad K_b = 0.82$$

$$R_b := \left[1.2\cdot\phi_{bck}\cdot C_n\cdot\left(E_p\cdot I_p\right)^{\frac{1}{3}}\cdot\left(\left(\phi_s\cdot M_{sCrown}\cdot K_b\right)\right)^{\frac{2}{3}}\right]\cdot R_h \qquad R_b = 2338\,\frac{kN}{m}$$

$$T_f = 1234\,\frac{kN}{m}$$

$$Status_{Bucklingtop} := if\left(R_b > T_f, \text{"OK"}, \text{"Redesign"}\right)$$

$$Status_{Bucklingtop} = \text{"OK"}$$

Unstiffened bottom arc without live load thrust

$$T_E := \frac{\gamma_{EMax}\cdot W_E}{2}$$

$$H_{bot} := H + 0.75\cdot R$$

$$R_h := \frac{11.4}{\left(11 + \frac{S}{H_{bot}}\right)} \qquad R_h = 0.98$$

$$C_n := 0.55$$

$$R_{bE} := \left[1.2\cdot\phi_{bck}\cdot C_n\cdot\left(E_p\cdot I_u\right)^{\frac{1}{3}}\cdot\left(\left(\phi_s\cdot M_{sBottom}\cdot K_b\right)\right)^{\frac{2}{3}}\right]\cdot R_h \qquad R_{bE} = 2789\,\frac{kN}{m}$$

$$T_E = 1221\,\frac{kN}{m}$$

$$Status_{Bucklingbottom} := if\left(R_b > T_E, \text{"OK"}, \text{"Redesign"}\right)$$

$$Status_{Bucklingbottom} = \text{"OK"}$$

FLEXURAL CAPACITY

Bending stiffness factor $S_B := \frac{\phi_s \cdot M_{sSide} \cdot S^3}{E_p \cdot I_p}$ $S_B = 42137$

Earth Load Moment

$K_{e_i} :=$

$0.05 \cdot \left(1 - \frac{S_B}{S_B + 400}\right)$
0.0025

$K_E := \max(K_e)$

$K_E = 0.0025$

$M_E := \gamma_s \cdot S^2 \cdot H \cdot K_E$ $M_E = 31.89 \frac{kN \cdot m}{m}$

Live Load Moment

$K_{ll_i} :=$

$0.02 \cdot \left(1.05 - \frac{S_B}{S_B + 800}\right)$
0.001

$K_{LL} := \max(K_{ll})$

$K_{LL} = 0.0014$

$M_{LL} := 2 \cdot W_{LL} \cdot R_t \cdot K_{LL}$ $M_{LL} = 0.21 \frac{kN \cdot m}{m}$

Lane Load Moment - Compute with same formula as earth load moment

$K_{Lane_i} :=$

$0.05 \cdot \left(1 - \frac{S_B}{S_B + 400}\right)$
0.0025

$K_{Lane} := \max(K_{Lane})$

$K_{Lane} = 0.0025$

$M_{Lane} := W_{Lane} \cdot S \cdot K_{Lane}$ $M_{Lane} = 0.05 \frac{kN \cdot m}{m}$

Check if total live load moment is greater than 15% of plastic moment capacity

$FlexureCheck := if\left[\gamma_{LL} \cdot (M_{LL} + M_{Lane}) > 0.15 \cdot (\phi_b \cdot M_p), \text{"Required"}, \text{"Not Required"}\right]$

FlexureCheck = "Not Required"

Construction Moment

Maximum allowed extension of top chord

$Topchord_{max} := 1.0$ times original top chord

Select R_{ntrial} to give $\delta_{chord} = 0.0$ $R_{ntrial} := 6.7 \cdot m$

$CurvMin := 0.005 \cdot m^{-1}$

$$\delta_{chord} := 2 \cdot R_{ntrial} \cdot \sin\left(\frac{\theta_{top} \cdot R_t}{2 \cdot R_{ntrial}}\right) - Topchord_{max} \cdot Topchord \qquad \delta_{chord} = 0.0000\,m$$

$$Curv := if\left(\left|\frac{1}{R_t} - \frac{1}{R_{ntrial}}\right| < CurvMin, CurvMin, \frac{1}{R_t} - \frac{1}{R_{ntrial}}\right) \qquad Curv = 0.005\,m^{-1}$$

$$M_{sidemax} := E_p \cdot I_p \cdot Curv$$

$$M_{sidemax} = 2.40 \frac{kN \cdot m}{m}$$

Minimum allowed top chord

$Topchord_{min} := 0.98$ times original top chord

Select R_{ntrial} to give $\delta_{chord} = 0.0$ $R_{ntrial} := 5.778 \cdot m$

$$\delta_{chord} := 2 \cdot R_{ntrial} \cdot \sin\left(\frac{\theta_{top} \cdot R_t}{2 \cdot R_{ntrial}}\right) - Topchord_{min} \cdot Topchord \qquad \delta_{chord} = 0.00\,m$$

$$Curv := if\left(\left|\frac{1}{R_t} - \frac{1}{R_{ntrial}}\right| < CurvMin, CurvMin, \frac{1}{R_t} - \frac{1}{R_{ntrial}}\right) \qquad Curv = -0.024\,m^{-1}$$

$$M_{sidemin} := E_p \cdot I_p \cdot Curv$$

$$M_{sidemin} = -11.42 \frac{kN \cdot m}{m}$$

$$MaxConstructionM := if\left(\left|M_{sidemax}\right| > \left|M_{sidemin}\right|, \left|M_{sidemax}\right|, \left|M_{sidemin}\right|\right)$$

