KANSAS STATE UNIVERSITY

Kansas Department of Transportation

Rigorous Yield Line Analysis to Evaluate the Capacity of RC Barriers Subjected to Vehicular Collision Force

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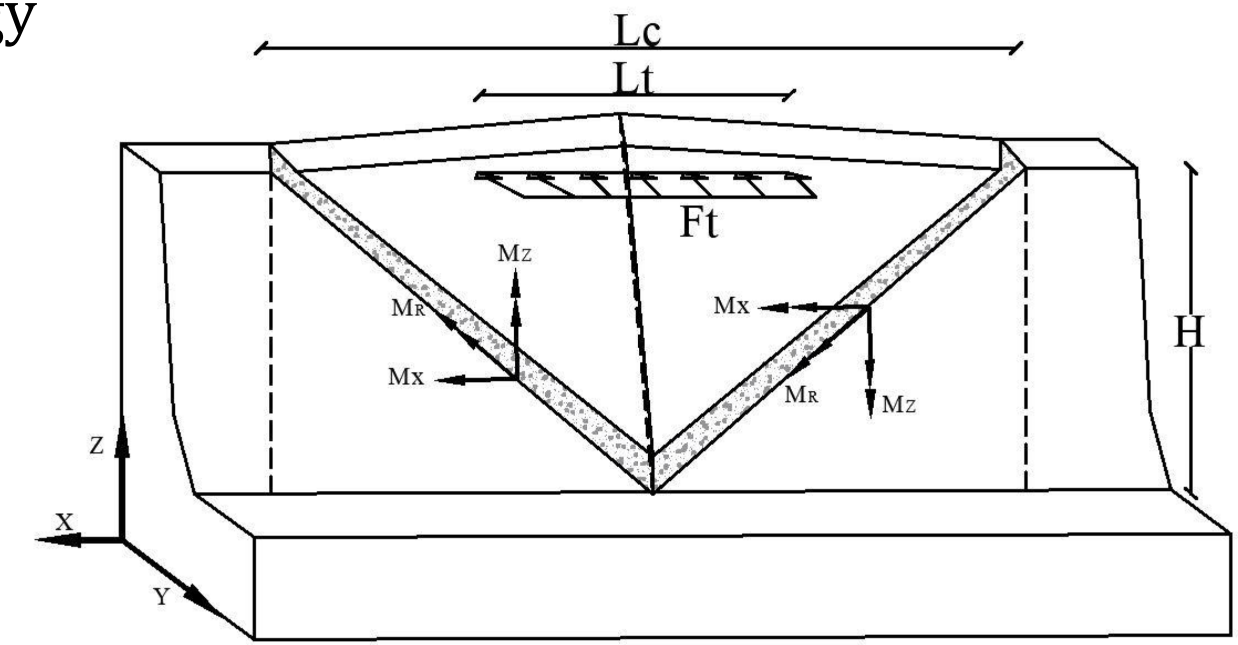
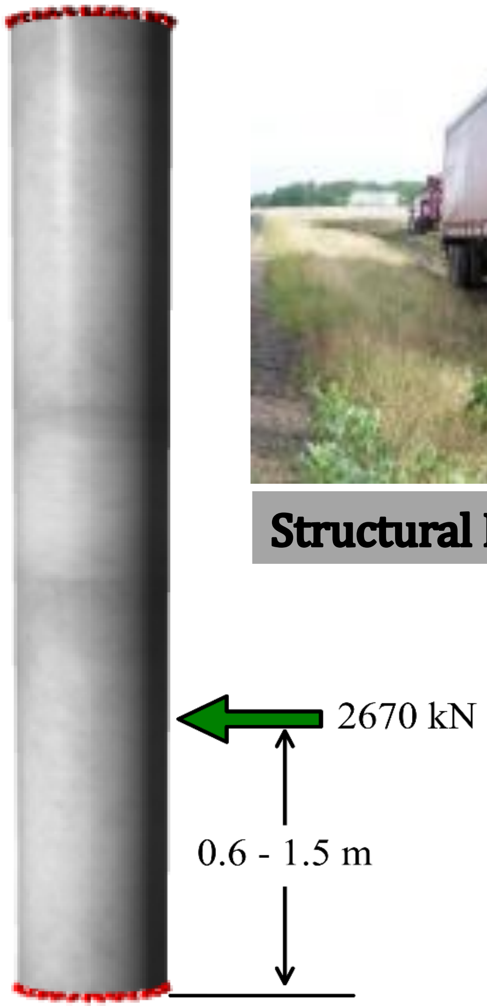


1. Introduction



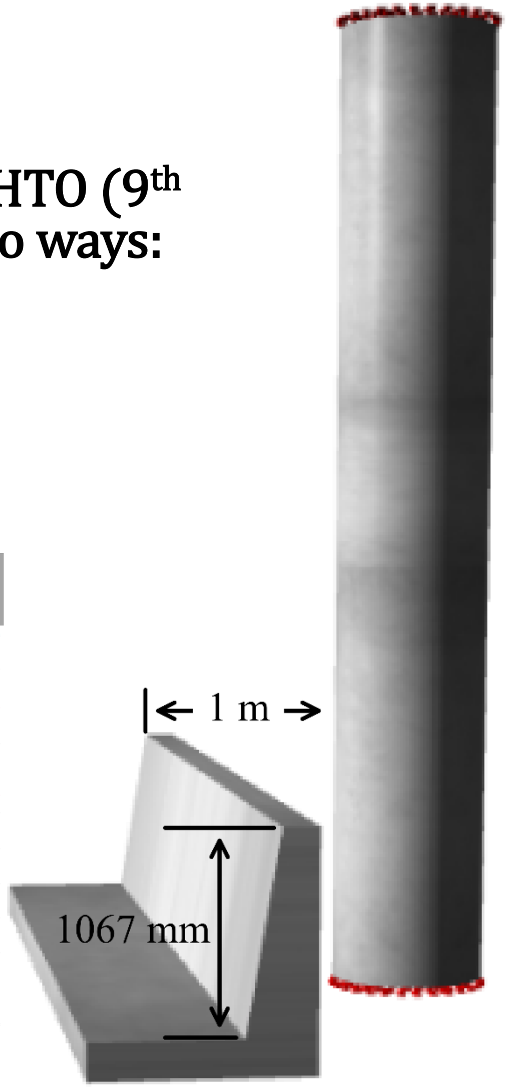
Addressing the VCF as per the current AASHTO (9th edition, 2020) can be achieved in one of two ways:

Structural Resistance

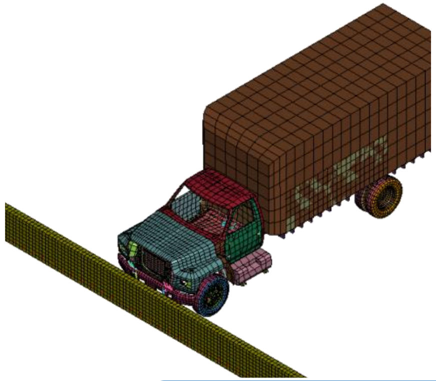
Intervening Structure

Vehicle Type	Small automobiles	Pickup truck	Single-unit truck	Tractor-trailer	Tractor-tanker-trailer
Mass (10^3 kg)	1.1 – 1.5	2.27	10	36	36
Angle of attack	25°	25°	15°	15°	15°
Speed (km/h)					
TL-1	50	50	N/A	N/A	N/A
TL-2	50	70	N/A	N/A	N/A
TL-3	100	100	N/A	N/A	N/A
TL-4	100	100	90	N/A	N/A
TL-5	100	100	N/A	80	N/A
TL-6	100	100	N/A	N/A	80

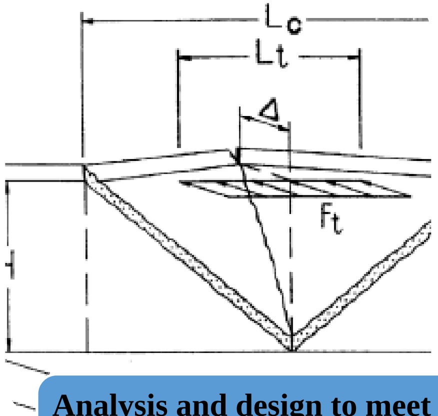
TL: Test Level



- **RC barriers** are commonly used as **intervening structures** protecting bridge piers against vehicular collision force (VCF)
- The **framework** that leads to a successful placement of these barriers includes **three main factors:**



Performance level
- Based on the use
- MASH



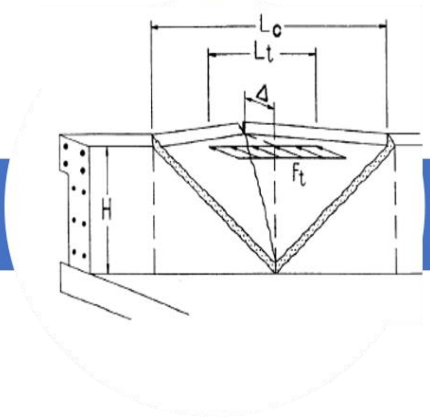
Analysis and design to meet the demands associated with the performance level
- Yield line analysis

Check the acceptance criteria
- Experimental
- Numerical

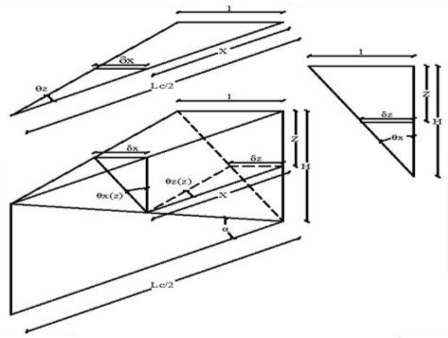
2. Research Contribution and Methodology

Develop **rigorous analysis and innovative methodology** to **accurately** evaluate the **transverse static structural capacity** of RC barriers.

