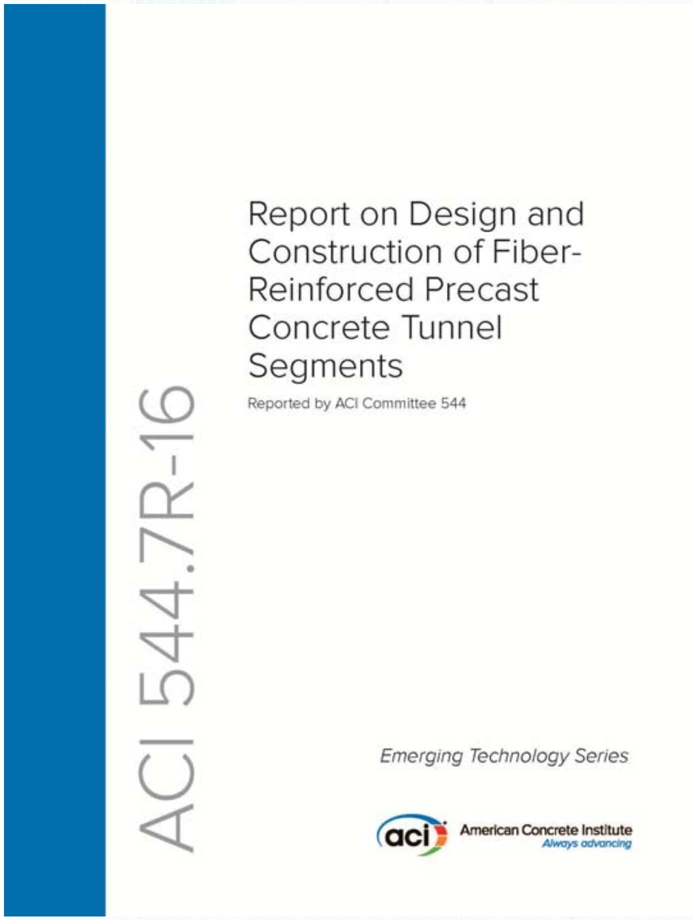

ACI 544.7R-16

Report on Design and Construction of Fiber-Reinforced Precast Concrete Tunnel Segments

Reported by ACI Committee 544

Emerging Technology Series

American Concrete Institute
Always advancing

ACI 544.7R16–Design and Construction of Fiber Reinforced Precast Concrete Tunnel Segments

Mehdi Bakhshi, PhD, PE

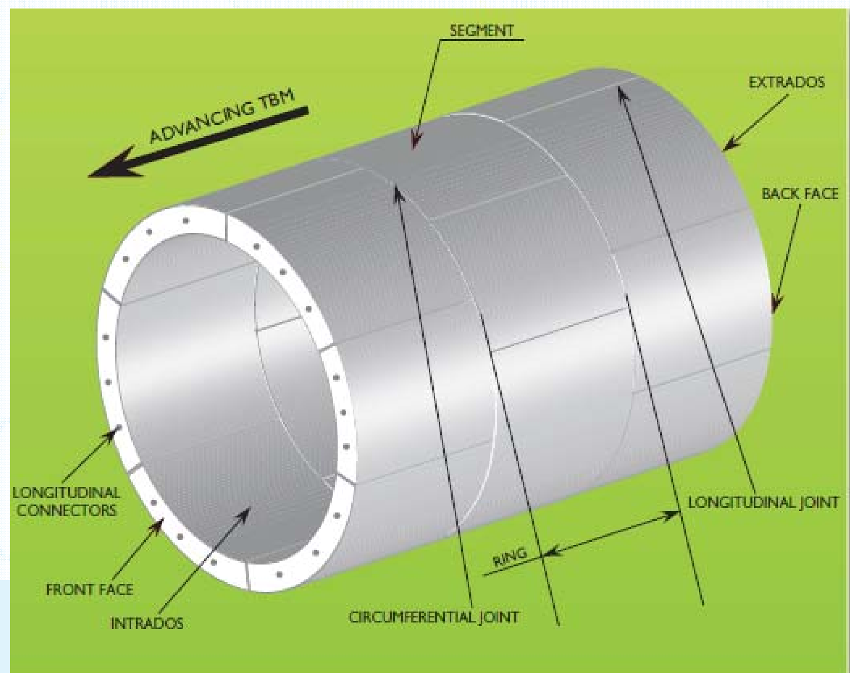
AECOM, New York

Outline

- Introduction to Precast Segments
- Strength Design Method for Segments (ULS):
  - Governing Load Cases, Load Factors & Load Combinations
- Methods of Analysis for Governing Load Cases
- Design with Fibers as an Alternative to Reinforcing Bars
- Strength Design Example for FRC Tunnel Segment
- Future Materials to be Added to Document
- Conclusions

Precast Segmental Tunnel Lining

- Serves as both **initial ground support & final lining** in modern TBM tunnels
- Providing the required operational **cross-section**
- Controlling **groundwater inflow**



Governing Loads Cases

- **Production and transient load cases:**
  Stripping (demolding), storage, transportation and handling

- **Construction load cases:**
  TBM thrust jack forces, tail skin grouting,
  secondary (localized) grouting

- **Final service load cases:**
  Ground, groundwater and surcharge loads, longitudinal
  joint bursting, additional distortion, other specific loads

Load and Resistance Factor Design (LRFD)

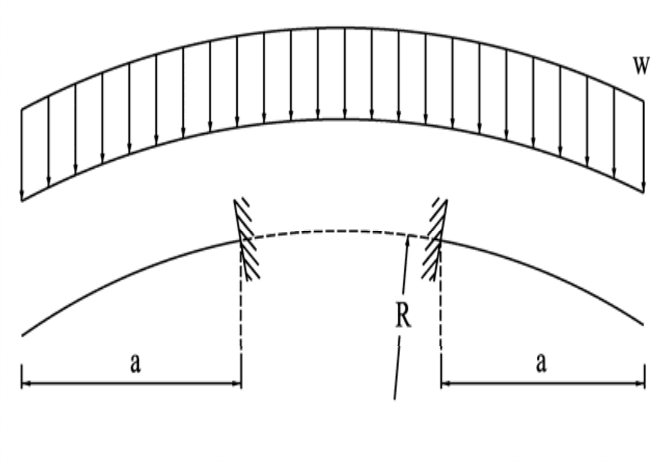
- **Load factors:** 1.25 -1.5 depends on nature of applied loads
- **Strength reduction factors:** 0.7 except bearing (0.65)
- **Load combinations:**

Load Case	Required Strength (U)
Load case 1: stripping	$U = 1.4w$
Load case 2: storage	$U = 1.4(w + F)$
Load case 3: transportation	$U = 1.4(w + F)$
Load case 4: handling	$U = 1.4w$
Load case 5: thrust jack forces	$U = 1.2J$
Load case 6: tail skin grouting	$U = 1.25(w + G)$
Load case 7: secondary grouting	$U = 1.25(w + G)$
Load case 8: earth pressure and groundwater load	$U = 1.25(w + WA_p) + 1.35(EH + EV) + 1.5\ ES$
Load case 9: longitudinal joint bursting	$U = 1.25(w + WA_p) + 1.35(EH + EV) + 1.5\ ES$
Load case 10: additional distortion	$U = 1.4M_{distortion}$

Note: w = self-weight; F = self-weight of segments positioned above; J = TBM jacking force; G = grout pressure; WA_p = groundwater pressure; EV = vertical ground pressure; EH = horizontal ground pressure; ES = surcharge load; and $M_{distortion}$ = Additional distortion effect

Segment Stripping & Segment Handling

- Simulated by two cantilevers loaded under its self weight (e.g. at 5-6 h)

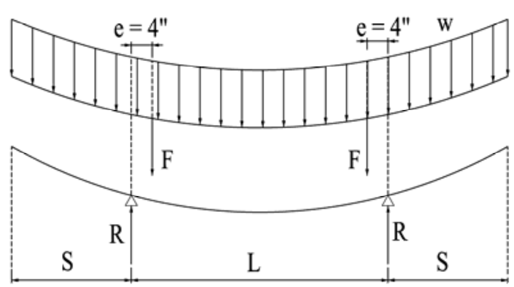


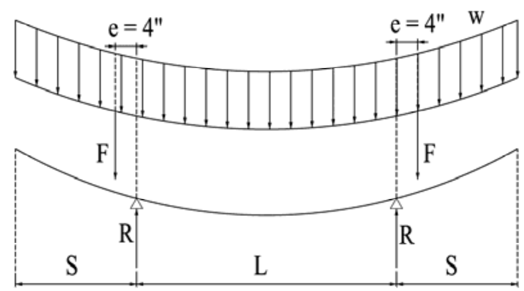
Phase	Dynamic Shock Factor	Maximum Developed Bending Moment	Key Design Parameters
Demolding	N.A	$wa^2/2$	f'_c and σ_p* at 5-6 h
Handling	2.0	$w(L^2/8-S^2/2)+w(L/2+S)f$ (slings) $wa^2/2$ (others)	f'_c and σ_p* at 28 d