$$ConstructionControl := if\left(MaxConstructionM < M_y, \text{"OK"}, \text{"Reduce Construction Moment"}\right)$$

$$ConstructionControl = \text{"OK"}$$

Total Moment

$$M_{u_i} :=$$

$$\begin{pmatrix} \gamma_{EMax} \cdot -M_{sidemin} - \gamma_{EMin} \cdot M_E + \gamma_{LL} \cdot (M_{LL}) \\ \gamma_{EMin} \cdot M_{sidemax} + \gamma_{EMax} \cdot M_E + \gamma_{LL} \cdot (M_{LL} + M_{Lane}) \end{pmatrix}$$

$$M_u = \begin{pmatrix} -13.49 \\ 44.08 \\ 0.00 \\ 0.00 \end{pmatrix} \frac{kN \cdot m}{m} \qquad M_U := max(M_u)$$

$$M_U = 44.08 \frac{kN \cdot m}{m}$$

Check total moment against total capacity

$$M_n := \phi_b \cdot M_p \qquad M_n = 24.71 \frac{kN \cdot m}{m}$$

$$Status_{Flexure} := if(M_n > M_U, "OK", "Redesign")$$

$$Status_{Flexure} = "Redesign"$$

COMBINED THRUST AND BENDING

Reduce thrust to reflect that peak thrust and moment do not occur at same location

$$T_{fSh} := \frac{0.67\cdot(\gamma_{EMax}\cdot W_E + \gamma_{LL}\cdot W_{LL} + \gamma_{LL}\cdot W_{Lane})}{2} \qquad T_{fSh} = 826\,\frac{kN}{m}$$

$$T_{fCr} := \frac{0.5\cdot\gamma_{EMax}\cdot W_E + \gamma_{LL}\cdot W_{LL} + 0.5\gamma_{LL}\cdot W_{Lane}}{2} \qquad T_{fCr} = 622\,\frac{kN}{m}$$

$$T_{fRed} := \text{if}(T_{fCr} > T_{fSh}, T_{fCr}, T_{fSh}) \qquad T_{fRed} = 826\,\frac{kN}{m}$$

$$\text{Combined}_i := \begin{array}{|c|}\hline \frac{T_{fRed}}{R_T} + \frac{8}{9}\cdot\frac{M_U}{M_n} \\ \hline \frac{T_{fRed}}{2\cdot R_T} + \frac{M_U}{M_n} \\ \hline \end{array} \qquad \text{Combined} = \begin{pmatrix} 2.26 \\ 2.12 \\ 0.00 \\ 0.00 \end{pmatrix} \qquad \frac{T_{fRed}}{R_T} = 0.67 \qquad \frac{M_U}{M_n} = 1.78$$

$$\text{Indx} := \text{if}\left(\frac{T_{fRed}}{R_T} \ge 0.2, 1, 2\right) \qquad \text{Indx} = 1.00$$

$$\text{Status}_{Combined} := \text{if}(\text{Combined}_{Indx} < 1, \text{"OK"}, \text{"Redesign"})$$

$$\text{Status}_{Combined} = \text{"Redesign"}$$

DESIGN SUMMARY

MinimumStiffness = "Stiffeners Required"

$MinimumStiffness_{side}$ = "Increase Side Stiffness"

$Status_{Thrust}$ = "OK"

$Status_{Bucklingtop}$ = "OK"

$Status_{Bucklingbottom}$ = "OK"

FlexureCheck = "Not Required"

$Status_{Flexure}$ = "Redesign"

$Status_{Combined}$ = "Redesign"

$Combined_{Indx} = 2.26$

$A = 7.74 \frac{mm^2}{mm}$

$I_u = 2395 \frac{mm^4}{mm}$

$I_p = 2395 \frac{mm^4}{mm}$

$M_p = 27.46 \frac{kN \cdot m}{m}$

$T_f = 1234 \frac{kN}{m}$

$M_U = 44.08 \frac{kN \cdot m}{m}$

ConstructionControl = "OK"

$Topchord_{max} = 1.00$

$Topchord_{min} = 0.98$

Notes

- Circumferential stiffeners are used to meet minimum stiffness requirement

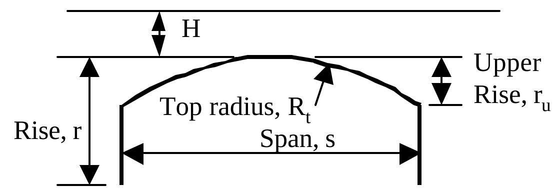
- Seam strength must also be checked and must be greater than $T_{f.}$

Long Span Concrete Culvert - Load Calculations

English Units

Input

Geometry



Outside span $s_o := 460 \cdot in$

Rise $r := 138 \cdot in$

Upper rise $r_u := 54.18 \cdot in$

Top Radius $R_t := 486 \cdot in$

Thick. $Side_t := 14 \cdot in$ $Arch_t := 12 \cdot in$

Soil & Backfill

Initial Values: $Lat_1 := 0$ $Lat_2 := 0.3$

Backfill type: Soil := "Sn95"

$Lat_1 := if(Soil = \text{"Sn95"}, 0.05, 0)$

Soil unit weight $\gamma_s := 120 \cdot \frac{lbf}{ft^3}$

$Lat_1 := if(Soil = \text{"Sn90"} \vee Soil = \text{"Si95"}, .025, Lat_1)$

$Lat_2 := if(Soil = \text{"Sn95"} \vee Soil = \text{"Sn90"} \vee Soil = \text{"Si95"}, 0.4, Lat_2)$