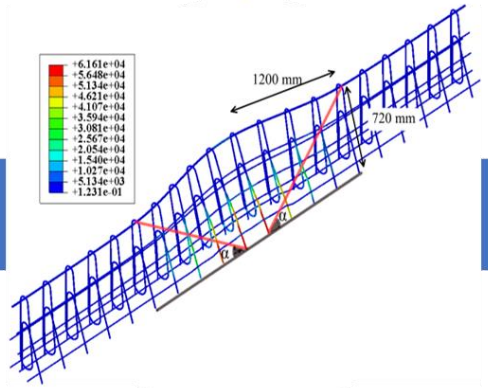
Reviewing existing methodologies to obtain the capacity of RC barriers



Deriving detailed analysis method based on theories and mechanics of reinforced concrete



Conducting an implicit FEA on a case study of RC barrier to validate the proposed methodologies and verify the solution



Developing rigorous analytical model to obtain the capcity of RC barriers subjected to lateral static force

3. Yield Line Analysis (YLA)

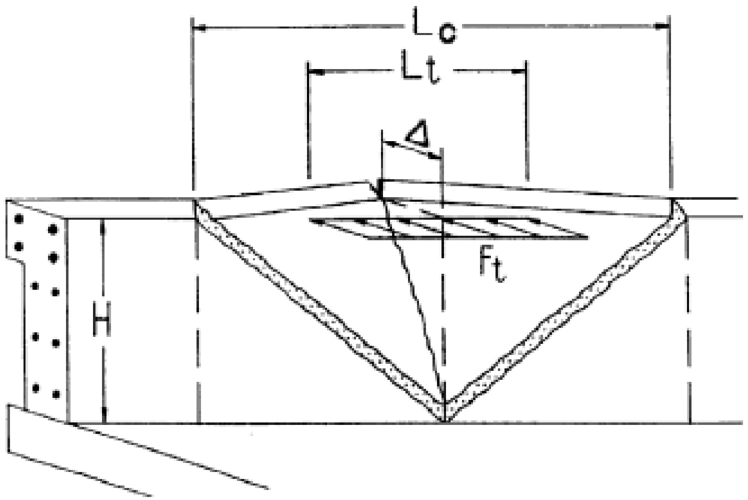
- The most common analysis method used to verify whether a proposed barrier design meets the requirements of a performance level is the YLA

- The YLA is currently adopted by AASHTO's LRFD Bridge Design Specifications (Section 13)

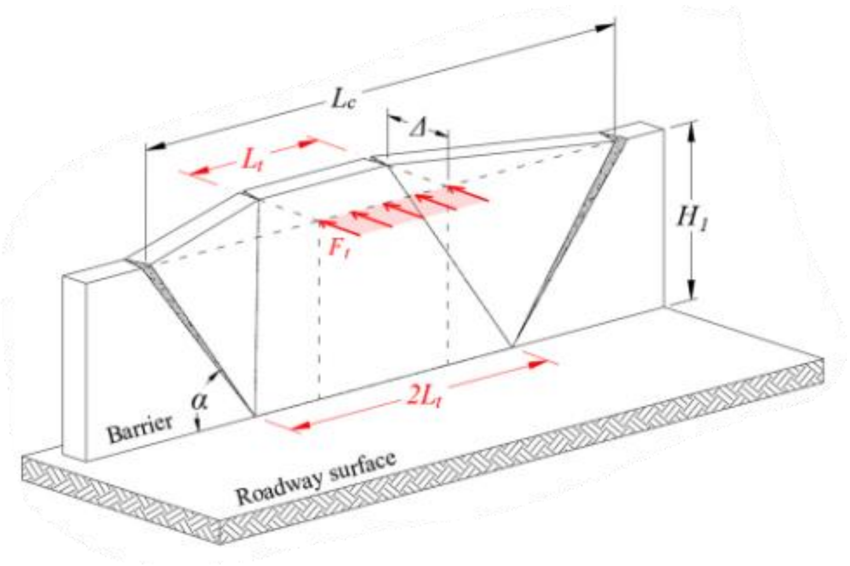
- This method is based on equating the work done by the **external applied forces (Ue) and the internal energy developed through the formation of yield lines along the failure pattern (Ui)**

4. AASHTO's procedure of YLA

- The current AASHTO procedure of YLA include some assumptions that are intended to simplify the analysis
- Many researchers criticized the simplified AASHTO's procedure of YLA in terms of the capacity estimation and the failure pattern



V-shape (AASHTO's procedure)



W-shape (Cao et al. 2020)

AASHTO’s assumptions

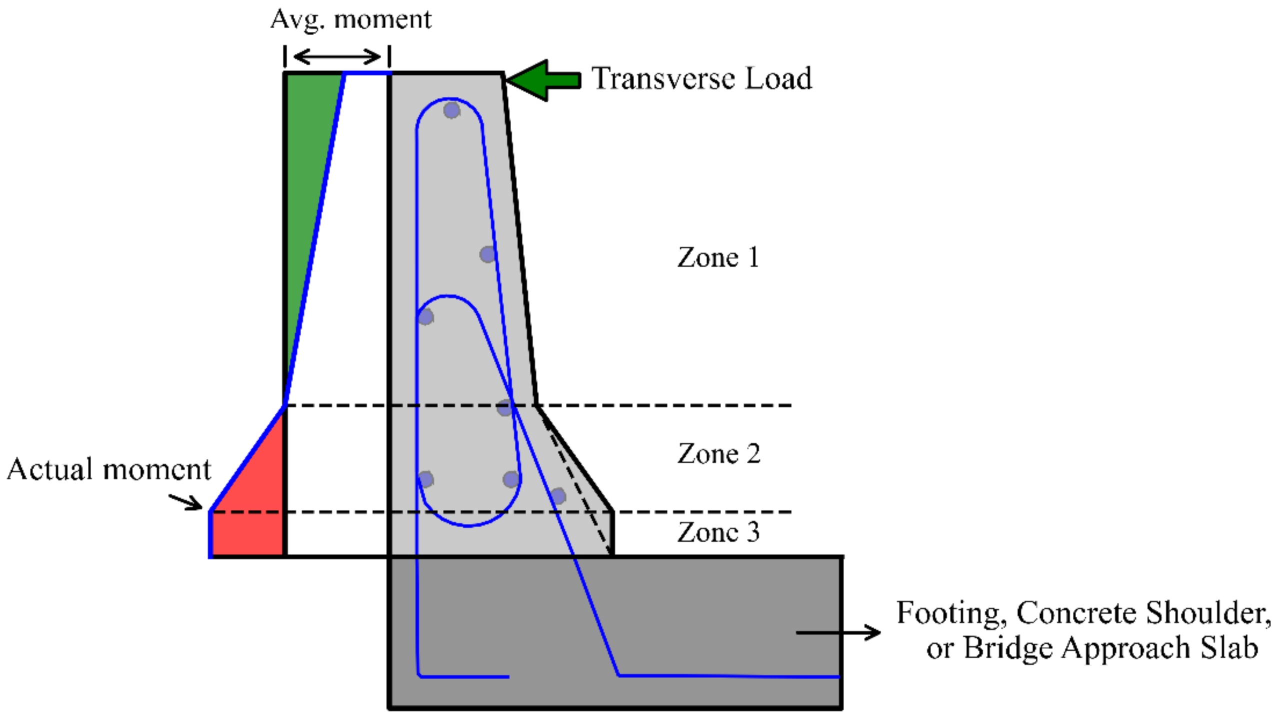
1. The deck has sufficient resistance to the applied transverse forces thus the yield line failure pattern will remain within the parapet.
2. The presence of sufficient longitudinal length of the parapet to produce the assumed V-shape yield line failure pattern.
3. The flexural capacity of the RC barrier is only from the concrete contribution; the contribution of the stirrups and/or ties is to prevent shear and diagonal tension.
4. The wall resistance as the average of its value along the height when the width of the barrier varies along the height.
5. The negative and positive wall resisting moments are equal

Assumptions

3. The flexural capacity of the RC barrier is only from the concrete contribution; the contribution of the stirrups and/or ties is to prevent shear and diagonal tension.

4. The wall resistance as the average of its value along the height when the width of the barrier varies along the height.

5. The negative and positive wall resisting moments are equal



Where:

Rw = total transverse resistance of the railing (kips)

Lc = critical length of yield line failure pattern (ft)

Lt = longitudinal length of distribution of impact force *Ft* (ft), specified in (Table A13.2-1) [3]

Mb = additional flexural resistance of beam in addition to *Mz*, if any, (kip-ft)

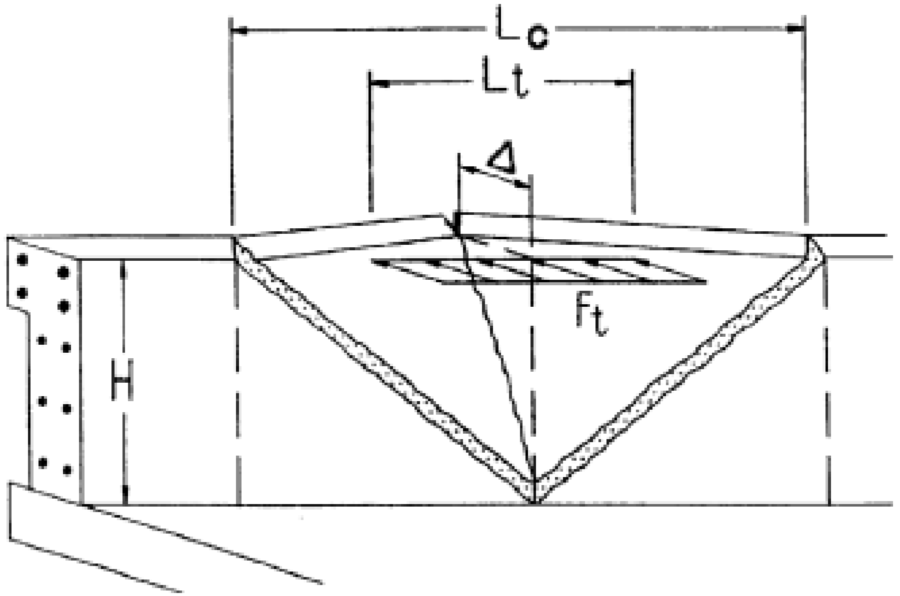
Mx = flexural resistance of cantilevered walls about an axis parallel to the longitudinal axis of the bridge (kip-ft/ft), (*Mc* in AASHTO's specifications).

Mz = flexural resistance of the wall about its vertical axis (kip-ft), (*Mw* in AASHTO's specifications).