* σ_p is the back calculated residual tensile strength for fiber reinforced concrete

Segment Storage & Transportation

- Simulated by simply supported beams loaded under its self-weight and eccentricity (e.g. 5-6 h)
- Segments comprising a ring piled up within one stock





Phase	Dynamic Shock Factor	Maximum Developed Bending Moment	Key Design Parameters
Storage	N.A	$w(L^2/8-S^2/2)+F_1e$ $w(S^2/2)+F_1e$	f'_c and σ_p* at 5-6 h
Transportation	2.0	$w(L^2/8-S^2/2)+F_2e$ $w(S^2/2)+F_2e$	f'_c and σ_p* at 28 d

* σ_p is the back calculated residual tensile strength for fiber reinforced concrete

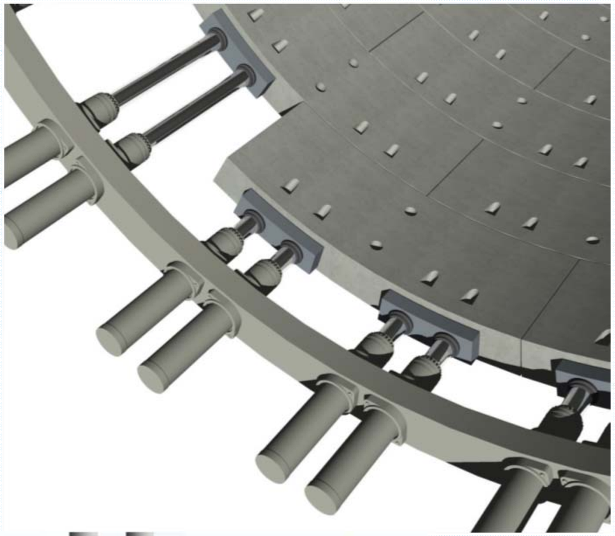
TBM Thrust Jack Forces

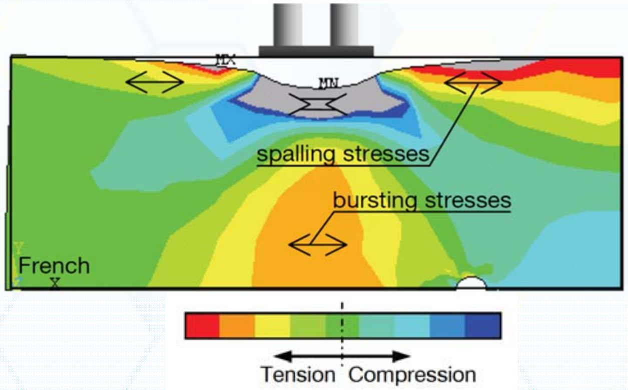
Design checks:

- Bursting tensile stresses
- Spalling tensile stresses
- Compressive stresses

Analysis and design methods:

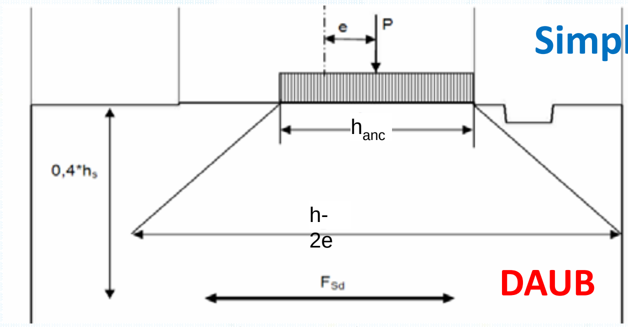
- Simplified equations
- Analytical methods
- Finite Element Analyses (2D/3D)
- Non-linear Fracture Mechanics



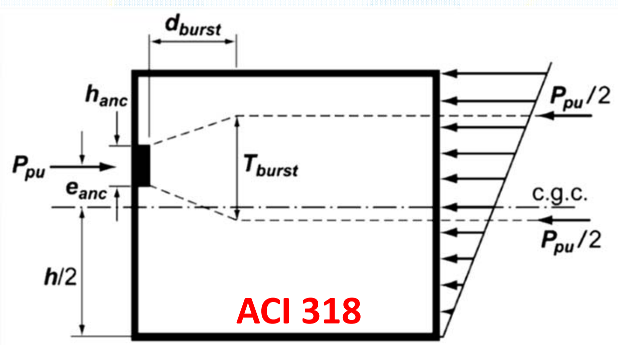


Analysis & Design Methods for Jack Forces

Simplified Equations

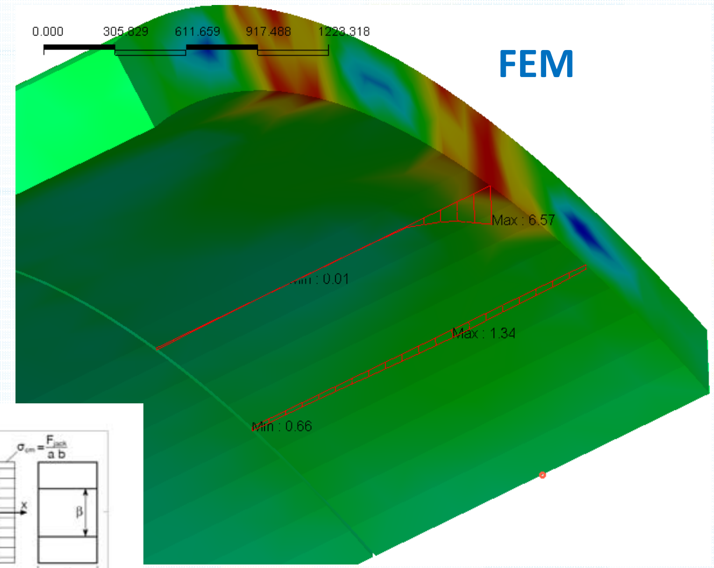


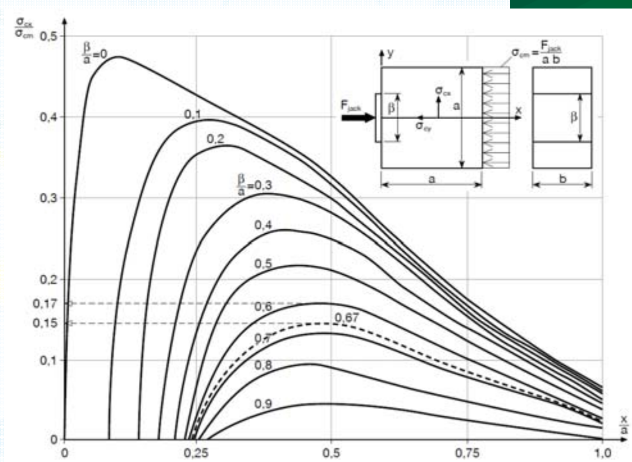
$$T_{burst} = 0.25 P_{pu}\left(1 - \frac{h_{anc}}{h - 2e_{anc}}\right);\ d_{burst} = 0.4(h - 2e_{anc})$$



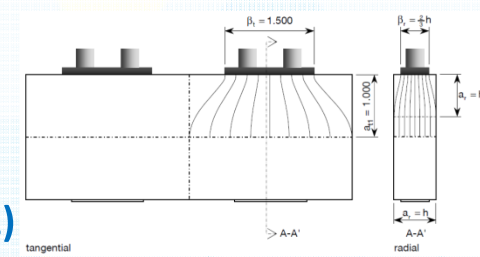
$$T_{burst} = 0.25 P_{pu}\left(1 - \frac{h_{anc}}{h}\right);\ d_{burst} = 0.5(h - 2e_{anc})$$

FEM





Analytical Methods (Iyengar, 1962)