Depth of fill $H := 2.0 \cdot ft$

$Lat_2 := if(Soil = \text{"Sn85"} \vee Soil = \text{"Si90"} \vee Soil = \text{"Cl95"}, 0.4, Lat_2)$

Lateral pressure coefficient

Final Values $Lat_1 = 0.050$ $Lat_2 = 0.40$

$$K_H := Lat_2 + Lat_1 \cdot \frac{H}{3.28 \cdot ft} \qquad K_H := if(K_H < 0.6, K_H, 0.6) \qquad K_H = 0.43$$

- No groundwater above footings of culvert
- Native soil: dense granular

Live load

Design Tandem, Load per axle $P := 25000 \cdot lbf$

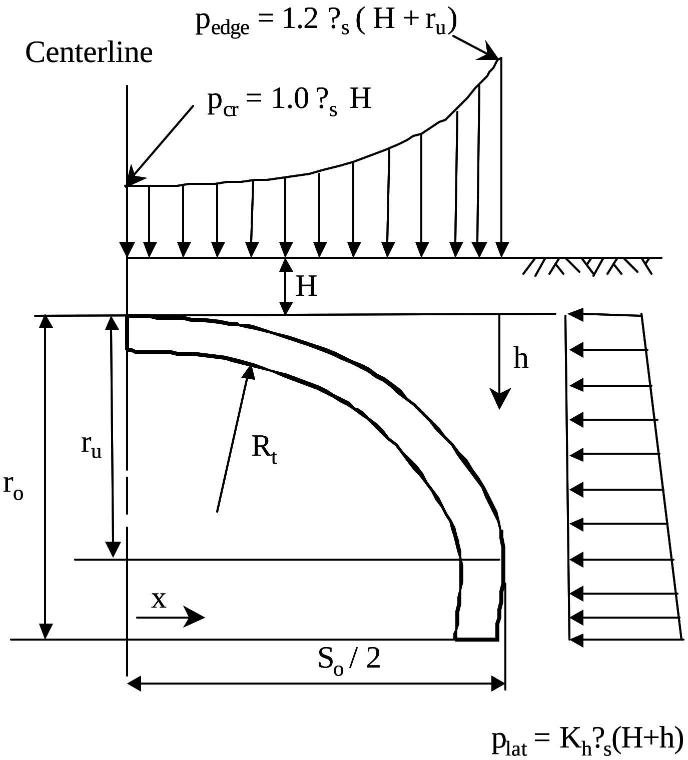
Multiple presence factor $mp := 1.2$

Impact Factor

$$I_0 := 1 + 0.33 \cdot \left(\frac{8 - \frac{H}{ft}}{8} \right)$$

$$I_1 := 1 \qquad IM := max(I) \qquad IM = 1.25$$

Earth Loads



Vertical Pressure

Soil prism load

$$K_{VAF} := 0.172 + 0.019 \cdot \frac{s_o}{r_u} \qquad K_{VAF} = 0.33$$

$$W_{sp} := \gamma_s \cdot s_o \cdot \left(H + K_{VAF} \cdot r_u\right) \qquad W_{sp} = 16123 \frac{lbf}{ft}$$

Soil pressure over crown

$$p_{cr} := \gamma_s \cdot H \qquad p_{cr} = 240 \frac{lbf}{ft^2} \qquad p_{cr} = 20.00 \frac{lbf}{in \cdot ft}$$

Soil pressure at edge

$$p_{edge} := 1.2 \cdot \gamma_s \cdot \left(H + r_u\right) \qquad p_{edge} = 938 \frac{lbf}{ft^2} \qquad p_{edge} = 78.18 \frac{lbf}{in \cdot ft}$$

Lateral Pressure

Top

$$p_{lattop} := K_H \cdot \gamma_s \cdot H \qquad p_{lattop} = 8.61 \frac{lbf}{in \cdot ft}$$

Bottom

$$p_{latbot} := K_H \cdot \gamma_s \cdot (H + r) \qquad p_{latbot} = 58.12 \frac{lbf}{in \cdot ft}$$

Total lateral load

$$P_{Lat} := \frac{\left(p_{lattop} + p_{latbot}\right)}{2} \cdot r \qquad P_{Lat} = 4604 \frac{lbf}{ft}$$

Note: Frame model used in analysis will be based on centerline dimensions. To assure that all load on culvert is placed on the model the pressures need to be scaled up by the ratio of the outside dimensions to the centerline dimensions.
Vertical Pressures:

$Scv := \frac{s_o}{s_o - Side_t}$ $\quad Scv = 1.03$ $\quad p_{cr} := p_{cr} \cdot Scv$ $\quad p_{cr} = 20.63 \frac{lbf}{in \cdot ft}$

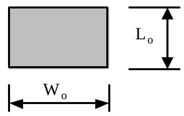
$p_{edge} := p_{edge} \cdot Scv$ $\quad p_{edge} = 80.63 \frac{lbf}{in \cdot ft}$

Lateral Pressures

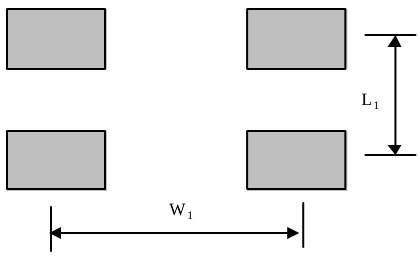
$Scl := \frac{r}{r - 0.5 \cdot Arch_t}$ $\quad Scl = 1.05$ $\quad p_{lattop} := p_{lattop} \cdot Scl$ $\quad p_{lattop} = 9.00 \frac{lbf}{in \cdot ft}$

$p_{latbot} := p_{latbot} \cdot Scl$ $\quad p_{latbot} = 60.76 \frac{lbf}{in \cdot ft}$