H = height of wall (ft)

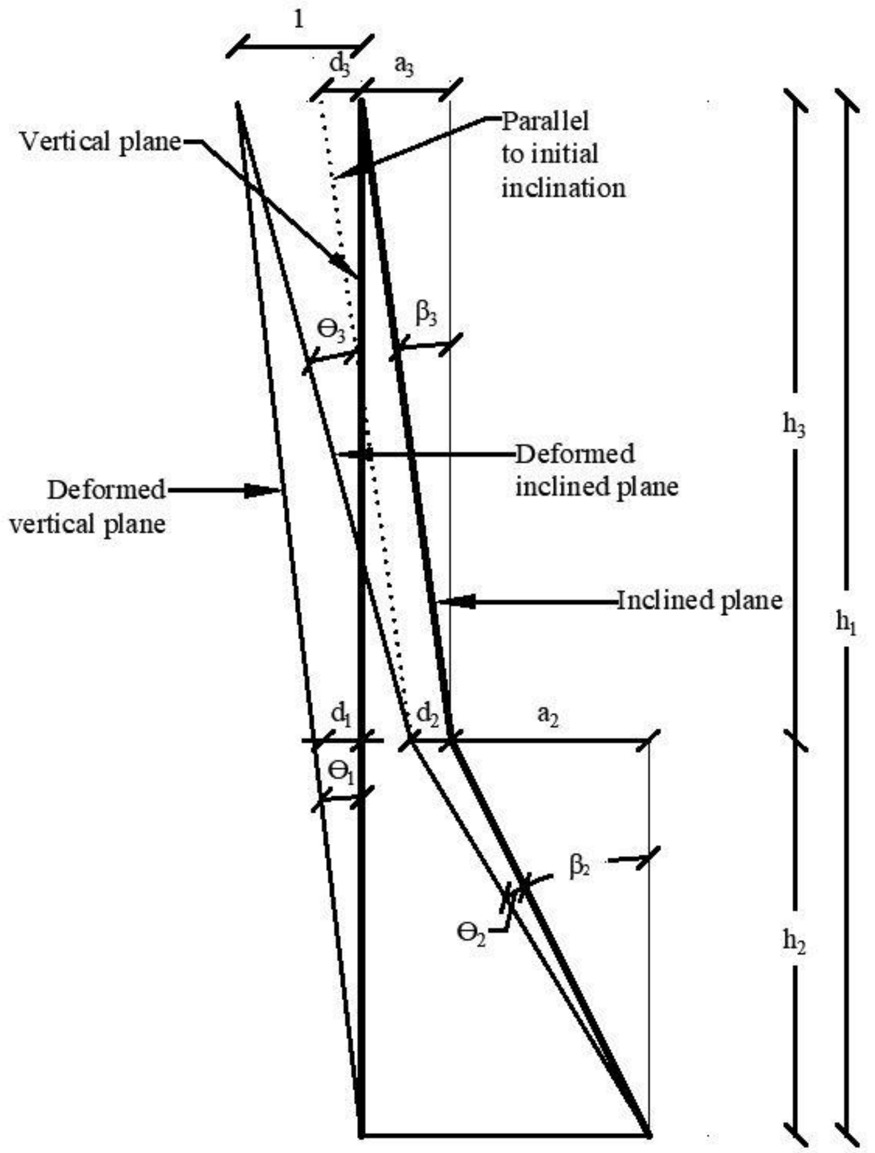
$$R_w = \left(\frac{2}{2L_c - L_t}\right) \times \left(8M_b + 8M_z + \frac{M_x {L_c}^2}{H}\right) \quad \textbf{Eq. 1}$$

$$L_c = \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{8H(M_b + M_z)}{M_x}} \quad \textbf{Eq. 2}$$



5. Rigorous YLA

This procedure is targeted to cover the **generalized case of RC barriers**



Assumptions

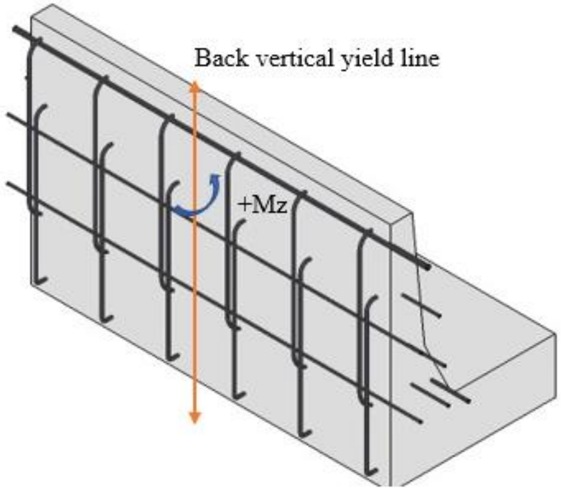
1. Concrete is inextensible through the thickness.
2. For barriers that have sloped sides, the value of the deformation angle measured with respect to an assumed vertical plane and the deformation angle of the actual sloped side is almost the same. Therefore, the angle used in the derivations are referenced with respect to the vertical plane.

$$\theta_1 = \tan^{-1}\frac{1}{h_1} \quad \text{Eq. 3}$$

$$\theta_2 = \tan^{-1}\frac{1}{h_1 + h_1\tan^2\beta_2 + \tan\beta_2} \quad \text{Eq. 4}$$

$$\theta_3 = \tan^{-1}\frac{1}{h_1 + h_1\tan^2\beta_3 + \tan\beta_3} \quad \text{Eq. 5}$$

Sectional capacity

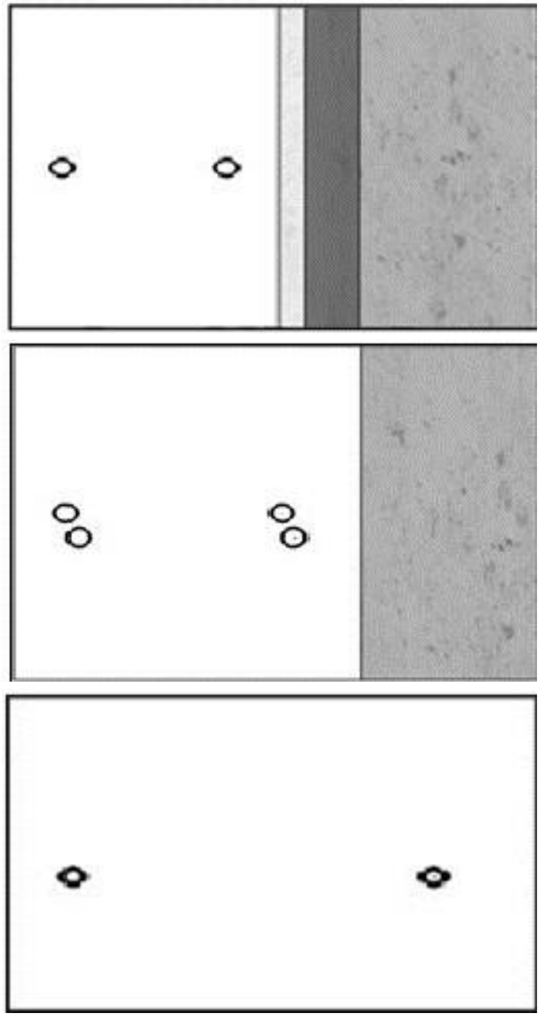


Vertical Axis

1. For each side of the barrier, sum the longitudinal reinforcement at that side and divide by the full heigh of the barrier to obtain the reinforcement ratio per unit height
2. For each side of the barrier, if the cover to the longitudinal reinforcement is not uniform, find a weighted average cover
3. Write the depth of reinforcment as a function of the height for the corresponding section along the height
4. For each side, obtain the sectional capacity as a beam section neglecting the compression steel
5. Write the sectional capacities as a function of the height

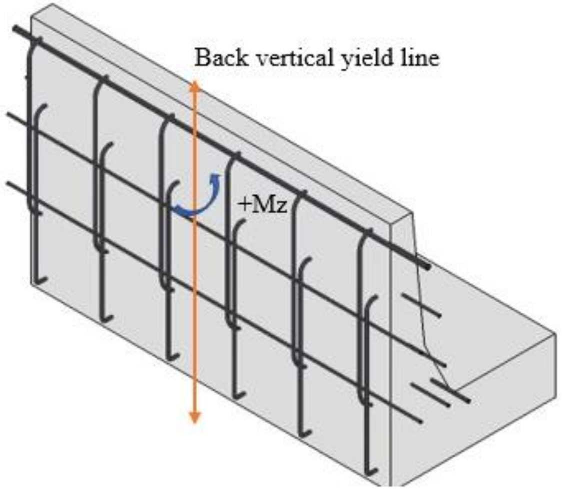
Longitudinal Axis

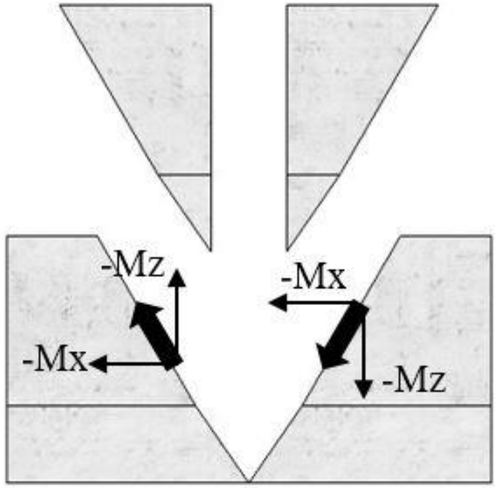
1. Cut the barrier's profile in plane at locations of width discontinuities
2. Considering a segment width equals to the stirrups' spacing, divide the area of stirrups' legs in each side by that width to obtain the reinforcement ratio per unit width
3. For each side, obtain the plan sectional capacity as a beam section neglecting the compression steel
4. Find the slopes between two consequtive sections with respect to the barrier's height
5. Considering linear variation of the moment function, connect the sectional capacities by the slopes to find the capacity as a function of the barrier's height

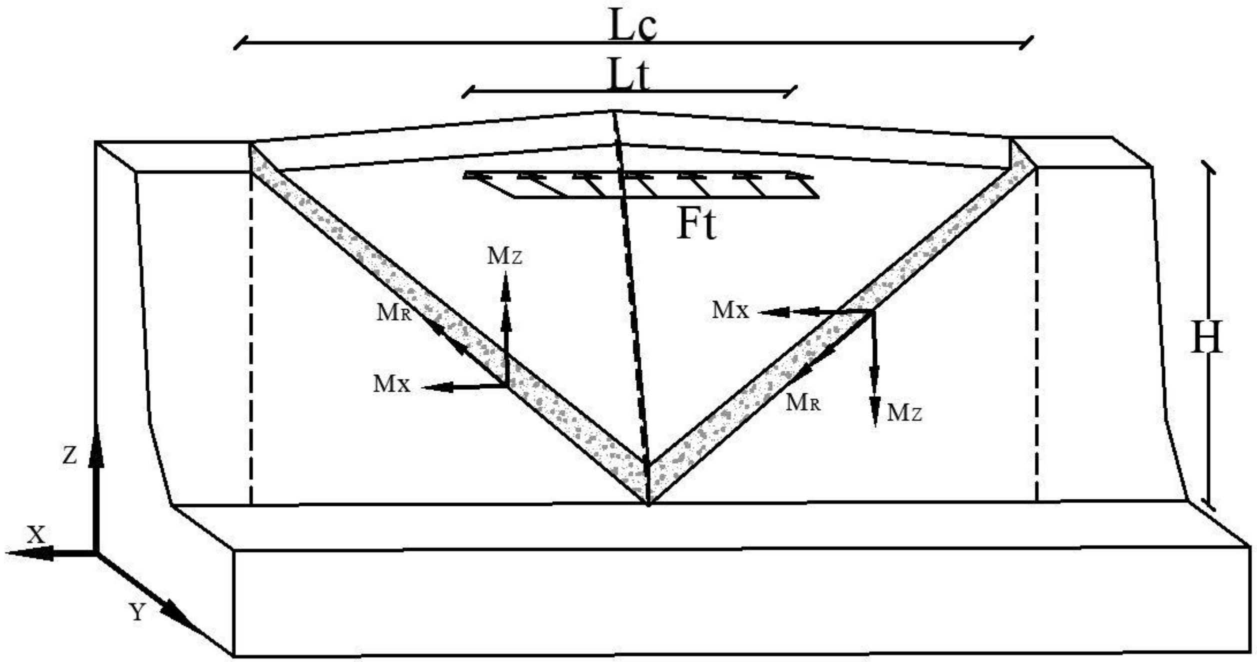


Formulation of yield lines

The internal work (Ui) along the yield lines is the **sum of the products of the yield moments and the rotations** through which they act integrated along the barriers height (z-axis).