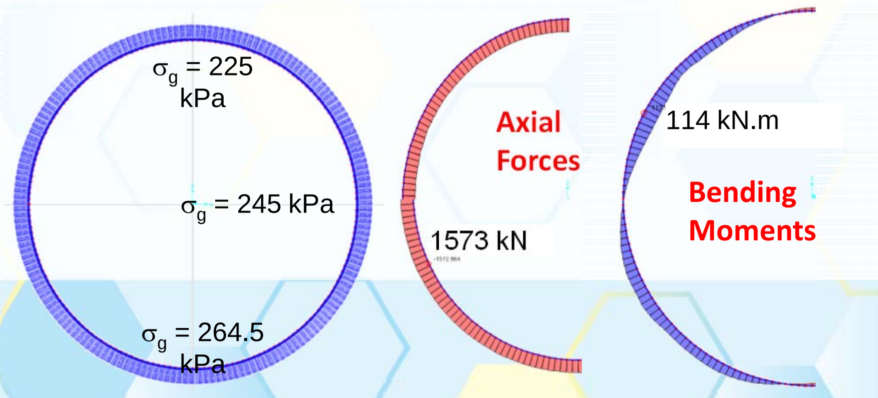
Tail Skin and Secondary Grouting Pressure

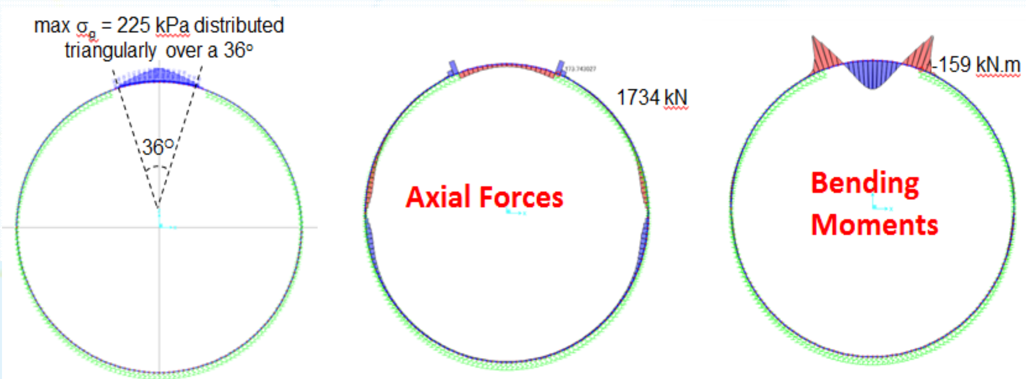
Tail Skin Grouting

- Simulated in 2D by a solid ring
- Grout pressure at crown is slightly higher than groundwater pressure
- Invert grout pressure calculated from equilibrium b/w grout pressure, self-weight and shear stresses of grout
- Radial pressure applied w/ linear distribution

Secondary Grouting

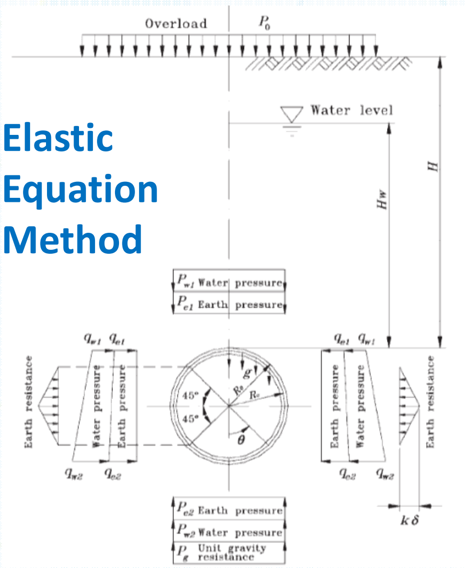
- To fill a local gap b/w lining & excavation profile after primary grouting
- Simulated in 2D
- Interaction with ground is modeled by radial springs
- Grout pressure applied w/ triangular distribution



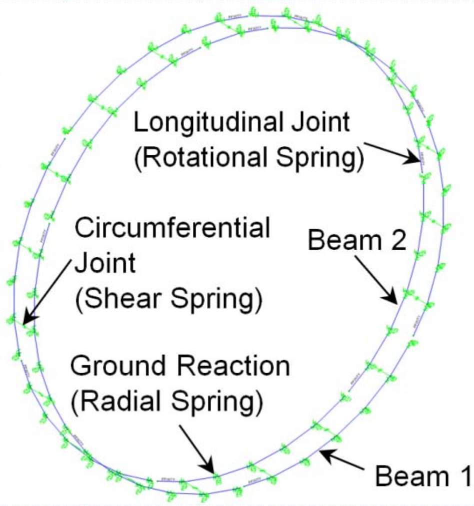


Ground and Groundwater Loads

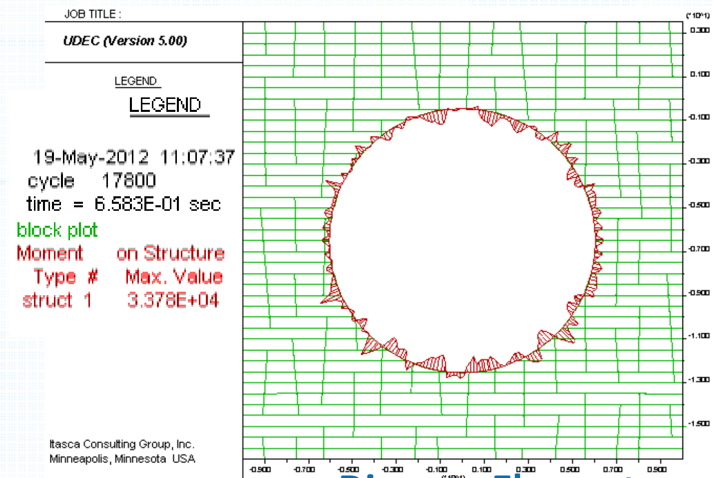
Elastic Equation Method



Load	Bending Moment	Axial Force	Shear Force
Vertical Load ($P= p_{e1}+p_{w1}$)	$(1-2S2)*P*R_c^2/4$	$S2*R_c*P$	$-SC*R_c*P$
Horizontal Load ($Q= q_{e1}+q_{w1}$)	$(1-2C2)*Q*R_c^2/4$	$C2*R_c*Q$	$-SC*R_c*Q$
Horizontal Triangular Load ($Q'= q_{e2}+q_{w2}-q_{e1}-q_{w1}$)	$(6-3C-12C2+4C3)*Q'*R_c^2/48$	$(C+8C2-4C3)*Q'*R_c/16$	$(S+8SC-4SC2)*Q'*R_c/16$
Soil Reaction ($P_k= k.\delta_h$)	$0\le\theta\le\pi/4$ $(0.2346-0.3536C)*R_c^2*k\delta$ $\pi/4\le\theta\le\pi$ $(-0.3487+0.5S2+0.2357C3)*R_c^2*k\delta$	$0\le\theta\le\pi/4$ $0.3536C*R_c*k\delta$ $\pi/4\le\theta\le\pi$ $(-0.7071C+C2+0.7071S2C)*R_c*k\delta$	$0\le\theta\le\pi/4$ $0.3536S*R_c*k\delta$ $\pi/4\le\theta\le\pi$ $(SC-0.7071C2S)*R_c*k\delta$

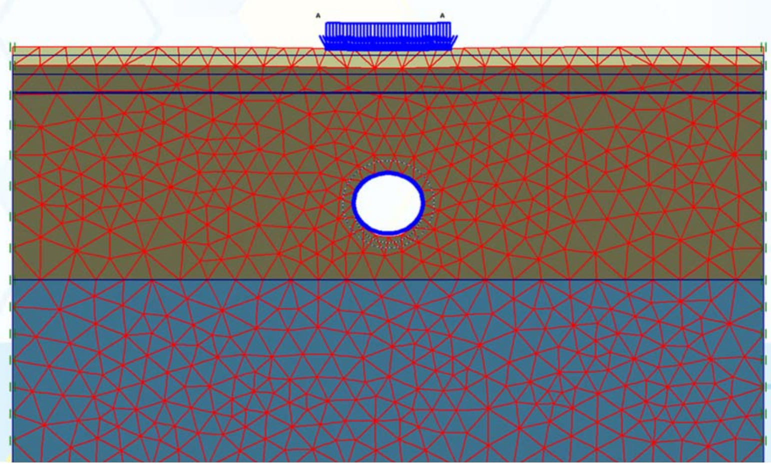


Beam-Spring Method



Discrete Element Method (DEM)

Finite Element Method (FEM)