Live Load



a) Single tire



b) Multiple tires

Live load distribution factor: $LLDF := 1.15$

Wheel length: $L_o := 10 \cdot in$

Wheel width $W_o := 20.in$

Wheel spacing $W_1 := 72 \cdot in$

Axle spacing (width) $L_1 := 48 \cdot in$

Distribution width $D_w := 40 \cdot in$

Single wheel load* $P_w := \frac{P \cdot mp \cdot IM}{2}$

*includes multiple presence and impact factors $P_w = 18713\,lbf$

At depth of structure:

Patch width for single wheel: $WS_0 := W_o + LLDF \cdot H + D_w$ $\quad WS_0 = 87.60\,in$

Patch width for multiple wheels: i.e. wheels interact. $WS_1 := (W_o + W_1) + LLDF \cdot H + D_w$ $\quad WS_1 = 159.60\,in$

Depth of interaction: $H_{wint} := \frac{(W_1 - W_o - D_w)}{LLDF}$ $\quad H_{wint} = 0.87\,ft$

Effective patch width: $W_s := if(H < H_{wint}, WS_0, WS_1)$ $\quad W_s = 159.60\,in$

$P_{wa} := if(H < H_{wint}, P_w, 2P_w)$ $\quad P_{wa} = 37425\,lbf$

Patch length for single wheel: $LS_0 := (L_o + LLDF \cdot H)$ $\quad LS_0 = 37.60\,in$

Patch length for multiple wheels: i.e. wheel pressures interact. $LS_1 := [(L_o + L_1) + LLDF \cdot H]$ $\quad LS_1 = 85.60\,in$

Depth of interaction: $H_{lint} := \frac{(L_1 - L_o)}{LLDF}$ $\quad H_{lint} = 2.754\,ft$

Effective patch length: $L_s := if(H < H_{lint}, LS_0, LS_1)$ $\quad L_s = 37.60\,in$

$P_{wb} := if(H < H_{lint}, P_{wa}, 2P_{wa})$ $\quad P_{wb} = 37425\,lbf$

Effective live load pressure on structure:

$$p := \frac{P_{wb}}{W_s \cdot L_s} \qquad p = 74.84 \frac{lbf}{in \cdot ft}$$

Length of effective pressure

$$L_s := if(L_s < s_o, L_s, s_o) \qquad L_s = 37.60\, in$$

Total live load $P := L_s \cdot p \qquad P = 2814 \frac{lbf}{ft}$

Notes: 1. This analysis assumes that the length dimension is parallel to the direction of travel and that the direction of travel is across the culvert span.

2. If H is less than H_{lint}, than the structure must be loaded with two loads of magnitude, P, and length L_s, spaced a distance L_1.

CALCULATIONS TO EVALUATE REINFORCING REQUIREMENTS FOR CONSPAN REINFORCED CONCRETE CULVERT - Depth of Fill = 2.0 ft (0.6 m)

DIMENSIONS AND MATERIAL STRENGTHS

Horizontal span of culvert.. $S_i := 36 \cdot ft$

Crown radius.. $r_t := 72 \cdot ft$

Clear cover over reinforcement.. $t_b := 1.5 \cdot in$

Width of section being designed.. $b := 12 \cdot in \cdot ft^{-1}$

Design compressive strength of concrete.. $f_{cp} := 6 \cdot ksi$

Yield strength of steel reinforcement.. $f_y := 65 \cdot ksi$

Maximum developable stirrup material strength (not greater than f_y or anchorage strength).... $f_v := 60 \cdot ksi$

Spacing of circumferential reinforcement.. $s := 2 \cdot in$

Circumferential reinforcemenT provided in one (n=1) or multiple (n=2) layers........................ $n := 1$

Reinforcement Type... $R_{type} := 2$

1 = smooth wire or plain bars

2 = welded smooth wire fabric with 8 in. maximum spacing of longitudinals

3 = welded deformed wire fabric, deformed wire, deformed bars or any reinforcement with stirrups

Load factor for selfweight.. $\gamma_{SW} := 1.35$

Load factor for earth pressure.. $\gamma_E := 0.9, 1.35$

Load factor for live load.. $\gamma_L := 1.35$

Resistance factor for flexure.. $\phi_f := 0.95$

Resistance factor for radial tension... $\phi_r := 0.90$

Resistance factor for diagonal tension... $\phi_v := 0.90$

Radial tension process factor... $F_{rp} := 1.0$

Diagonal tesion process factor... $F_{vp} := 1.0$

Crack control factor.. $F_{cr} := 0.9$

DESIGN FORCES (See next sheet for definitions and units)

Array index: $i := 1, 2 .. 17$

Design Forces From Frame Analysis:

$$M_{uactual} := \begin{pmatrix} 0.00 \\ -208.05 \\ -431.82 \\ -669.29 \\ -796.93 \\ -927.41 \\ -1060.47 \\ -804.51 \\ -580.65 \\ -381.99 \\ -203.63 \\ -41.14 \\ 108.06 \\ 246.50 \\ 376.38 \\ 473.09 \\ 497.71 \end{pmatrix} \quad N_u := \begin{pmatrix} 22.33 \\ 21.98 \\ 21.63 \\ 21.28 \\ 21.09 \\ 20.87 \\ 21.67 \\ 20.21 \\ 19.05 \\ 18.13 \\ 17.36 \\ 16.74 \\ 16.22 \\ 15.78 \\ 15.42 \\ 15.05 \\ 14.98 \end{pmatrix} \quad M_s := \begin{pmatrix} 0.00 \\ -129.55 \\ -276.57 \\ -438.81 \\ -528.03 \\ -620.41 \\ -715.65 \\ -532.10 \\ -375.01 \\ -238.77 \\ -119.33 \\ -13.13 \\ 82.00 \\ 168.13 \\ 247.01 \\ 304.89 \\ 319.81 \end{pmatrix} \quad N_s := \begin{pmatrix} 16.21 \\ 15.95 \\ 15.68 \\ 15.41 \\ 15.26 \\ 15.09 \\ 15.61 \\ 14.60 \\ 13.79 \\ 13.16 \\ 12.65 \\ 12.24 \\ 11.90 \\ 11.62 \\ 11.39 \\ 11.17 \\ 11.12 \end{pmatrix} \quad V_{vuactual} := \begin{pmatrix} -10.84 \\ -11.75 \\ -12.54 \\ -13.23 \\ -13.55 \\ -13.83 \\ 12.34 \\ 10.77 \\ 9.53 \\ 8.53 \\ 7.75 \\ 7.11 \\ 6.58 \\ 6.16 \\ 5.80 \\ 2.96 \\ 0.36 \end{pmatrix}$$

Forces from frame analysis:

Moments are in.-k/ft
Thrusts and shears are k/ft

$M_{uactual}$ = factored moment with proper sign + for tension on inside, - for tension on outside
M_u = moment with all signs positive.
N_u = factored thrust, + is compression
$V_{vuactual}$ = factored shear with proper sign
V_{vu} = factored shear with all signs positive
M_s = service load moment
N_s = service load thrust

Add Units to arrays and convert moments and shears to all positive signs:

$$M_u := M_{uactual} \cdot (in \cdot k) \cdot ft^{-1}$$

$$M_{u_i} := if\left(M_{u_i} < 0, -M_{u_i}, M_{u_i}\right)$$

$$N_u := N_u \cdot k \cdot ft^{-1}$$

$$M_s := M_s \cdot in \cdot k \cdot ft^{-1}$$

$$M_{s_i} := if\left(M_{s_i} < 0, -M_{s_i}, M_{s_i}\right)$$

$$N_s := N_s \cdot k \cdot ft^{-1}$$

$$V_{vu} := V_{vuactual} \cdot k \cdot ft^{-1}$$

$$V_{vu_i} := if\left(V_{vu_i} < 0, -V_{vu_i}, V_{vu_i}\right)$$

$$M_{vu_i} := M_{u_i}$$

$$N_{vu_i} := N_{u_i}$$

Note: Structure and all loads are symmetric, only Nodes 1 to 17 are presented in analysis.

Node 1 is base of leg
Node 7 is corner of segment
Node 17 is crown

Wall Thickness and Depth to Centroid from Compression Face

$$i = \begin{array}{|r|}\hline 1\\ \hline 2\\ \hline 3\\ \hline 4\\ \hline 5\\ \hline 6\\ \hline 7\\ \hline 8\\ \hline 9\\ \hline 10\\ \hline 11\\ \hline 12\\ \hline 13\\ \hline 14\\ \hline 15\\ \hline 16\\ \hline 17\\ \hline\end{array} \qquad h := \begin{pmatrix} 14.00\\ 14.00\\ 14.00\\ 14.31\\ 15.91\\ 20.04\\ 23.24\\ 20.84\\ 16.14\\ 13.30\\ 12.21\\ 12.0\\ 12.00\\ 12.00\\ 12.00\\ 12.00\\ 12.00 \end{pmatrix} \qquad d := \begin{pmatrix} 12.02\\ 12.02\\ 12.02\\ 12.33\\ 13.93\\ 18.06\\ 21.26\\ 18.96\\ 14.16\\ 11.32\\ 10.23\\ 10.02\\ 10.02\\ 10.02\\ 10.02\\ 10.02\\ 10.02 \end{pmatrix}$$

Add units:

$$h := h \cdot in$$

$$d := d \cdot in$$

1.1 Reinforcement for Flexural Strength

Define the compressive strength per inch of thickness as........................ $g := 0.85 \cdot b \cdot f_{cp}$

$g = 5.10\,\text{ksi}$

Required area of flexural steel

$$A_{sf_i} := \frac{1}{f_y} \cdot \left[g \cdot \phi_f \cdot d_i - N_{u_i} - \sqrt{g \cdot \left[g \cdot \left(\phi_f \cdot d_i\right)^2 - N_{u_i} \cdot \left(2 \cdot \phi_f \cdot d_i - h_i\right) - 2 \cdot M_{u_i} \right]} \right]$$

$A_{sf} =$ (in $\frac{in^2}{ft}$)

	1
1	-0.210
2	0.081
3	0.403
4	0.730
5	0.780
6	0.675
7	0.641
8	0.528
9	0.514
10	0.397
11	0.165
12	-0.094
13	0.021
14	0.259
15	0.488
16	0.663
17	0.708

1.2 Minimum Flexural Reinforcement

Minimum reinforcement area....

$$A_{smin_i} := \text{for } j \in i$$
$$\left(\text{if}\,(i < 7, 0.002 \cdot 12 \cdot 14, .002 \cdot 12 \cdot 12) \cdot in^2 \cdot ft^{-1}\right)$$

Governing Reinforcement......... $A_{sf_i} := \text{if}\left(A_{smin_i} > A_{sf_i}, A_{smin_i}, A_{sf_i}\right)$

$A_{sf} =$ (in $\frac{in^2}{ft}$)

	1
1	0.336
2	0.336
3	0.403
4	0.730
5	0.780
6	0.675
7	0.641
8	0.528
9	0.514
10	0.397
11	0.288
12	0.288
13	0.288
14	0.288
15	0.488
16	0.663
17	0.708