$$\theta z(z) = \frac{\delta_z}{x}$$ Eq. 6

$$\delta_z = \frac{H-z}{H}$$ Eq. 7

$$x = \frac{(H-z)}{\tan\alpha}$$ Eq. 8

$$\theta z(z) = \frac{\delta_z}{x} = \frac{(H-z)\tan\alpha}{H(H-z)} = \frac{\tan\alpha}{H}$$ Eq. 9

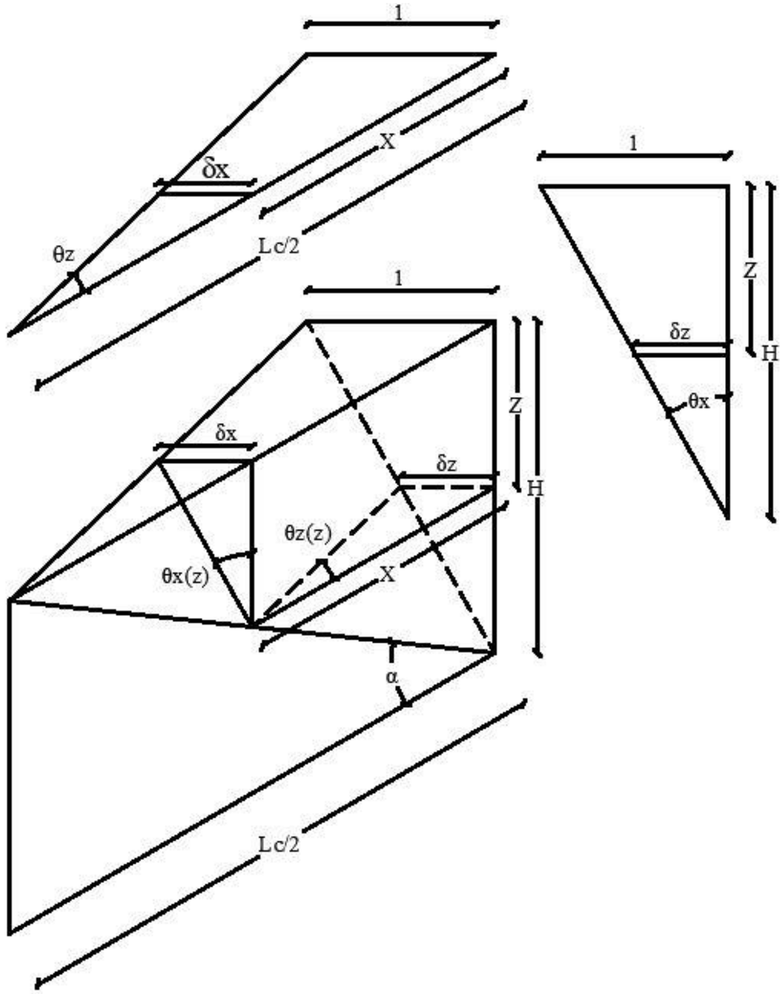
$$\theta x(z) = \frac{\delta_x}{z}$$ Eq. 10

$$\delta_x = 1 - \frac{2x}{L_c}$$ Eq. 11

$$x = \frac{(H-z)}{\tan\alpha}$$ Eq. 12

$$1 = \frac{2H}{L_c \tan\alpha}$$ Eq. 13

$$\theta x(z) = \frac{1}{H}$$ Eq. 14

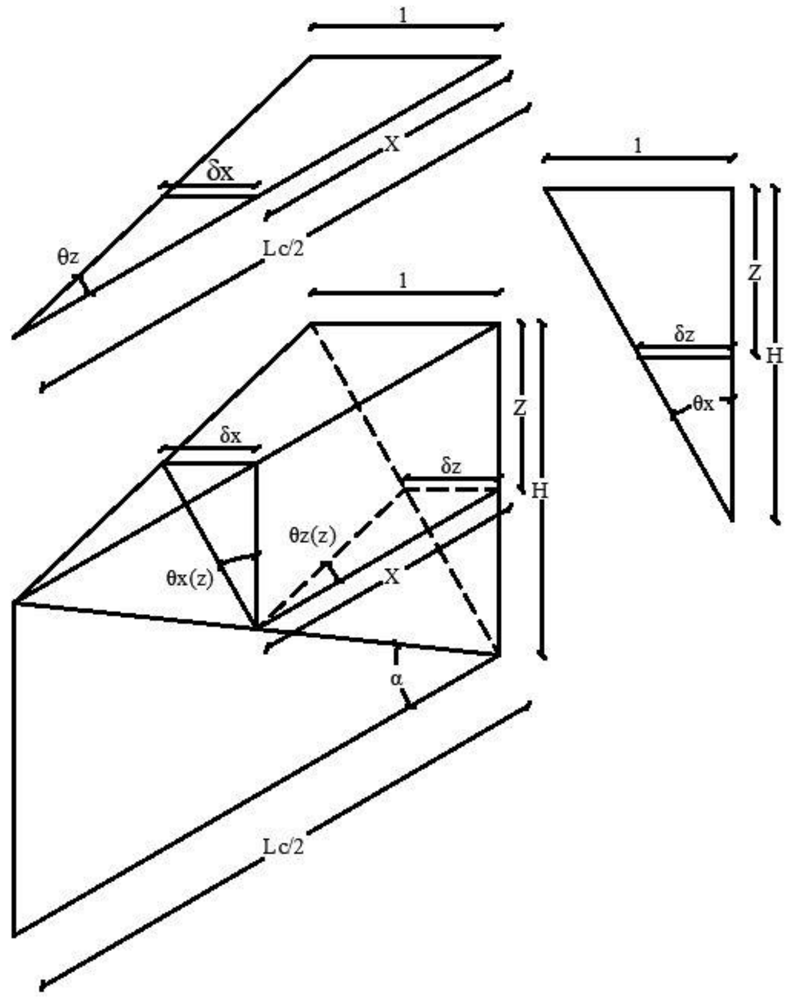


$$d_s = \sqrt{dx^2 + dz^2} = dz\sqrt{\left(\frac{dx}{dz}\right)^2 + 1} = dz\sqrt{1 + cot^2\alpha} = dz.\csc\alpha$$ **Eq. 15**

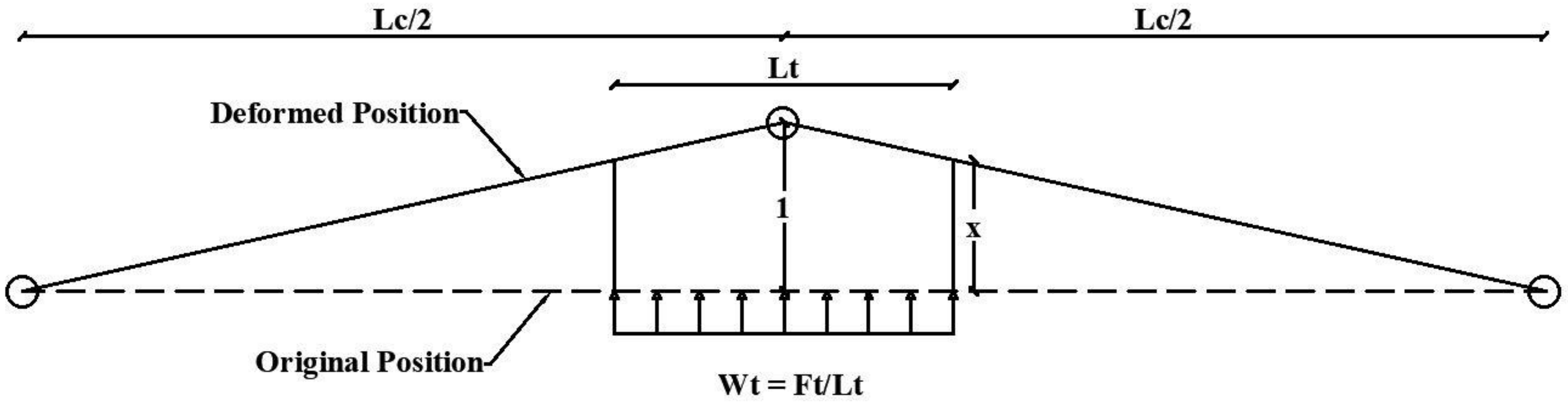
$$U_i = \int M_{z\,back}(z) \times 2\theta_z \times dz + 2\int M_{s\,front}(z) \times \theta_s \times ds$$ **Eq. 16**

$$U_i = 2\int M_{z\,back}(z) \times \theta_z \times dz + 2\int M_{x\,front}(z) \times \theta_x \times ds + 2\int M_{z\,front}(z) \times \theta_z \times ds$$ **Eq. 17**

$$U_i = 2\int \frac{M_{z\,back}(z) \times tan\,\alpha \times dz}{H} + 2\int \frac{M_{x\,front}(z) \times csc\,\alpha\,dz}{H} + 2\int \frac{M_{z\,front}(z) \times tan\,\alpha\,csc\,\alpha \times dz}{H}$$ **Eq. 18**



The length of contact between the vehicle and the concrete barrier is L_t and the force that is applied by the vehicle is equal to F_t, then **the external work (Ue)** is given as:



$$U_e = \frac{1}{2} \times (1 + x) \times \frac{L_t}{2} \times W_t \times 2 = \frac{L_t\, W_t\,(1 + x)}{2}$$ **Eq. 19**

$$x = 1 - \frac{L_t}{L_c}$$ **Eq. 20**

$$U_e = L_t\, W_t \left(1 - \frac{L_t \tan\alpha}{4H}\right)$$ **Eq. 21**

Equating the internal work from **Eq. 18** with the external work from **Eq. 21** yields the solution for **Wt** as in **Eq. 22**.