Longitudinal Joint Bursting Forces

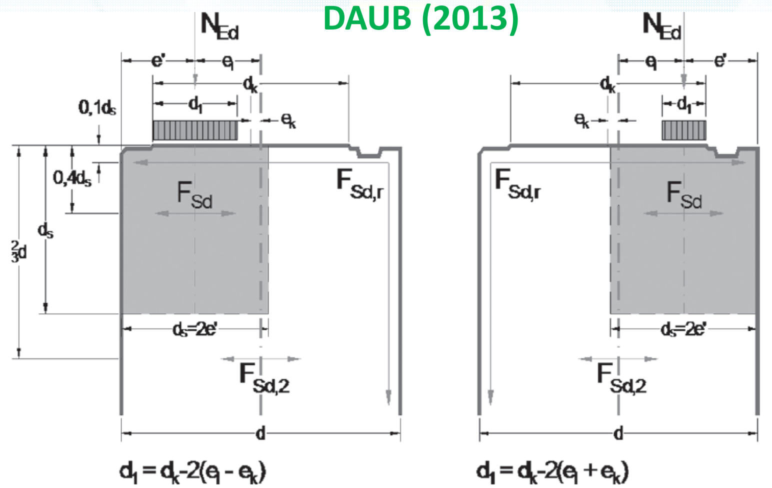
Design checks:

- Bursting tensile stresses
- Compressive stresses

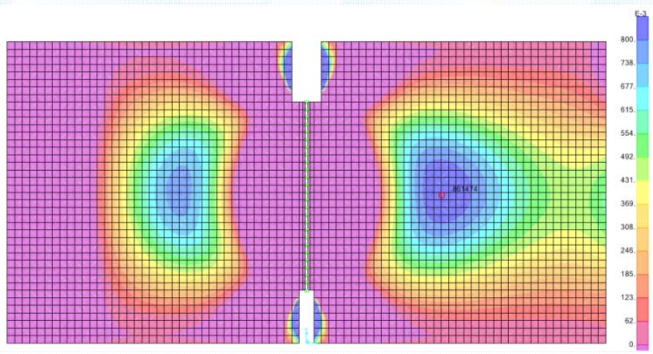
Analysis and design methods:

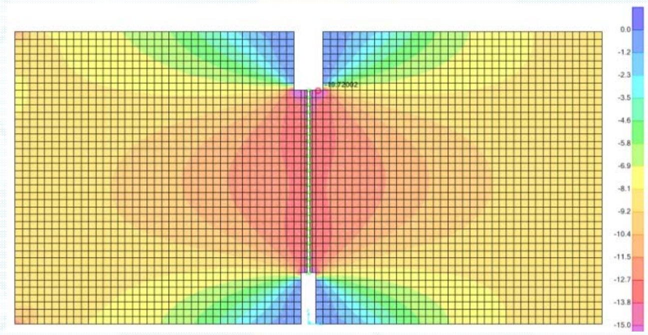
- Simplified equations
- Analytical methods
- Finite Element Analyses (2D/3D)

DAUB (2013)



Tensile Stress





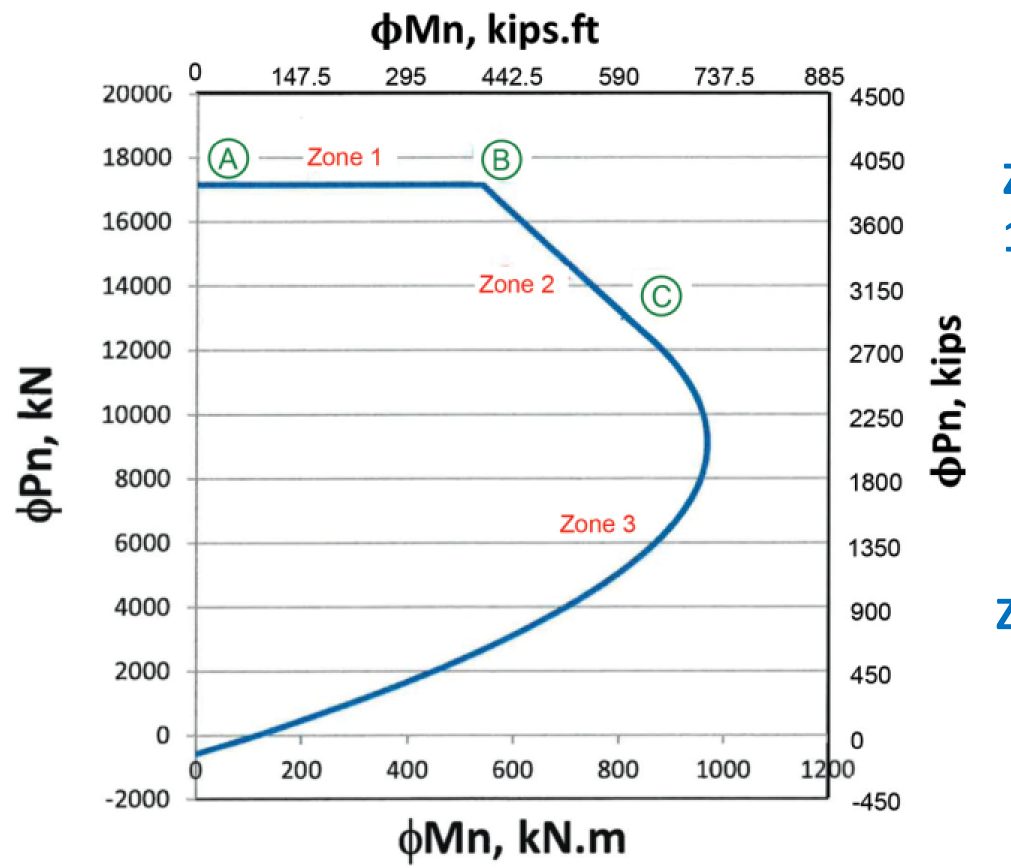
Compressive Stresses

Fibers as an Alternative to Reinforcing Bars

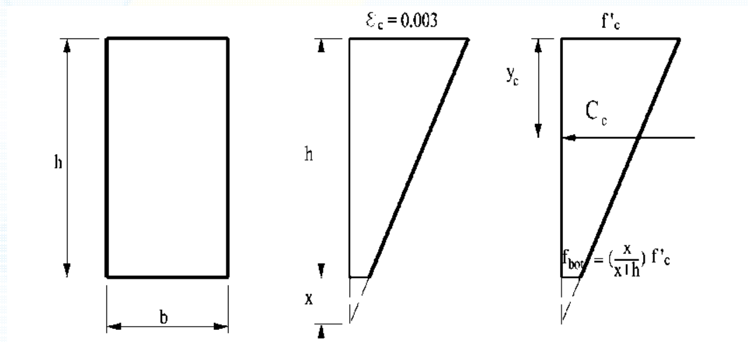
Advantages

- Cost saving (10-40%)
- Improved precast production efficiency
- Reduce spalling or bursting of concrete cover at vulnerable edges and corners
- Ductility & robustness
- Crack width reduction
- High strength against unintentional impact loads

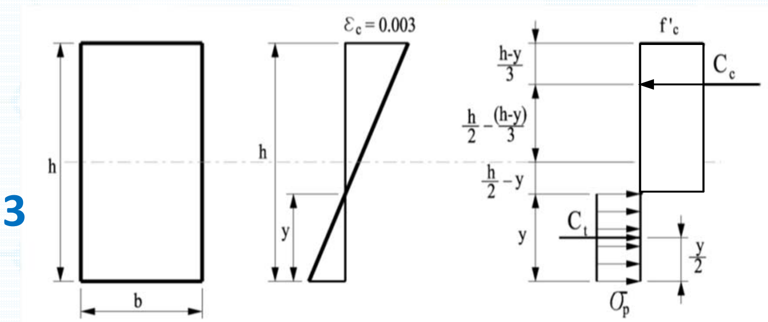
FRC (Only) Segments: Axial Force-Bending Moment Interaction Diagram