1.3 Maximum Flexural Reinforcement without Stirrups (Radial Tension)

Radius of the inside layer of reinforcement.................. $r_s := r_t + t_b$ .... $r_s = 865.50\,in$

Size factor for radial tension, fixed value for large span culverts... $F_{rt} := 0.8$

Radial tension index:

$$M_{max} := -\min\left(M_{uactual}\right)\cdot in\cdot k\cdot ft^{-1}$$

$$a_i := \text{for } j \in i \quad \text{if}\left(\frac{-M_{max}}{in\cdot k\cdot ft^{-1}} \neq M_{uactual_i}, 0, i\right)$$

$nndx := \max(a)$ $nndx = 7.00$

Parameters at Critical Radial Tension Section

$M_{max} = 1.06 \times 10^3\,in\cdot k\cdot ft^{-1}$ $N_{u_{nndx}} = 21.67\,k\cdot ft^{-1}$ $d_{nndx} = 21.26\,in$

$$R_{rt} := \frac{M_{max} - 0.45\cdot N_{u_{nndx}}\cdot d_{nndx}}{1.2\cdot b\cdot d_{nndx}\cdot \phi_r\cdot r_s\cdot \sqrt{f_{cp}\cdot psi}\cdot F_{rt}\cdot F_{rp}}$$

$R_{rt} = 0.06$

Maximum Reinforcement Area

$$\beta_1 := \text{if}\left[f_{cp} < 4\cdot ksi, 0.85, \text{if}\left[f_{cp} > 8ksi, 0.65, 0.85 - 0.05\cdot\left(\frac{f_{cp}}{ksi} - 4\right)\right]\right]$$

$\beta_1 = 0.75$

$$A_{smax} := \frac{1}{f_y}\cdot\left(\frac{55\cdot\phi_f\cdot\beta_1\cdot d\cdot f_{cp}}{87 + f_y\cdot ksi^{-1}} - 0.75\cdot N_u\right)$$

$A_{smax} =$ (in units of $\frac{in^2}{ft}$)

	1
1	3.17
2	3.18
3	3.18
4	3.28
5	3.73
6	4.92
7	5.82
8	5.18
9	3.82
10	3.02
11	2.72
12	2.67
13	2.67
14	2.68
15	2.68
16	2.69

Evaluate limits on Maximum Reinforcement

$$RadialTension := if(R_{rt} < 1, "ok", "Stirrups Required")$$

RadialTensi

$$MaxCompression_i := if(A_{sf_i} < A_{smax_i}, "ok", "NotOK")$$

Note: If maximum compression is "NotOK" then the options for redesign include:
- increase concrete strength
- increase depth of section
- design section as a compression member with ties

MaxCompression =

	1
1	"ok"
2	"ok"
3	"ok"
4	"ok"
5	"ok"
6	"ok"
7	"ok"
8	"ok"
9	"ok"
10	"ok"
11	"ok"
12	"ok"
13	"ok"
14	"ok"
15	"ok"
16	"ok"

1.4 Flexural Reinforcement Requirements for Crack Width Control

Crack control coefficients........ $B_1 := \left(\frac{t_b \cdot s}{2 \cdot n \cdot in^2}\right)^{0.333}$ .... $B_1 = 1.145$

$C_1 := if\left(R_{type} \geq 3, 1.9, if\left(R_{type} \geq 2, 1.5, 1.0\right)\right)$.................................... $C_1 = 1.50$

Service level load eccentricity............................ $e_i := \frac{M_{s_i}}{N_{s_i}} + d_i - \frac{h_i}{2}$

Lower bound enforced for $^e/_d$ ratio....................... $edratio_i := if\left(\frac{e_i}{d_i} > 1.15, \frac{e_i}{d_i}, 1.15\right)$

Flexural design parameter................................ $j_i := if\left(0.9 < 0.74 + \frac{edratio_i}{10}, 0.9, 0.74 + \frac{edratio_i}{10}\right)$

Flexural design parameter................................ $i_{cr_i} := \left(1 - \frac{j_i}{edratio_i}\right)^{-1}$

Moment-thrust contribution factor........................ $K_i := \frac{1}{i_{cr_i} \cdot j_i} \cdot \left[M_{s_i} + N_{s_i} \cdot \left(d_i - \frac{h_i}{2}\right)\right]$

Required area of flexural reinforcement steel for crack width control at service load design based upon **Equation B.7**.. $A_{scr_i} := \frac{B_1 \cdot psi^{-1}}{30000 \cdot \phi_f \cdot d_i \cdot F_{cr}} \cdot \left[K_i - C_1 \cdot \left(h_i\right)^2 \cdot \sqrt{f_{cp} \cdot psi}\right]$

$A_{scr_i} := if\left[\left(A_{scr_i}\right) < 0, 0, A_{scr_i}\right]$

$e_i =$ (in)	$edratio_i =$	$j_i =$	$i_{cr_i} =$	$A_{scr_i} =$ ($in^2 \cdot ft^{-1}$)
5.02	1.15	0.86	3.90	0.00
13.14	1.15	0.86	3.90	0.00
22.66	1.89	0.90	1.91	0.00
33.65	2.73	0.90	1.49	0.36
40.58	2.91	0.90	1.45	0.39
49.15	2.72	0.90	1.49	0.00
55.49	2.61	0.90	1.53	0.00
44.99	2.37	0.90	1.61	0.00
33.28	2.35	0.90	1.62	0.00
22.81	2.02	0.90	1.81	0.00
13.56	1.33	0.87	2.93	0.00
5.09	1.15	0.86	3.90	0.00
10.91	1.15	0.86	3.90	0.00
18.49	1.85	0.90	1.95	0.00
25.71	2.57	0.90	1.54	0.05
31.32	3.13	0.90	1.40	0.34
32.78	3.27	0.90	1.38	0.41