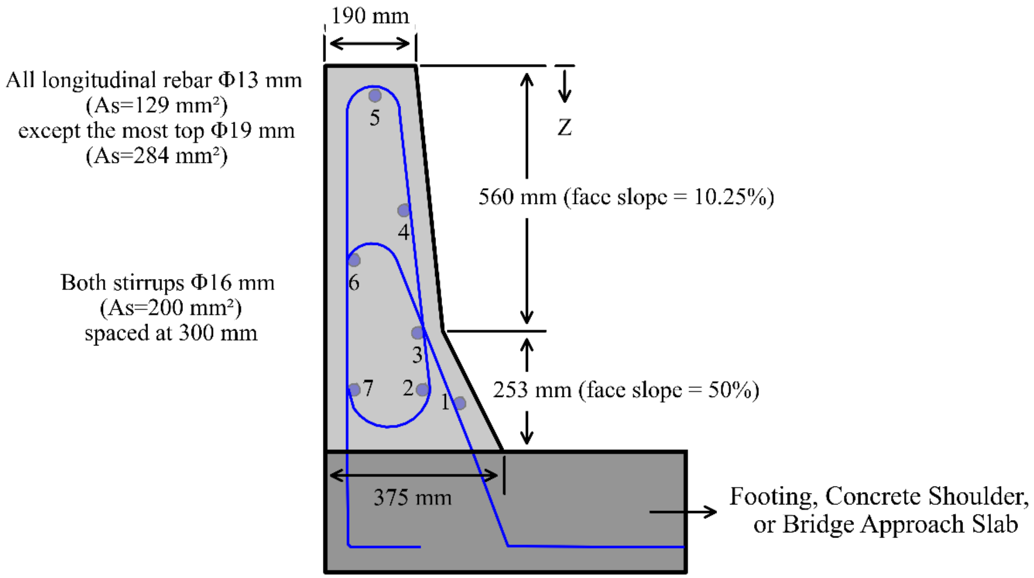
A closed form solution for **Eq. 22** can be obtained by solving **dWt/dα=0**

$$\boldsymbol{W_t = \frac{2\left(\int M_{z\,back}(z) \times tan\,\alpha \times dz + \int M_{x\,front}(z) \times csc\,\alpha\,dz + \int M_{z\,front}(z) \times tan\,\alpha\,csc\,\alpha \times dz\right)}{H \times L_t\left(1 - \frac{L_t\,tan\,\alpha}{4H}\right)}} \quad \textbf{Eq. 22}$$

6. Case Study

- The design of the barrier was provided by Kansas Department of Transportation (KDOT)
- The concrete compressive strength (f'c) is 27.6 MPa (4000 psi) and the steel yield stress (fy) is 413 MPa (60 ksi)

	Front side					Back side		
Bar Id	1	2	3	4	5	5	6	7
Area (mm^2)	129	129	129	129	284	284	129	129
Cover (mm)	45	122	76	76	107	92	60	60



AASHTO's YLA

$$f_r = \frac{M_r \times c}{I_g}$$ **Eq. 23**

$$f_r = 7.5\,\lambda\sqrt{fc} = 0.474\ ksi$$ **Eq. 24**

Property	Mz		Mx (for 1ft segment width)		
	Section 1 (Z_1= 0-22 in)	Section 2 (Z_1= 22-32 in)	Section 1 (Z_1= 0 in)	Section 2 (Z_2= 22 in)	Section 3 (Z_3= 32 in)
b (in)	22	10	12	12	12
h (in)	(7.5+9.75)/2=8.62	(14.75+9.75)/2=12.25	7.5	9.75	14.75
c (in)	4.3125	6.125	3.75	4.875	7.375
Ig (in^4)	1176.3	1531.8	421.875	926.86	3209
Moment	118.64 kip.in	129.38 kip.in	53.4 kip.in	90.2 kip.in	206.4 kip.in
	Sum = 248 kip.in = 20.67 kip.ft		Weighted avg. = (0.5(53.4+90.2)22+0.5 (90.2+206.4)10)/32 = 95.7 kip.in = 8 kip.ft		

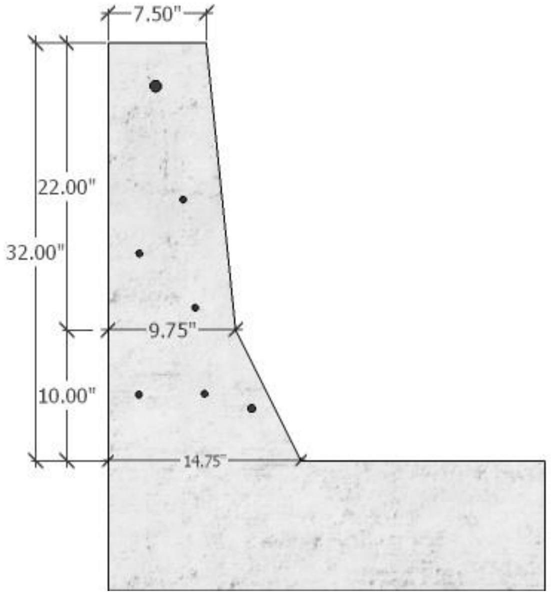


Table A13.2-1—Design Forces for Traffic Railings

Design Forces and Designations	Railing Test Levels					
	TL-1	TL-2	TL-3	TL-4	TL-5	TL-6
F_t Transverse (kips)	13.5	27.0	54.0	54.0	124.0	175.0
F_L Longitudinal (kips)	4.5	9.0	18.0	18.0	41.0	58.0
F_v Vertical (kips) Down	4.5	4.5	4.5	18.0	80.0	80.0
L_t and L_L (ft)	4.0	4.0	4.0	3.5	8.0	8.0
L_v (ft)	18.0	18.0	18.0	18.0	40.0	40.0
H_e (min) (in.)	18.0	20.0	24.0	32.0	42.0	56.0
Minimum H Height of Rail (in.)	27.0	27.0	27.0	32.0	42.0	90.0

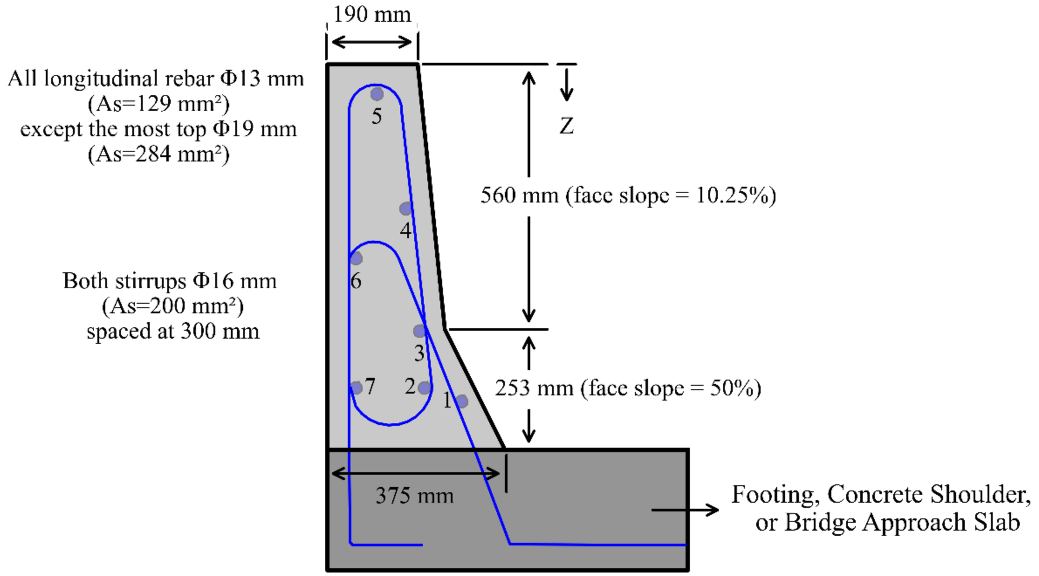
$$R_w = \left(\frac{2}{2L_c - L_t}\right) \times \left(8M_b + 8M_z + \frac{M_x {L_c}^2}{H}\right) \quad \textbf{Eq. 1}$$

$$L_c = \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{8H(M_b + M_z)}{M_x}} \quad \textbf{Eq. 2}$$

$L_c = 9.39$ ft and $R_w = 56.2$ (250 kN).

Rigorous YLA

	Front side					Back side		
Bar Id	1	2	3	4	5	5	6	7
Area (mm^2)	129	129	129	129	284	284	129	129
Cover (mm)	45	122	76	76	107	92	60	60



	Back side	
Step	Section 1 (Z_1= 0 - 560)	Section 2 (Z_2= 560 - 813)
1	$\frac{As}{h} = \frac{284+129+129}{813} = 0.67\ mm^2/mm$	
2	$Avg.Cover = \frac{92 \times 284 + 60 \times 129 + 60 \times 129}{542} = 76.7\ mm$	
3	$d_0 = 190 - 76.7 = 113.23\ mm$ $d_{z1} = 113.23 + Slope1 \times Z_1$ $= 113.23 + 0.1025\ Z_1$	$d_0 = 190 + Slope1 \times Z_1 - 76.7$ $d_{z2} = 170.7 + Slope2 \times Z_2$ $= 170.7 + 0.5\ Z_2$
4	$M_{Z1} = A_s\ f_y \left(d - \frac{a}{2}\right)$ $a = \frac{A_s\ f_y}{0.85\ fc'b} = \frac{542 \times\ 413}{0.85\ \times 27.6 \times 813}$ $= 11.74\ mm$ M_{Z1} $= 0.67 \times 413$ $\times \left(113.23 + 0.1025\ Z_1 - \frac{11.74}{2}\right)$	$M_{Z2} = A_s\ f_y \left(d - \frac{a}{2}\right)$ $a = \frac{A_s\ f_y}{0.85\ fc'b} = \frac{542 \times\ 413}{0.85\ \times 27.6 \times 813}$ $= 11.74\ mm$ $M_{Z2} = 0.67 \times 413 \times \left(170.7 + 0.5\ Z_2 - \frac{11.74}{2}\right)$
5	$M_{Z1} = 29.7 + 0.0283 \times Z_1\ kN.mm/mm$	$M_{Z2} = 45.6 + 0.138 \times Z_2\ kN.mm/mm$ $M_{Z2} = 80.6 - 0.138\ (813 - Z_2)\ kN.mm/mm$

Vertical Axis

For each side of the barrier, sum the longitudinal reinforcement at that side and divide by the full heigh of the barrier to obtain the reinforcement ratio per unit height 1

↓

For each side of the barrier, if the cover to the longitudinal reinforcement is not uniform, find a weighted average cover 2

↓

Write the depth of reinforcment as a function of the height for the corresponding section along the height 3

↓

For each side, obtain the sectional capacity as a beam section neglecting the compression steel 4