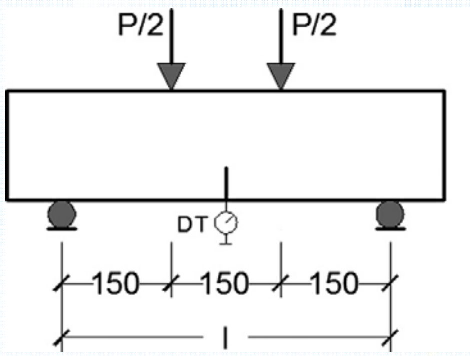
Zones 1&2



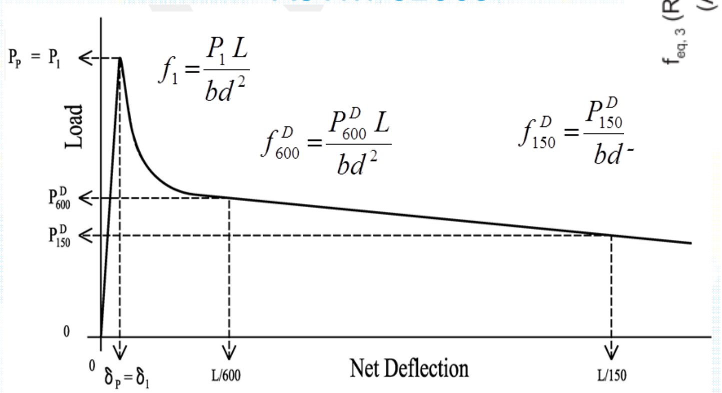
Zone 3

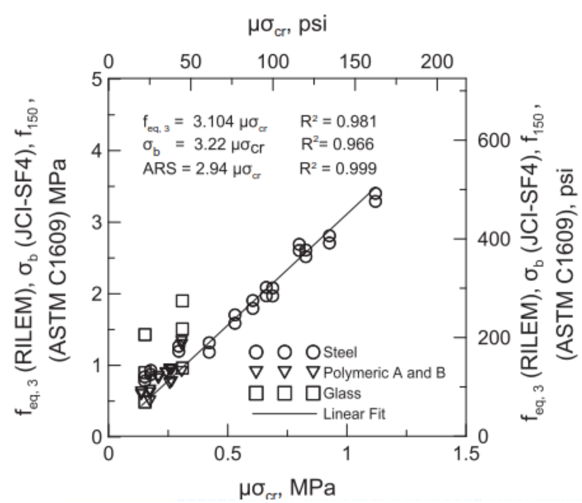


How to Implement FRC Residual Strength

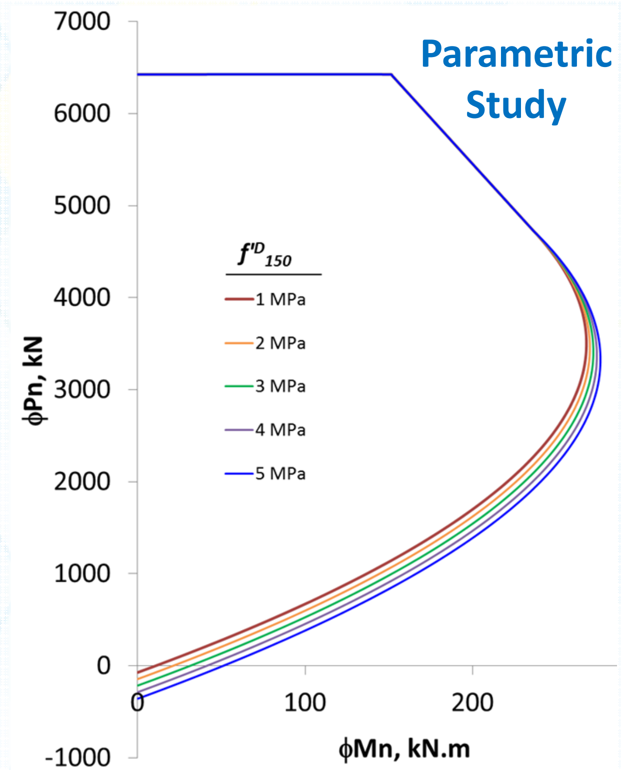


ASTM C1609

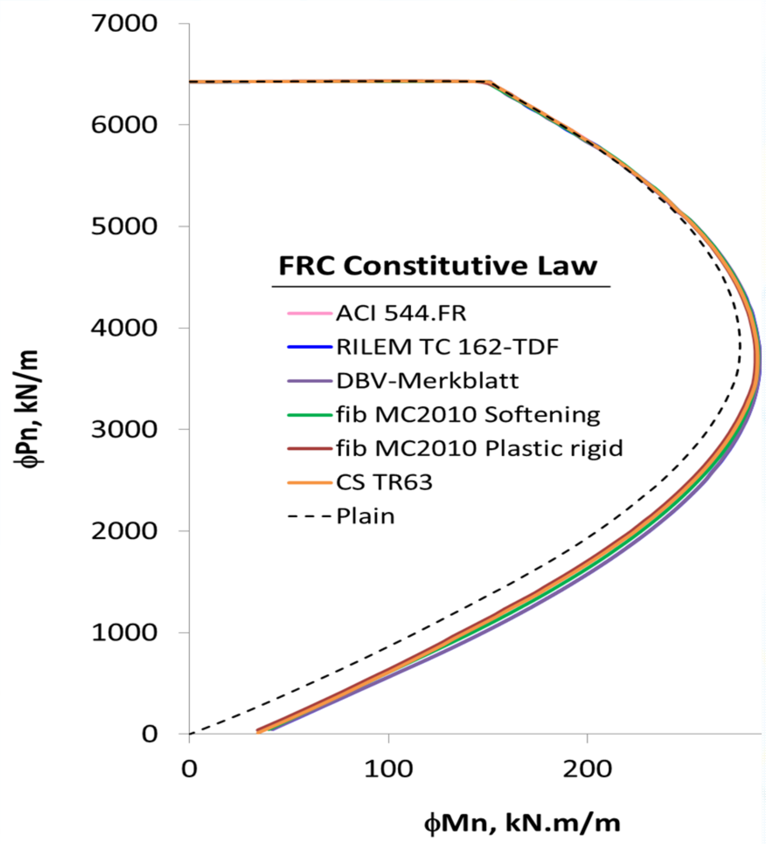


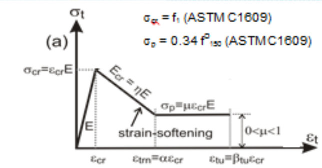
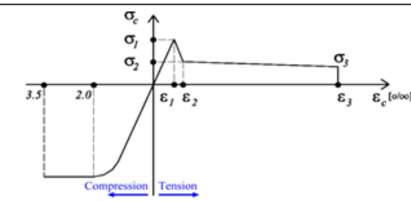
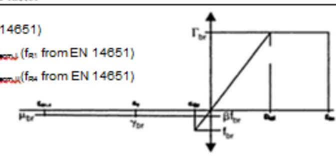
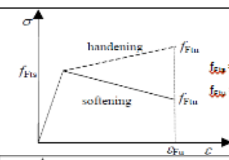
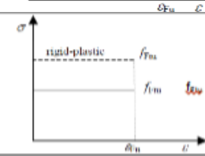
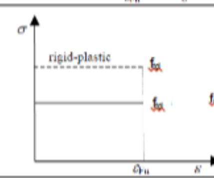


Required Reduction Factor



FRC Segments: Choice of Constitutive Law



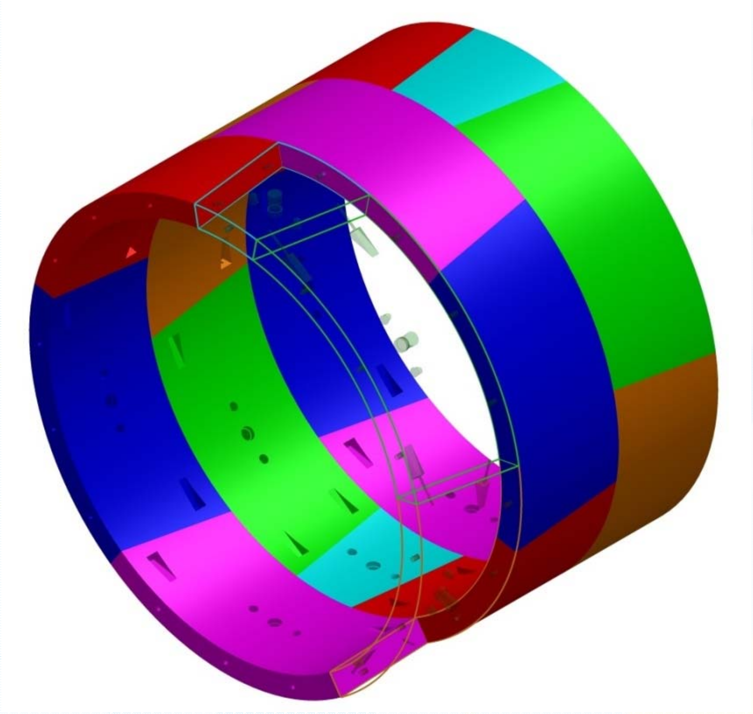
ACI 544.FR Report	 $\sigma_{cr} = f_1$ (ASTM C1609); $\sigma_p = 0.34 f^D_{150}$ (ASTM C1609)
RILEM TC 162-TDF Recommendation New Zealand NZS 3101.2 standard	 $\sigma_1 = 0.7 f_{fctm,fl} (1.6 - d)$ (d in m) (N/mm²); $\sigma_2 = 0.45 f_{R,1} \kappa_h$ (N/mm²); $\sigma_3 = 0.37 f_{R,4} \kappa_h$ (N/mm²); $E_c = 9500 (f_{fcm})^{1/3}$; κ_h : size factor; $\epsilon_1 = \sigma_1 / E_c$; $\epsilon_2 = \epsilon_1 + 0.1$ ‰; $\epsilon_3 = 25$ ‰; f_{fctm}, f_{R1}, f_{R4} obtained from EN 14651
DBV (German society of concrete) Recommendation	$f_{br} = f_L$ (EN 14651); $\beta_{br} = 0.45 f_{eq,I}$ (f_{R1} from EN 14651); $\mu_{br} = 0.37 f_{eq,II}$ (f_{R4} from EN 14651) 
-fib Model Code 2010 -Italian Guide CNR-DT 204/2006 -Spanish Concrete Code EHE-08 -ÖVBB (Austrian society for construction technology) Guide	 $f_{Fts} = 0.45 f_{R1}$ (f_{R1} from EN 14651); $f_{Ftu} = 0.5 f_{R3} - 0.2 f_{R1}$ (f_{R3} from EN 14651)
-fib Model Code 2010 -Italian Guide CNR-DT 204/2006 -Spanish Concrete Code EHE-08	 $f_{Ftu} = 0.33 f_{R3}$ (f_{R3} from EN 14651)
CS (Concrete Society)TR63 Report	 $f_{ld} = 0.37 f_{R3}$ (f_{R3} from EN 14651)