Select limiting area based on cracking & flexure:.. $A_{s_i} := \text{if}\left(A_{scr_i} > A_{sf_i}, A_{scr_i}, A_{sf_i}\right)$

$i2 := 1, 2 .. 2$

$M_{uactual_1} = 0.00$

Governing positive reinforcement

$$A_{smpos_i} := \text{if}\left(M_{uactual_i} > 0, A_{s_i}, 0 \cdot \frac{in^2}{ft}\right)$$

$A_{sg_1} := \max(A_{smpos})$

$A_{sg_1} = 0.71 \frac{in^2}{ft}$

Governing Negative reinforcement

$$A_{smneg_i} := \text{if}\left(M_{uactual_i} < 0, A_{s_i}, 0 \cdot \frac{in^2}{ft}\right)$$

$A_{sg_2} := \max(A_{smneg})$

$A_{sg_2} = 0.78 \frac{in^2}{ft}$

$A_s =$ (units: $\frac{in^2}{ft}$)

	1
1	0.34
2	0.34
3	0.40
4	0.73
5	0.78
6	0.67
7	0.64
8	0.53
9	0.51
10	0.40
11	0.29
12	0.29
13	0.29
14	0.29
15	0.49
16	0.66
17	0.71

Depth to tension reinforcement at governing locations:

User input is required

$d_{g_1} := d_{17}$

$d_{g_2} := d_3$

$$A_{sg} = \begin{pmatrix} 0.71 \\ 0.78 \end{pmatrix} \frac{in^2}{ft}$$

$$d_g = \begin{pmatrix} 10.02 \\ 12.02 \end{pmatrix} in$$

1.5 Shear Strength Calculations

Moment for $^{M}/_{Vd}$ ratio .... $M_{nu_i} := M_{vu_i} - N_{vu_i} \cdot \left(\frac{4 \cdot h_i - d_i}{8}\right)$ $\quad M_{nu_i} := \text{if}\left(M_{nu_i} < 0, 0, M_{nu_i}\right)$

Reinforcement ratio................................ $\rho_{i2} := \text{if}\left(0.02 < \frac{A_{sg_{i2}}}{b \cdot d_{g_{i2}}}, 0.02, \frac{A_{sg_{i2}}}{b \cdot d_{g_{i2}}}\right)$ $\quad \rho_{i2} =$

0.0059
0.0054

$\rho_{g_i} := \text{if}\left(M_{uactual_i} > 0, \rho_2, \rho_1\right)$

Factor for depth of section .... $F_{d_i} := 0.8 + \frac{1.6 \cdot in}{d_i}$ $\quad F_{d_{i2}} := \text{if}\left(F_{d_{i2}} > 1.3, 1.3, F_{d_{i2}}\right)$

Thrust factor .... $F_{n_i} := 1 + \frac{N_{vu_i} \cdot psi^{-1}}{24000 \cdot h_i}$

F_c factor for shear capacity calculation........... $F_{c_i} := 1 + \frac{d_i}{r_t + 0.5 \cdot h_i}$ $\quad F_{c_i} := \text{if}\left(i < 7, 1, \text{if}\left(i > 26, 1, F_{c_i}\right)\right)$

$M_{nu} =$ (in·k/ft)

	1
1	0
2	87
3	313
4	550
5	666
6	765
7	866
8	642
9	461
10	287
11	120
12	0
13	31
14	172
15	303
16	402
17	427

$\rho_g =$

	1
1	$5.89 \cdot 10^{-3}$
2	$5.89 \cdot 10^{-3}$
3	$5.89 \cdot 10^{-3}$
4	$5.89 \cdot 10^{-3}$
5	$5.89 \cdot 10^{-3}$
6	$5.89 \cdot 10^{-3}$
7	$5.89 \cdot 10^{-3}$
8	$5.89 \cdot 10^{-3}$
9	$5.89 \cdot 10^{-3}$
10	$5.89 \cdot 10^{-3}$
11	$5.89 \cdot 10^{-3}$
12	$5.89 \cdot 10^{-3}$
13	$5.41 \cdot 10^{-3}$
14	$5.41 \cdot 10^{-3}$
15	$5.41 \cdot 10^{-3}$
16	$5.41 \cdot 10^{-3}$
17	$5.41 \cdot 10^{-3}$

$F_d =$

	1
1	0.93
2	0.93
3	0.93
4	0.93
5	0.91
6	0.89
7	0.88
8	0.88
9	0.91
10	0.94
11	0.96
12	0.96
13	0.96
14	0.96
15	0.96
16	0.96
17	0.96

$F_n =$

	1
1	1.01
2	1.01
3	1.01
4	1.01
5	1.00
6	1.00
7	1.00
8	1.00
9	1.00
10	1.00
11	1.00
12	1.00
13	1.00
14	1.00
15	1.00
16	1.00
17	1.00

$F_c =$

	1
1	1.00
2	1.00
3	1.00
4	1.00
5	1.00
6	1.00
7	1.02
8	1.02
9	1.02
10	1.01
11	1.01
12	1.01
13	1.01
14	1.01
15	1.01
16	1.01
17	1.01

Shear capacity at critical section...................