↓

Write the sectional capacities as a function of the height 5

	Front side	
Step	Section 1 (Z_1= 0 - 560)	Section 2 (Z_2= 560 - 813)
1	$\frac{As}{h} = \frac{284+129+129+129+129}{813} = 0.984\ mm^2/mm$	
2	$Avg.Cover = \frac{107\times 284+76\times 129+76\times 129+122\times 129+45\times 129}{800} = 89.4\ mm$	
3	$d_0 = 190 - 89.4 = 100.57\ mm$ $d_{z1} = 100.57 + Slope1 \times Z_1$ $= 100.57 + 0.1025\ Z_1$	$d_0 = 190 + Slope1 \times Z_1 - 89.4$ $d_{z2} = 158 + Slope2 \times Z_2$ $= 158 + 0.5\ Z_2$
4	$M_{Z1} = A_s\ f_y \left(d - \frac{a}{2}\right)$ $a = \frac{A_s\ f_y}{0.85\ fc'b} = \frac{800\times\ 413}{0.85\ \times 27.6\times 813}$ $= 17.323\ mm$ M_{Z1} $= 0.984 \times 413$ $\times \left(100.57 + 0.1025\ Z_1 - \frac{17.323}{2}\right)$	$M_{Z2} = A_s\ f_y \left(d - \frac{a}{2}\right)$ $a = \frac{A_s\ f_y}{0.85\ fc'b} = \frac{800\times\ 413}{0.85\ \times 27.6\times 813} = 17.323\ mm$ $M_{Z2} = 0.984 \times 413 \times \left(158 + 0.5\ Z_2 - \frac{17.323}{2}\right)$
5	$M_{Z1} = 37.35 + 0.0417 \times Z_1\ kN.mm/mm$	$M_{Z2} = 60.69 + 0.203 \times Z_2\ kN.mm/mm$ $M_{Z2} = 112.26 - 0.203\ (813 - Z_2)\ kN.mm/mm$

Vertical Axis

For each side of the barrier, sum the longitudinal reinforcement at that side and divide by the full heigh of the barrier to obtain the reinforcement ratio per unit height 1

For each side of the barrier, if the cover to the longitudinal reinforcement is not uniform, find a weighted average cover 2

Write the depth of reinforcment as a function of the height for the corresponding section along the height 3

For each side, obtain the sectional capacity as a beam section neglecting the compression steel 4

Write the sectional capacities as a function of the height 5

Step	Back side		
1	Section 1 (Z_1= 0 mm)	Section 2 (Z_2= 560 mm)	Section 3 (Z_3= 813 mm)
2	$\frac{As}{b} = \frac{0}{300} = 0\ mm^2/mm$	$\frac{As}{b} = \frac{400}{300} = 1.33\ mm^2/mm$	$\frac{As}{b} = \frac{200}{300} = 0.67\ mm^2/mm$
3	$M_{Z1} = \frac{f_r\, I}{h/2}\frac{1}{300}$ $fr = 0.62\sqrt{27.6} = 3.257\ MPa$ $I = \frac{bh^3}{12} = \frac{300 \times 190^3}{12}$ $= 171.475 \times 10^6 mm^4$ $M_{Z1} = \frac{3.257\ \times 171.48 \times 10^6}{190 \times 300/2}$ $= 19.57\ kN.mm/mm$	$d\ = 190 + Slope1 \times Z_2 - cover - 0.5 \times \emptyset_{stirrup}$ $d\ = 190 + 0.1025 \times 560 - 38.3 - 8$ $= 201.1\ mm$ $M_{Z2} = A_s\, f_y\, \left(d - \frac{a}{2}\right)$ $a = \frac{A_s\, f_y}{0.85\, fc'b} = \frac{400 \times\ 413}{0.85\ \times 27.6 \times 300} = 23.47\ mm$ $M_{Z2} = 1.33 \times 413 \times \left(201.1 - \frac{23.47}{2}\right)$ $= 104.27\ kN.mm/mm$	$d\ = 375 - cover - 0.5 \times \emptyset_{stirrup}$ $d\ = 375 - 38.3 - 8 = 328.7\ mm$ $M_{Z3} = A_s\, f_y\, \left(d - \frac{a}{2}\right)$ $a = \frac{A_s\, f_y}{0.85\, fc'b} = \frac{200 \times\ 413}{0.85\ \times 27.6 \times 300}$ $= 11.74\ mm$ $M_{Z3} = 0.67 \times 413 \times \left(328.7 - \frac{11.74}{2}\right)$ $= 88.89\ kN.mm/mm$
4	$slope_{12}\ = 0.1514$		
		$slope_{23}\ = -0.0605$	
5	$M_{x\_back}(z) = \begin{cases} M_{Z1} + slope_{12}\, Z\ kN.\frac{mm}{mm}, & 0 \le z \le 560 \\ M_{Z3} - slope_{23}(height - Z)\ kN.\frac{mm}{mm}, & 560 \le z \le 813 \end{cases} \rightarrow M_{x\_back}(z) = \begin{cases} 19.6 + 0.1514\, Z\ kN.\frac{mm}{mm}, & 0 \le z \le 560 \\ 88.89 + 0.06(813 - \ Z)\ kN.\frac{mm}{mm}, & 560 \le z \le 813 \end{cases}$		

Longitudinal Axis

Cut the barrier's profile in plane at locations of width discontinuities 1

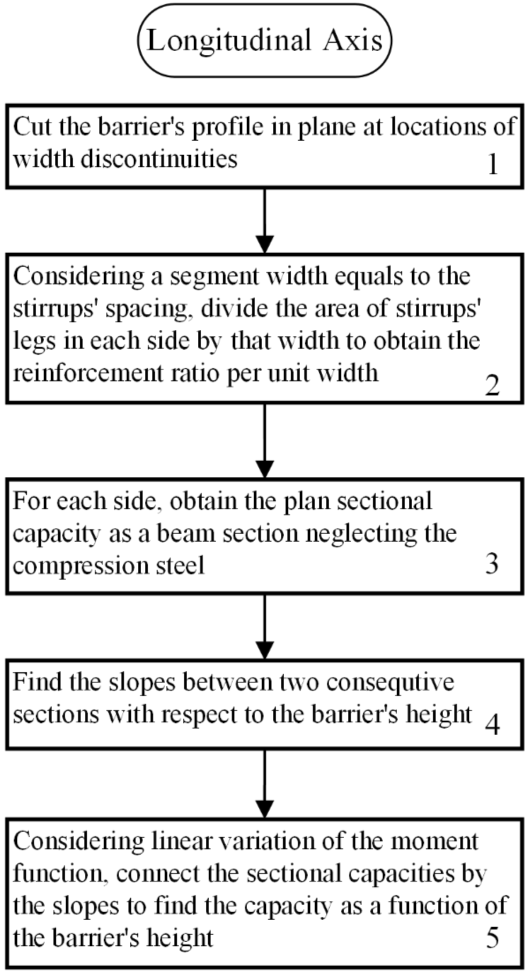
Considering a segment width equals to the stirrups' spacing, divide the area of stirrups' legs in each side by that width to obtain the reinforcement ratio per unit width 2

For each side, obtain the plan sectional capacity as a beam section neglecting the compression steel 3

Find the slopes between two consequtive sections with respect to the barrier's height 4

Considering linear variation of the moment function, connect the sectional capacities by the slopes to find the capacity as a function of the barrier's height 5

Step	Front side		
1	Section 1 (Z_1= 0 mm)	Section 2 (Z_2= 560 mm)	Section 3 (Z_3= 813 mm)
2	$\frac{As}{b} = \frac{0}{300} = 0\ mm^2/mm$	$\frac{As}{b} = \frac{400}{300} = 1.33\ mm^2/mm$	$\frac{As}{b} = \frac{200}{300} = 0.67\ mm^2/mm$
3	$M_{Z1} = \frac{f_r I}{h/_2}\frac{1}{300}$ $fr = 0.62\sqrt{27.6} = 3.257\ MPa$ $I = \frac{bh^3}{12} = \frac{300 \times 190^3}{12} = 171.475 \times 10^6 mm^4$ $M_{Z1} = \frac{3.257\ \times 171.48 \times 10^6}{190 \times 300/_2}$ $= 19.57\ kN.mm/mm$	$d\ = 190 + Slope1 \times Z_2 - cover - 0.5 \times \emptyset_{stirrup}$ $d\ = 190 + 0.1025 \times 560 - 54 - 8 = 185.4\ mm$ $M_{Z2} = A_s\ f_y\ \left(d - \frac{a}{2}\right)$ $a = \frac{A_s\ f_y}{0.85\ fc'b} = \frac{400 \times\ 413}{0.85\ \times 27.6 \times 300} = 23.47\ mm$ $M_{Z2} = 1.33 \times 413 \times \left(201.1 - \frac{23.47}{2}\right)$ $= 96.2\ kN.mm/mm$	$d\ = 375 - cover - 0.5 \times \emptyset_{stirrup}$ $d\ = 375 - 75 - 8 = 292\ mm$ $M_{Z3} = A_s\ f_y\ \left(d - \frac{a}{2}\right)$ $a = \frac{A_s\ f_y}{0.85\ fc'b} = \frac{200 \times\ 413}{0.85\ \times 27.6 \times 300} = 11.74\ mm$ $M_{Z3} = 0.67 \times 413 \times \left(292 - \frac{11.74}{2}\right)$ $= 78.82\ kN.mm/mm$
4	$slope_{12} = 0.137$		
		$slope_{23} = -0.0684$	
5	$M_{x\_front}(z) = \begin{cases} M_{Z1} + slope_{12}\ Z\ kN.\frac{mm}{mm}, & 0 \le z \le 560 \\ M_{Z3} - slope_{23}(height - Z)\ kN.\frac{mm}{mm}, & 560 \le z \le 813 \end{cases} \rightarrow M_{x\_front}(z) = \begin{cases} 19.6 + 0137\ Z\ kN.\frac{mm}{mm}, & 0 \le z \le 560 \\ 78.82 + 0.0684\ (813 - Z)\ kN.\frac{mm}{mm}, & 560 \le z \le 813 \end{cases}$		



$$M_{z\_back}(z) = \begin{cases} 29.7 + 0.0284\, z\; kN.\dfrac{mm}{mm}, & 0 \le z \le 560 \\ 80.6 - 0.1378\,(813 - z)\; kN.\dfrac{mm}{mm}, & 560 \le z \le 813 \end{cases}$$ **Eq. 25**

$$M_{z\_front}(z) = \begin{cases} 37.35 + 0.0418\, z\; kN.\dfrac{mm}{mm}, & 0 \le z \le 560 \\ 112.26 - 0.203\,(813 - z)\; kN.\dfrac{mm}{mm}, & 560 \le z \le 813 \end{cases}$$ **Eq. 26**