Strength Design Example–FRC Segment

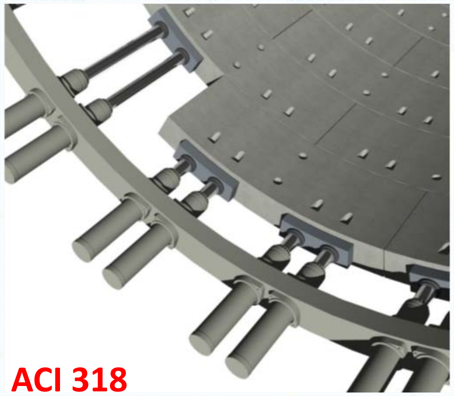
Geometry and Strength Parameters

- D_i = 5.5 m (18 ft)
- b = 1.5 m (5 ft)
- h = 0.3 m (12 in)
- L_{curved} = 3.4 m (11.2 ft)
- f'_c @ 4h: 15 MPa (2,200 psi)
- f'_c @ 28d: 45 MPa (6,500 psi)
- f_1 = 3.8 MPa (540 psi)
- f'^{D}_{150} @ 4h: 2.5 MPa (360 psi)
- f'^{D}_{150} @ 28d: 4 MPa (580 psi)
- TH_{TBM} = 20,000 kN on 16 jack pairs
- Jack Shoes Contact Area: 0.2 x 0.87m

- Ring composed of 5+1 segments
- Tunnel excavated in fractured rock



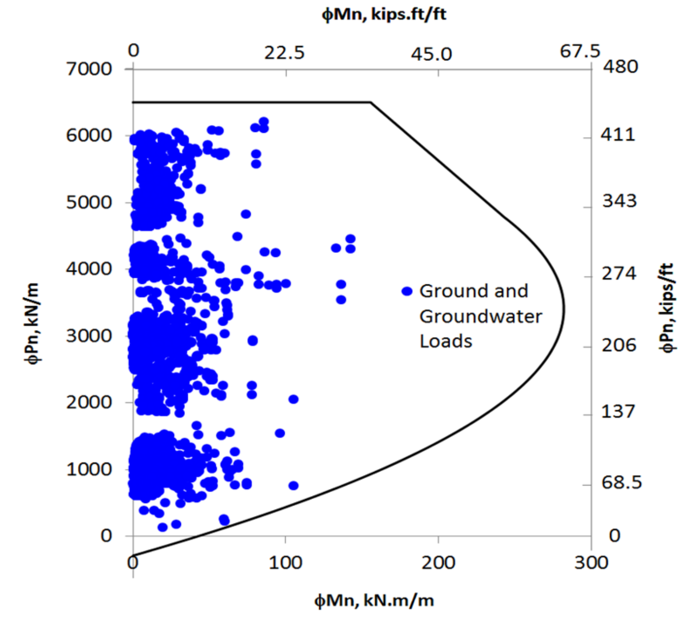
Design Checks for Strength (ULS)



ACI 318

$$\text{Tangential direction:}\quad \sigma_p = \frac{1.2T_{burst}}{\phi h_{anc} d_{burst}} = \frac{1.2\times17.32\times1000}{0.7\times8\times1.77\times12} = 174\ psi\ \ (1.2\,MPa)$$

$$\text{Radial direction:}\quad \sigma_p = \frac{1.2T_{burst}}{\phi a_l d_{burst}} = \frac{1.2\times17.55\times1000}{0.7\times34\times5} = 177\ psi\ \ (1.22\,MPa)$$



Phase	Specified Residual Strength, MPa (psi)	Maximum Bending Moment, kNm/m (kipf-ft/ft)	Bending Moment Strength, kNm/m (kipf-ft/ft)
Demolding	2.5 (360)	5.04 (1.13)	26.25 (5.91)
Storage	2.5 (360)	18.01 (4.05)	26.25 (5.91)
Transportation	4.0 (580)	20.80 (4.68)	42.00 (9.44)
Handling	4.0 (580)	10.08 (2.26)	42.00 (9.44)

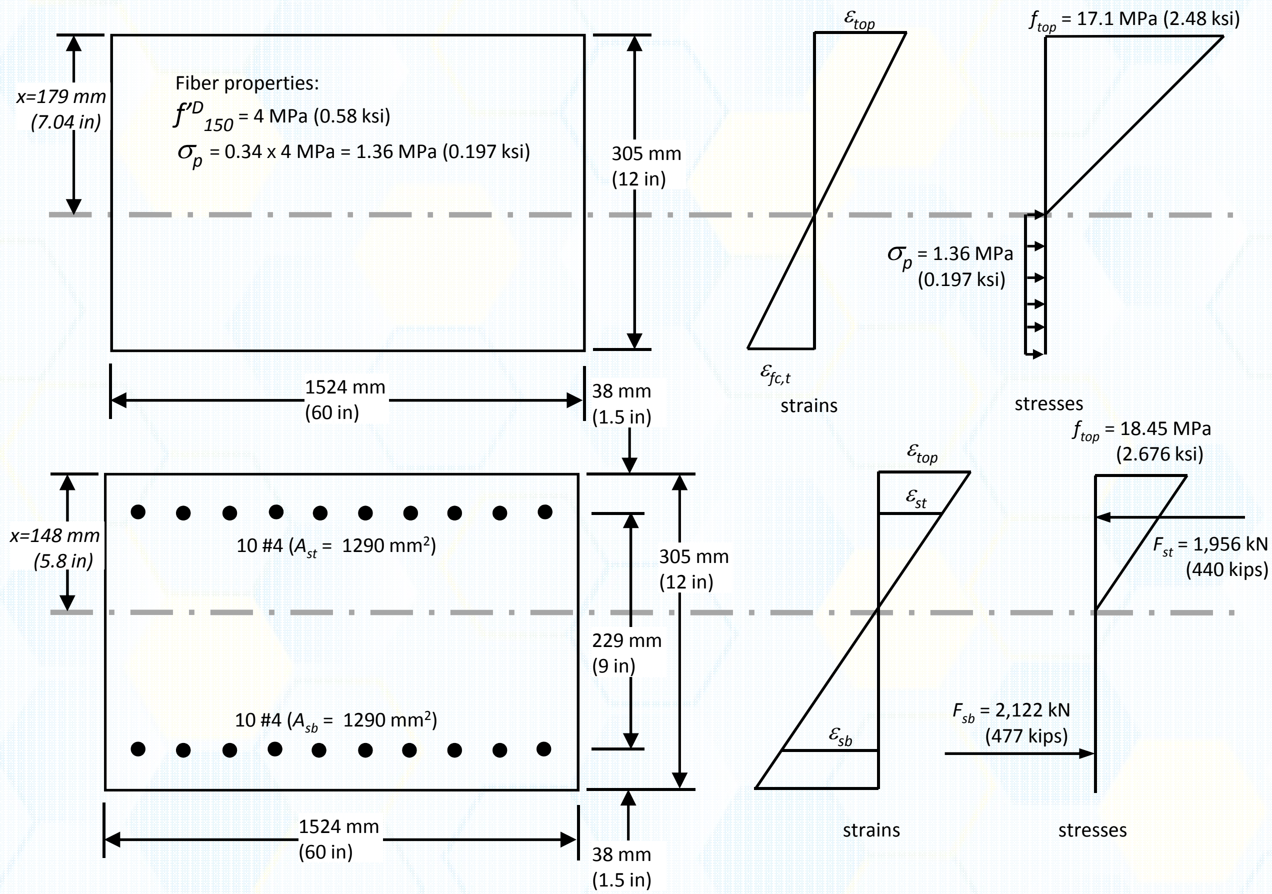
Future Materials: Design for Service-Crack Width