$$V_{b_i} := \phi_v \cdot b \cdot d_i \cdot F_{vp} \cdot \sqrt{f_{cp} \cdot psi} \cdot \left(1.1 + 63 \cdot \rho_{g_i}\right) \cdot \frac{F_{d_i} \cdot F_{n_i}}{F_{c_i}}$$

$$MVD_i := \text{if}\left(\frac{M_{nu_i}}{V_{vu_i} \cdot d_i} > 3, 3, \frac{M_{nu_i}}{V_{vu_i} \cdot d_i}\right)$$

$$V_{c_i} := \text{if}\left(V_{b_i} \cdot \frac{4}{MVD_i + 1} > 4.5 \cdot \sqrt{f_{cp} \cdot psi} \cdot d_i, 4.5 \cdot \sqrt{f_{cp} \cdot psi} \cdot d_i, \frac{V_{b_i} \cdot 4}{MVD_i + 1}\right)$$

Diagonal tension index.................................

$$R_{dt_i} := \frac{V_{vu_i}}{V_{c_i}}$$

Evaluate Diagonal Tension Strength

$$DT_{strength_i} := \text{if}\left(R_{dt_i} > 1, \text{"Strength Exceeded"}, \text{"OK"}\right)$$

$V_b =$ (k/ft)

	1
1	13.88
2	13.88
3	13.88
4	14.18
5	15.76
6	19.82
7	22.43
8	20.27
9	15.72
10	13.01
11	11.96
12	11.76
13	11.51
14	11.51
15	11.51
16	11.51
17	11.51

$MVD_i =$	$V_{c_i} =$ (k/ft)	$R_{dt_i} =$
0.00	50.28	0.22
0.62	34.32	0.34
2.08	18.05	0.69
3.00	14.18	0.93
3.00	15.76	0.86
3.00	19.82	0.70
3.00	22.43	0.55
3.00	20.27	0.53
3.00	15.72	0.61
2.97	13.10	0.65
1.51	19.05	0.41
0.00	41.91	0.17
0.47	31.31	0.21
2.78	12.18	0.51
3.00	11.51	0.50
3.00	11.51	0.26
3.00	11.51	0.03

$DT_{strength} =$

	1
1	"OK"
2	"OK"
3	"OK"
4	"OK"
5	"OK"
6	"OK"
7	"OK"
8	"OK"
9	"OK"
10	"OK"
11	"OK"
12	"OK"
13	"OK"
14	"OK"
15	"OK"
16	"OK"
17	"OK"

Check if Circumferential Reinforcement Can Be Increased to Improve Shear Strength

$$A_{sinc_i} := \text{if}\left[R_{dt_i} > 1, \frac{0.01587 \cdot V_{vu_i}}{\phi_v \cdot F_{vp} \cdot \sqrt{f_{cp} \cdot psi}} \cdot \left(\frac{F_{c_i}}{F_{d_i} \cdot F_{n_i}}\right) - ((0.01746)) \cdot d_i, A_{s_i}\right]$$

$$\rho_{inc_i} := \frac{A_{sinc_i}}{b \cdot d_i} \qquad A_{sinc_i} := \text{if}\left(\rho_{inc_i} > 0.02, 10^5 \cdot in^2 \cdot ft^{-1}, A_{sinc_i}\right)$$

$$DT_{inc_i} := \text{if}\left(\rho_{inc_i} > 0.02, \text{"Stirrups Requ'd"}, \text{"OK"}\right)$$

If increased reinforcement ratio is greater than 2% than stirrups must be used

Governing Design

$$A_{si_i} := \text{if}\left(M_{uactual_i} > 0, A_{sinc_i}, 0 \cdot \frac{in^2}{ft}\right) \qquad A_{sinside} := \max(A_{si})$$

$$A_{so_i} := \text{if}\left(M_{uactual_i} < 0, A_{sinc_i}, 0 \cdot \frac{in^2}{ft}\right) \qquad A_{soutside} := \max(A_{so})$$

$A_{sinc} =$ ($\frac{in^2}{ft}$)

	1
1	0.336
2	0.336
3	0.403
4	0.730
5	0.780
6	0.675
7	0.641
8	0.528
9	0.514
10	0.397
11	0.288
12	0.288
13	0.288
14	0.288
15	0.488
16	0.663
17	0.708

$A_{si_i} =$ ($\frac{in^2}{ft}$)	$A_{so_i} =$ ($\frac{in^2}{ft}$)	$\rho_{inc_i} =$
0.00	0.00	0.002
0.00	0.34	0.002
0.00	0.40	0.003
0.00	0.73	0.005
0.00	0.78	0.005
0.00	0.67	0.003
0.00	0.64	0.003
0.00	0.53	0.002
0.00	0.51	0.003
0.00	0.40	0.003
0.00	0.29	0.002
0.00	0.29	0.002
0.29	0.00	0.002
0.29	0.00	0.002
0.49	0.00	0.004
0.66	0.00	0.006
0.71	0.00	0.006

$DT_{inc} =$

	1
1	"OK"
2	"OK"
3	"OK"
4	"OK"
5	"OK"
6	"OK"
7	"OK"
8	"OK"
9	"OK"
10	"OK"
11	"OK"
12	"OK"
13	"OK"
14	"OK"
15	"OK"
16	"OK"
17	"OK"

Design Summmary:

Flexural Criteria Only

$$A_{sg} = \begin{pmatrix} 0.71 \\ 0.78 \end{pmatrix} \frac{in^2}{ft}$$

Flexure, crack, and diagonal tension criteria

$$A_{sinside} = 0.71 \frac{in}{f}$$

$$A_{soutside} = 0.78 \frac{i}{}$$

Note - If As is listed as 10^5 in^2/ft, the shear strength cannot be adequately increased by increasing the circumferential reinforcement. Stirrup reinforcement, a thicker section or increased concrete strength are possible adjustements to the design.