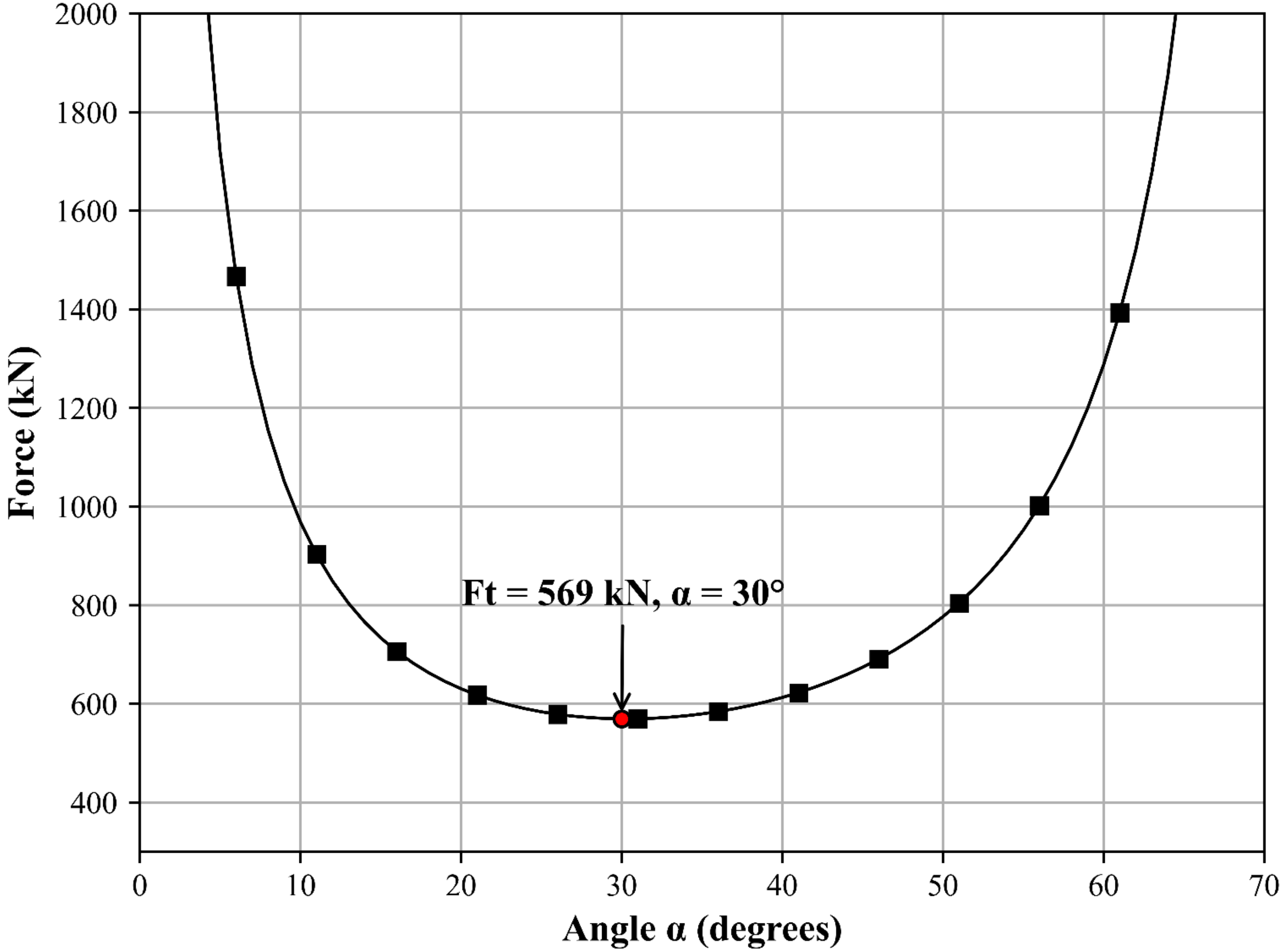
$$M_{x\_back}(z) = \begin{cases} 19.6 + 0.1514\, z\; kN.\dfrac{mm}{mm}, & 0 \le z \le 560 \\ 88.89 + 0.06(813 - z)\; kN.\dfrac{mm}{mm}, & 560 \le z \le 813 \end{cases}$$ **Eq. 27**

$$M_{x\_front}(z) = \begin{cases} 19.6 + 0137\, z\; kN.\dfrac{mm}{mm}, & 0 \le z \le 560 \\ 78.82 + 0.0684\,(813 - z)\; kN.\dfrac{mm}{mm}, & 560 \le z \le 813 \end{cases}$$ **Eq. 28**

$$W_t = \frac{2\left(\int M_{z\,back}(z) \times tan\,\alpha \times dz + \int M_{x\,front}(z) \times csc\,\alpha\,dz + \int M_{z\,front}(z) \times tan\,\alpha\,csc\,\alpha \times dz\right)}{H \times L_t\left(1 - \frac{L_t\,tan\,\alpha}{4H}\right)}$$ **Eq. 29**

For the distributed load along L_t = 1067 mm (3.5 ft)

$$W_t = \frac{91.19\tan\alpha + 134.3\csc\alpha + 121.47\sec\alpha}{1067\left(1 - \frac{1067\tan\alpha}{4 \times 813}\right)}$$ **Eq. 30**


2000
1800
1600
1400
1200
1000
800
600
400
Force (kN)
Ft = 569 kN, α = 30°
0
10
20
30
40
50
60
70
Angle α (degrees)

Finite Element Analysis (FEA) by Abaqus

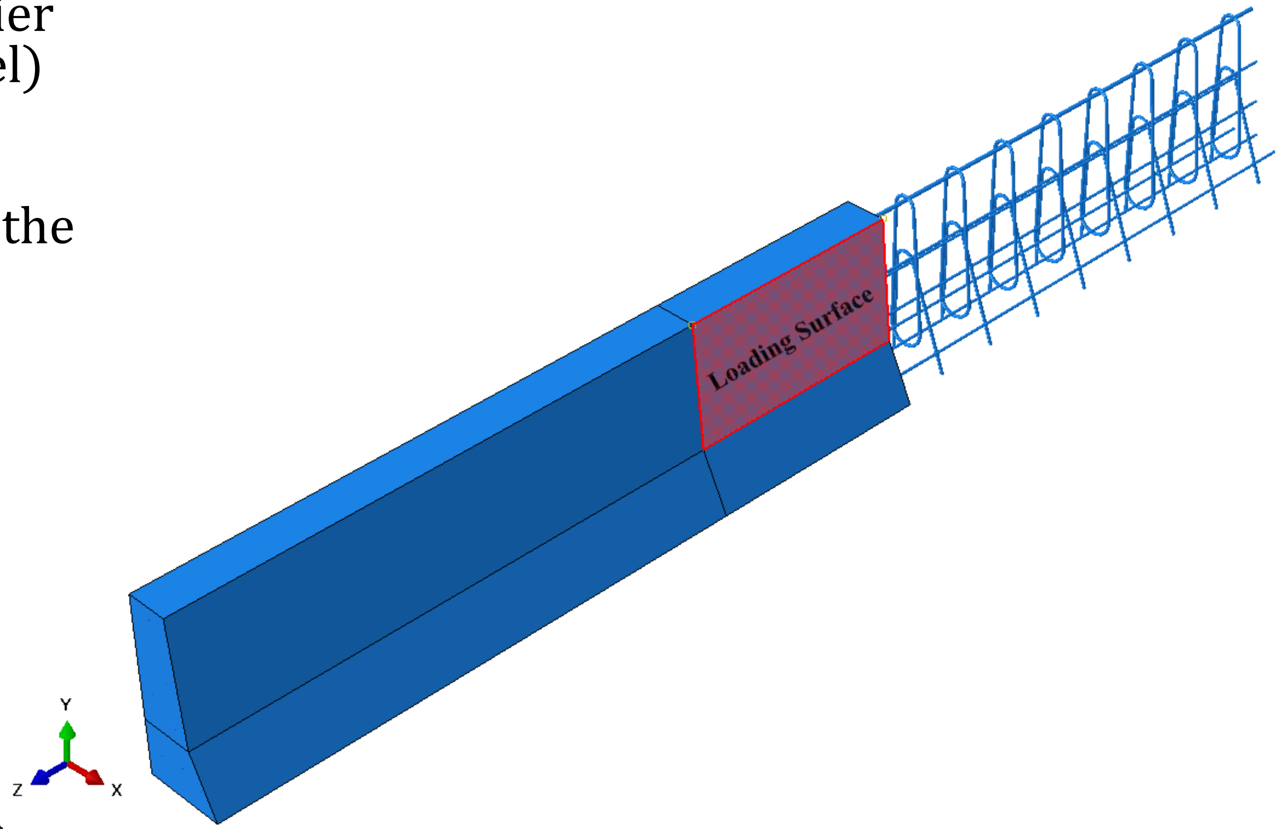
- The model assembly consisted of the barrier (concrete) part and the reinforcement (steel) parts

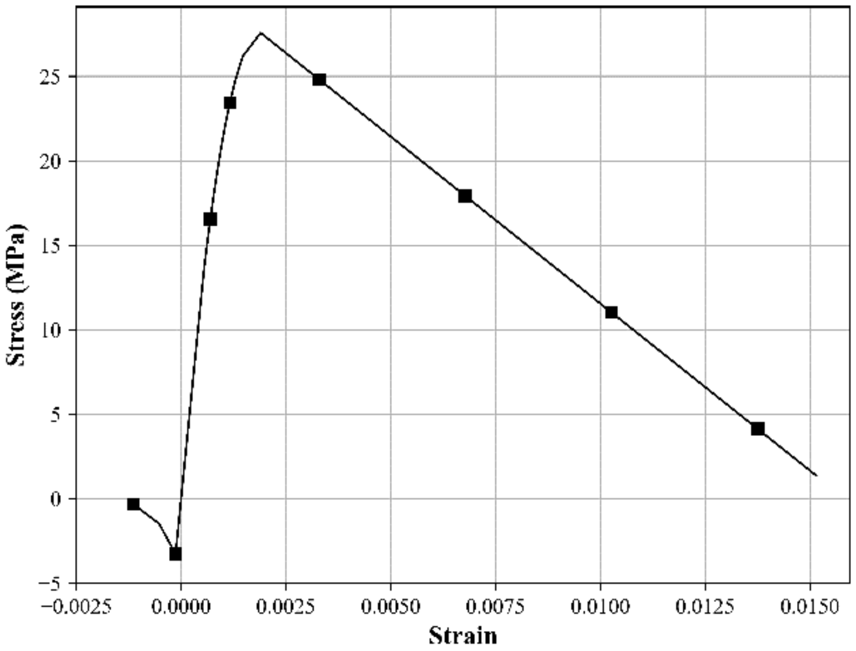
- The concrete material was modeled using the concrete damage plasticity model