Steps for FRC segments:

1- Determination of neutral axis

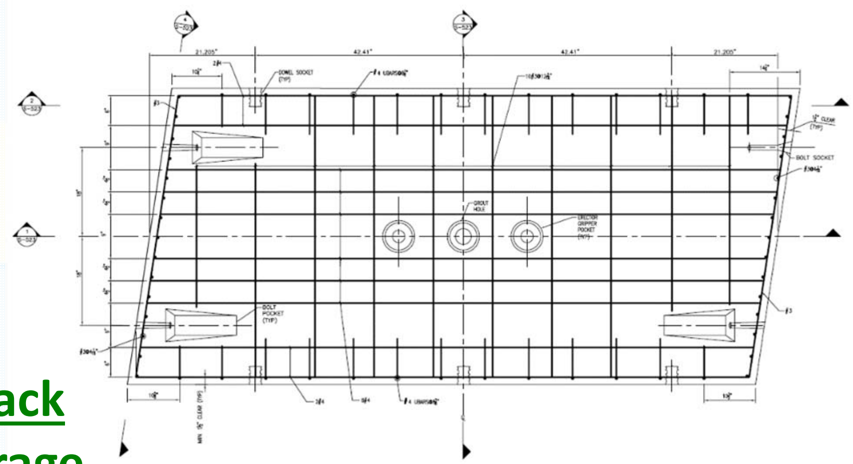
2- Determination of compressive/tensile strains at extreme fibers

3- Calculation of crack width using gauge length concept



Future Materials: Crack Width Reduction Under Excessive Service Loads

Service Loads:
M = 239 kN.m (177 kips-ft)
N = 2,068 kN (465 kips)



Alternatives:
1- RC
2- FRC

FRC results in ~45% crack width reduction in average

Maximum Crack Width in RC Segments	
ACI 224.1R (2007) - Gergely & Lutz	0.10 mm (0.0039 in)
ACI 224.1R (2007) - Frosch	**0.14 mm (0.0056 in)**
JSCE (2007)	0.14 mm (0.0053 in)
EN 1992-1-1 (2004)	**0.07 mm (0.0028 in)**

Maximum Crack Width in FRC Segments	
fib Model Code (2010) CNR-DT 204 (2006)	**0.10 mm (0.0040 in)**
RILEMTC 162-TDF (2003)	**0.04 mm (0.0017 in)**
DAfStb (2012)	0.047 mm (0.0018 in)

Future Materials: Allowable SLS Crack Width

Concrete Codes:

- ACI 224.1R (2007): 0.3 mm (0.012 in)
- EN 1992-1-1 (2004): 0.3 mm (0.012 in)
- Model Code (2010): 0.2 mm (0.008 in)

Tunnel Codes:

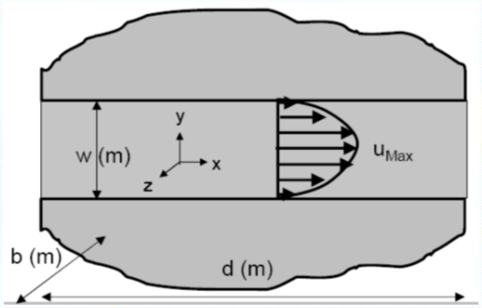
- LTA (2007): 0.3 mm (0.012 in)
- DAUB (2013): 0.2 mm (0.008 in)
- JSCE (2007): 0.004 d_c
- ÖVBB (2011):

Requirement Class	Designation	Application	Requirement	Allowable Crack Width
AT1	Largely dry	- One-pass lining with very tight waterproofing requirements - Portal areas	Impermeable	**0.20 mm (0.008 in)**
AT2	Slightly moist	- One-pass lining for road and railway tunnels with normal waterproofing requirements (excluding portals)	Moist, no running water in tunnel	**0.25 mm (0.010 in)**
AT3	Moist	- One-pass lining without waterproofing requirements - two-pass lining systems	Water dripping from individual spots	**0.30 mm (0.012 in)**
AT4	Wet	- One-pass lining without waterproofing requirements - two-pass lining as drained system	Water running in some places	**0.30 mm (0.012 in)**

Ongoing Studies: Crack Width vs. Infiltration

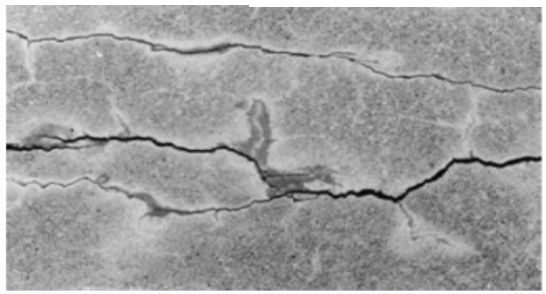
Flow through parallel plates

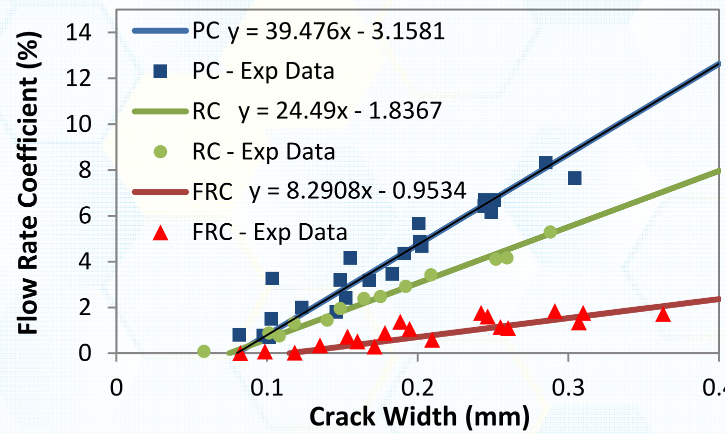
$$Q = \frac{w^3 \cdot b \cdot \Delta P}{12\mu \cdot d}$$

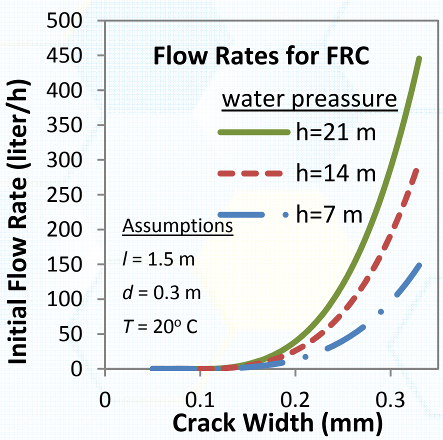


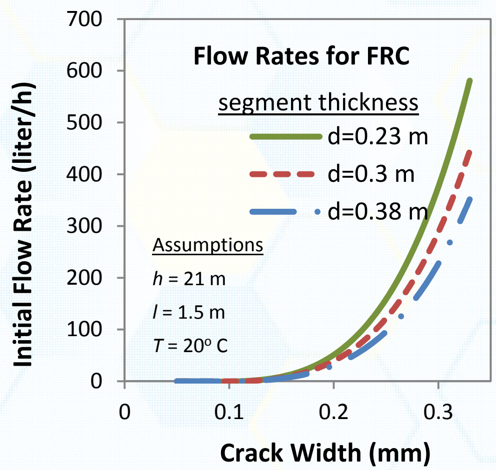
Flow through Concrete

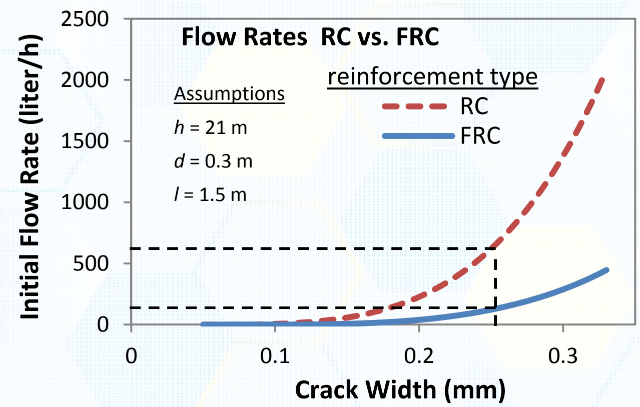
$$Q = \xi \frac{\Delta P l w^3}{12\mu d} = \xi \frac{g l I w^3}{12\nu}$$