- The steel material was modeled bilinearly with a post yielding modulus of 5% of the initial modulus

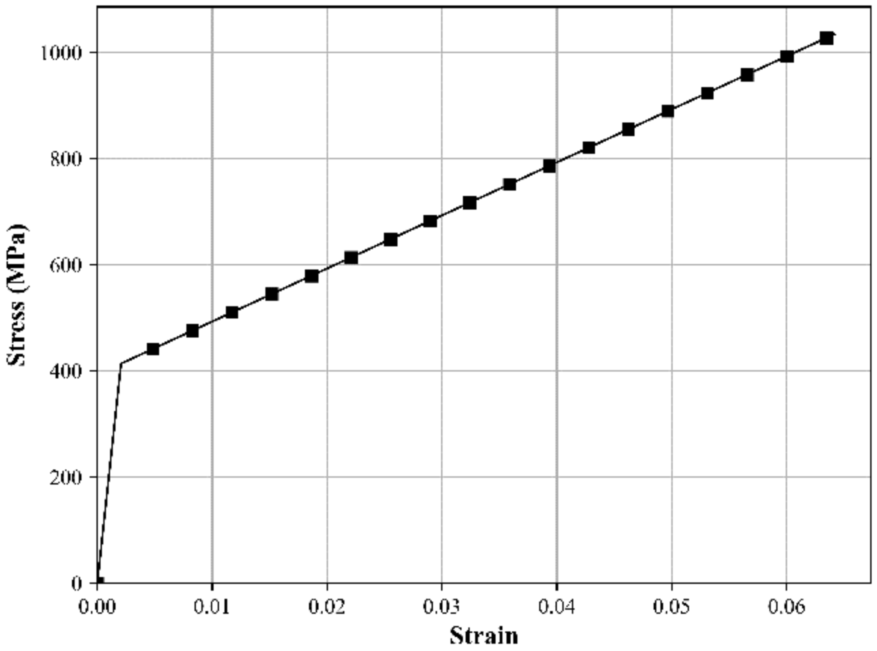
- The concrete elements had solid sections with an 8-node linear brick element type (C3D8R)

- The steel elements were modeled as beam elements





Concrete model



Steel model

- To describe the model mesh, the largest concrete element had dimensions in mm as 60x60x40 amounting to a total of 5044 solid elements

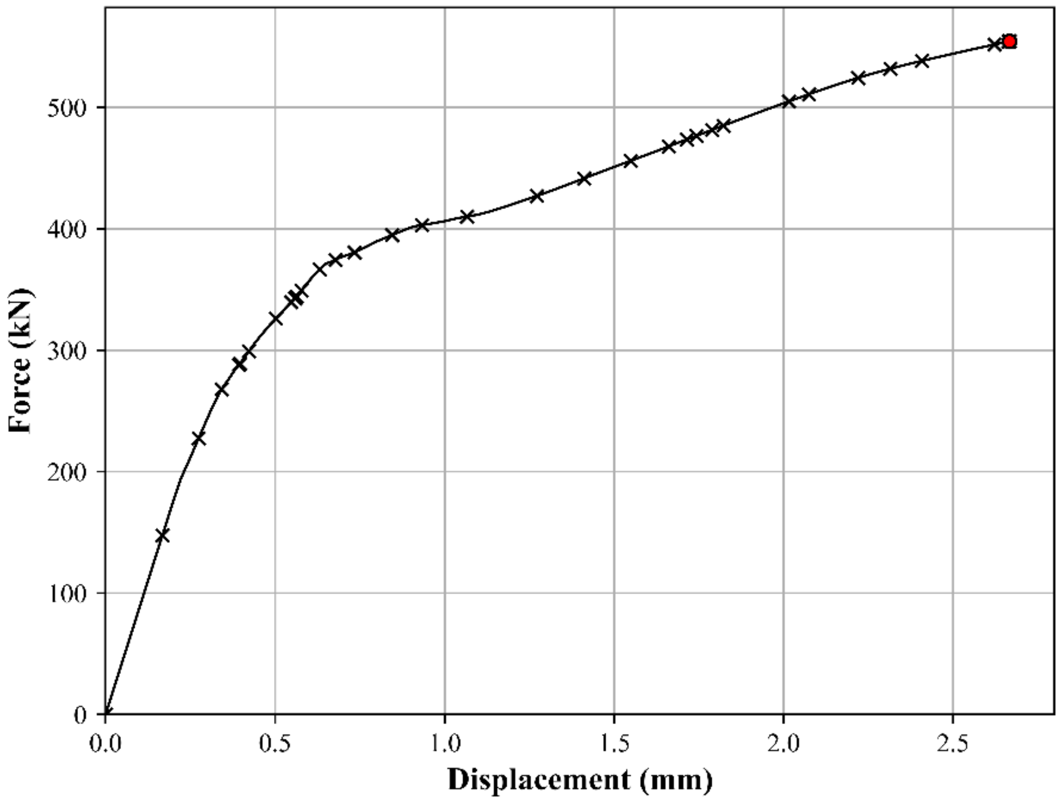
- The barrier's boundary condition was fixed by restraining the translational degrees of freedom of the concrete elements at the base

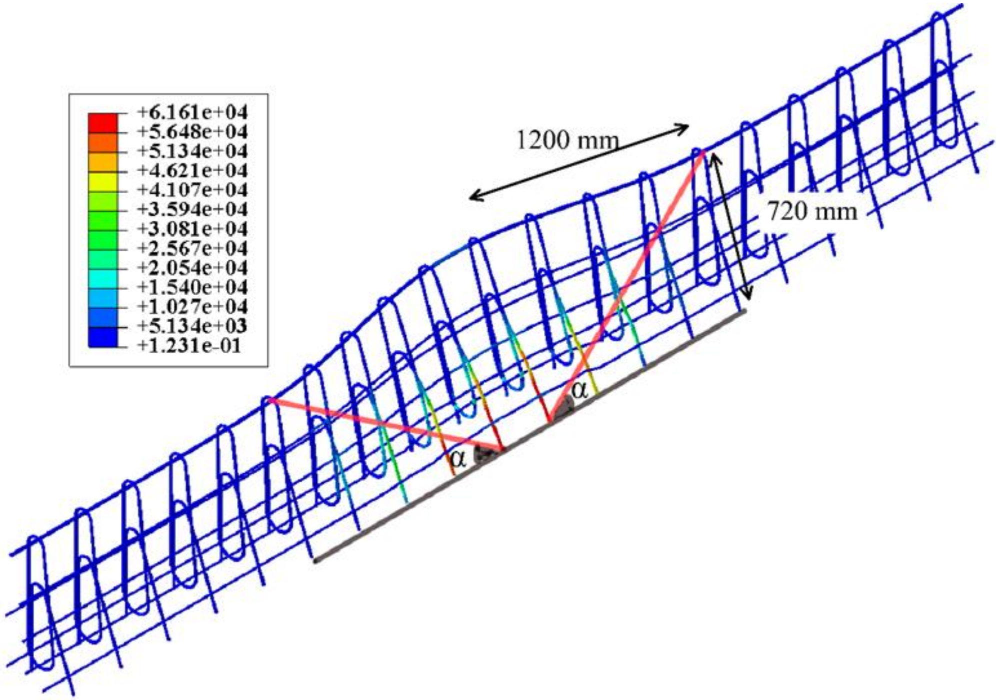
- The analysis type was nonlinear static Riks with the loading defined as a pressure applied at the loading surface

- The loading surface has a length equals to 1067 mm (3.5 ft) and its width extends down until the discontinuity in the barrier's height occurs at 560 mm

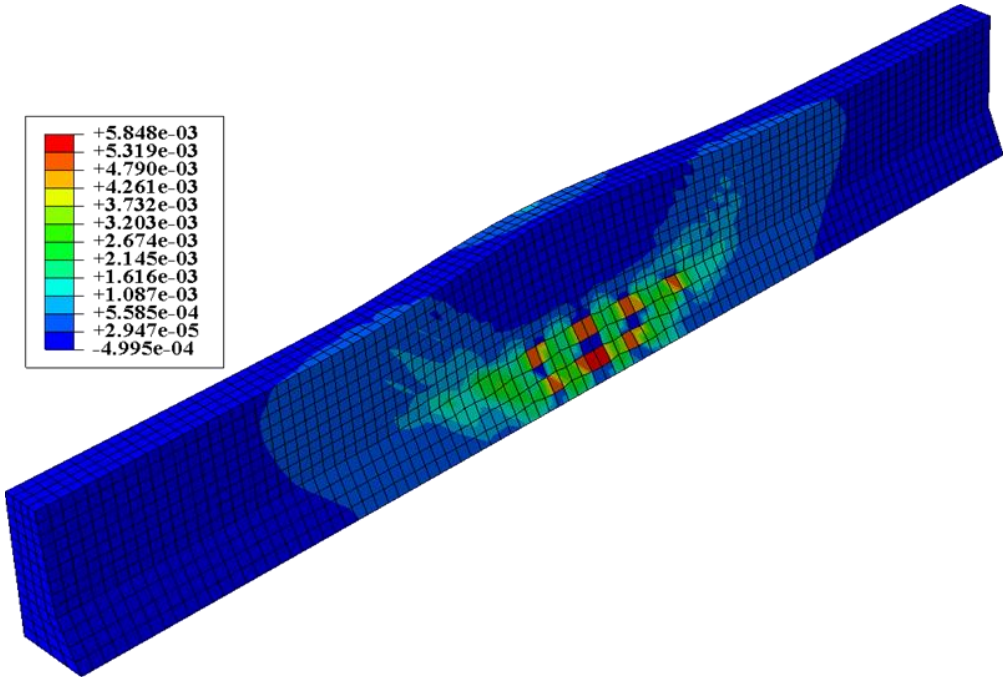
- The target pressure was set to 1.72 MPa (250 psi); considering the area of pressure application, this is equivalent to a target load of 1027 kN

- The analysis predicts a proportionality factor of 0.55 of the target load (1027 kN). This results in a peak capacity of 0.55x1027 = 554 kN





Stress profile in the barrier's reinforcement



max. absolute principal strain in concrete

7. Summary and Conclusion

Loading Pattern	Method	Static transverse capacity	Normalized to AASHTO
Distributed	AASHTO's YLA	250 kN	1
	Rigorous YLA	569 kN	2.276
	FEA by Abaqus	554 kN	2.216

1. The current AASHTO's YLA underestimated the barrier's transverse capacity by more than 50% compared to the detailed YLA and the FEA

2. The proposed rigorous YLA is very powerful in obtaining the barrier's accurate transverse capacity

3. The current AASHTO's YLA can be used to initially proportion barriers for design purposes. However, estimating the actual capacity of existing barrier needs more accurate procedures such as the Rigorous YLA or FEA

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Thank You