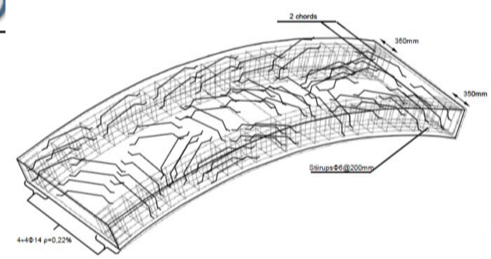
Future Materials: Hybrid Reinforcement

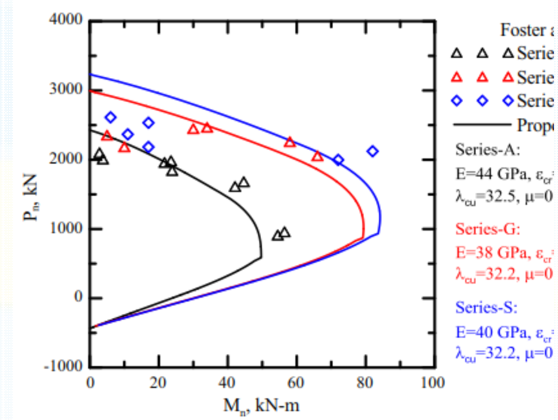
Materials and Structures (2018)51:35
https://doi.org/10.1617/s11527-018-1159-2

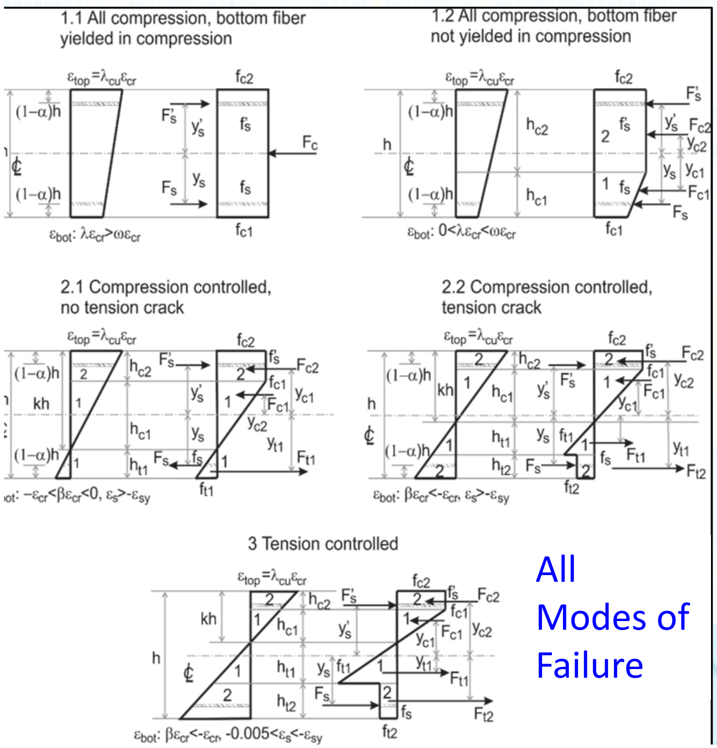
ORIGINAL ARTICLE

Interaction diagrams for design of hybrid fiber-reinforced tunnel segments

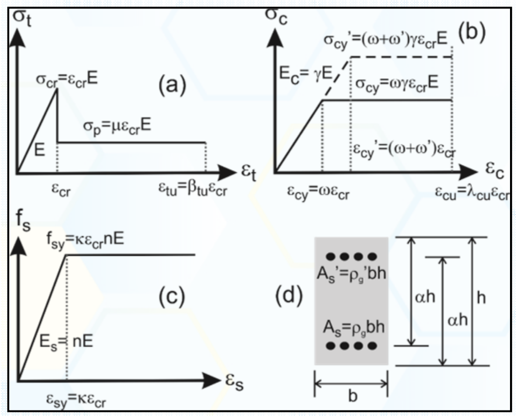
Yiming Yao · Mehdi Bakhshi · Verya Nasri · Barzin Mobasher







All Modes of Failure



Material Models

	Mode	P'
Force	1.1	$P'_{11}=2\kappa n\rho_g+\omega\gamma$
	1.2	$P'_{12}=\frac{(\lambda^2+\omega^2-2\omega\lambda_{cu})\gamma+2n\rho_g(\chi+\kappa)(\lambda-\lambda_{cu})}{2(\lambda-\lambda_{cu})}$
	2.1	$P'_{21}=-\frac{(\omega^2\gamma-2\omega\gamma\lambda_{cu}+\beta\lambda_{cu})k}{2\lambda_{cu}}+n\rho_g(\chi+\kappa)+\frac{\beta}{2}$
	2.2	$P'_{22}=(-\frac{\omega^2\gamma}{2\lambda_{cu}}+\omega\gamma)k+\frac{2\beta\mu+2\mu-1}{2\beta}(k-1)+n\rho_g(\chi+\kappa)$
	3.1	$P'_{31}=(-\frac{\omega^2\gamma}{2\lambda_{cu}}+\omega\gamma)k+\frac{2\beta\mu+2\mu-1}{2\beta}(k-1)$
	3.2	$P'_{32}=(-\frac{\omega^2\gamma}{2\lambda_{cu}}+\omega\gamma)k+\frac{2\beta\mu+2\mu-1}{2\beta}(k-1)-n\rho_g(\lambda_{cu}-\kappa)+\frac{n\rho_g(\alpha-1)}{k}\lambda_{cu}$
Moment	1.1	$M'_{11}=0$
	1.2	$M'_{12}=\frac{C_1\lambda_{cu}^2+C_2\lambda_{cu}+C_3\beta^2+2\omega^3\gamma}{2(\beta-\lambda_{cu})^2}$
	2.1	$M'_{21}=C_4k^2+C_5k+C_6$
	2.2	$M'_{22}=C_7k^2+C_8k+C_9(\chi-\kappa)+C_{10}$
	3.1	$M'_{31}=C_7k^2+C_8k-2C_9+C_{10}$
	3.2	$M'_{32}=C_7k^2+C_8k+C_{11}+\frac{C_{12}}{k}$

where $k=\frac{\lambda_{cu}}{\beta+\lambda_{cu}}$, $C_1=6n\rho_g(2\alpha-1)(\chi-\kappa)$, $C_2=12\beta^2n\rho_g(2\alpha+1)(\kappa-\chi)-3\beta\gamma\omega(\omega-2\lambda_{cu})$, $C_3=\beta^2C_1-\gamma\omega^2(2\omega-3\lambda_{cu})$, $C_4=-\frac{\omega^3\gamma}{\lambda_{cu}^2}+\frac{3\omega^2\gamma}{\lambda_{cu}}-3\omega\gamma+\beta$, $C_5=-\frac{1}{2}(\frac{3\omega^2\gamma}{\lambda_{cu}}-6\omega\gamma+\beta)$, $C_6=3n\rho_g(2\alpha-1)(\chi-\kappa)-\frac{\beta}{2}$, $C_7=-\frac{\omega-3\lambda_{cu}}{\lambda_{cu}^2}\gamma\omega^2-3(\gamma\omega+\mu)-\frac{6\mu-3}{\beta}+\frac{3\mu-2}{\beta^2}$, $C_8=-\frac{3\gamma\omega^2}{2\lambda_{cu}}+3(\gamma\omega+\mu)+\frac{18\mu-9}{2\beta}+\frac{6\mu-4}{\beta^2}$, $C_9=-3n\rho_g(2\alpha-1)$, $C_{10}=-\frac{6\mu-3}{2\beta}-\frac{3\mu-2}{\beta^2}$,

Closed-Form Solution

Conclusion

- ACI 544.7R successfully addressed the demand in industry for a guide on FRC segments
- In mid-size tunnels use of fiber reinforcement can lead to elimination of steel bars required for strength, resulting in construction cost saving of up to 40%.
- Use of fiber in tunnel segments results in reduction of crack width by ~45% under the service load for Serviceability Limit State (SLS) design.
- Service design and hybrid reinforcement strength design will be added in the future to ACI 544.7R.

Thank you for your attention

Mehdi Bakhshi, PhD, PE
Senior Tunnel Engineer at AECOM
Member of ACI committees 305, 350, 506, 544, and 533
mehdi.bakhshi@aecom.com
D 212.896.0257 C 480.370.1685
125 Broad St, 16th floor, New York, NY 10004