AECOM

Workshop on FRC Precast Segmental Lining of TBM Tunnels

May 27, 2025 – Warsaw, Poland

Design Fundamentals

Verya Nasri, PhD, PE

Chief Tunnel Engineer, AECOM

Warsaw University of Technology
Faculty of Civil Engineering

ITA AITES

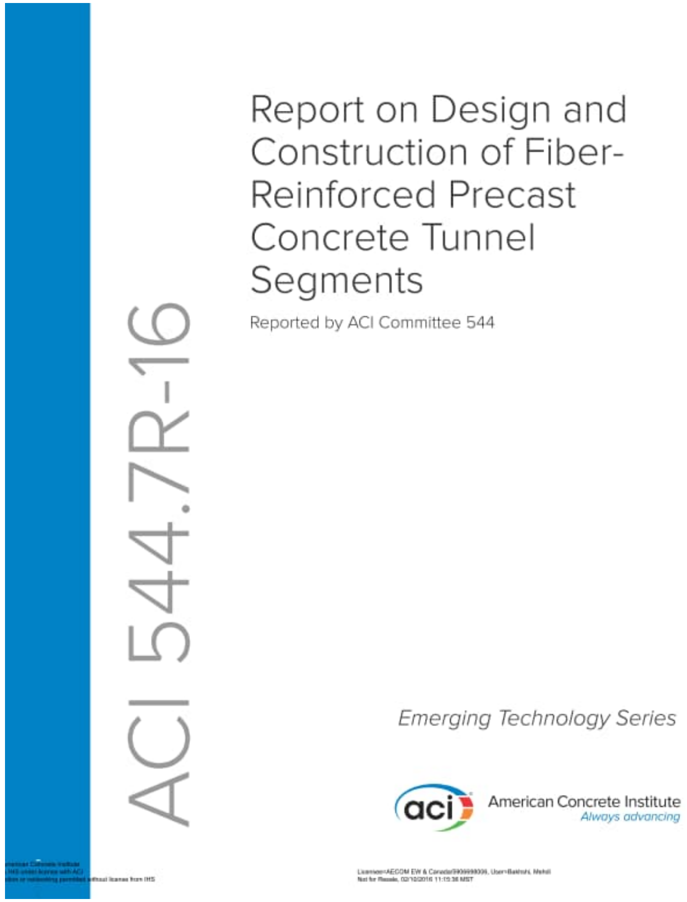
ITACET Foundation

Bekaert

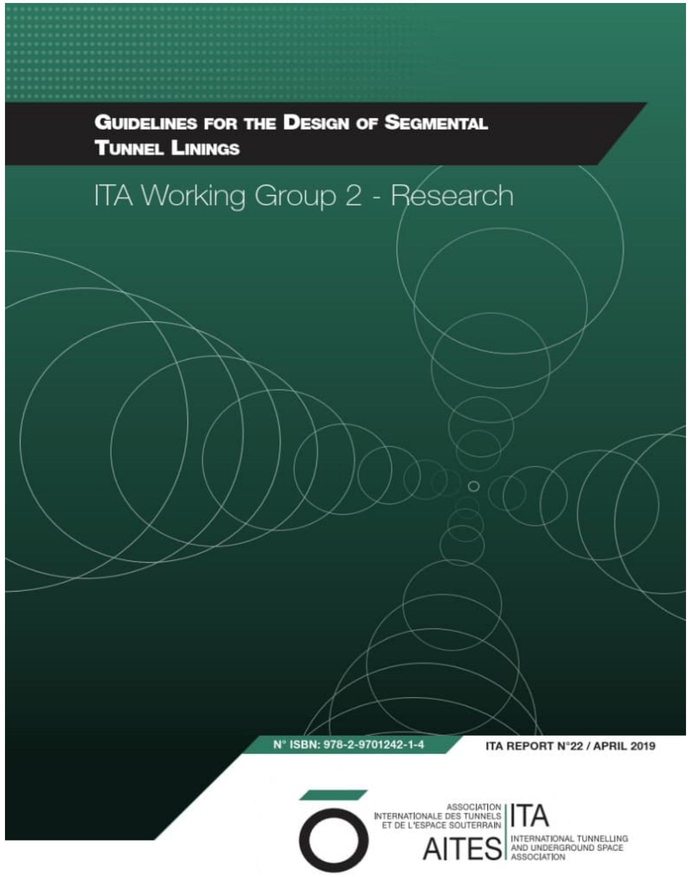
Delivering a better world

aecom.com

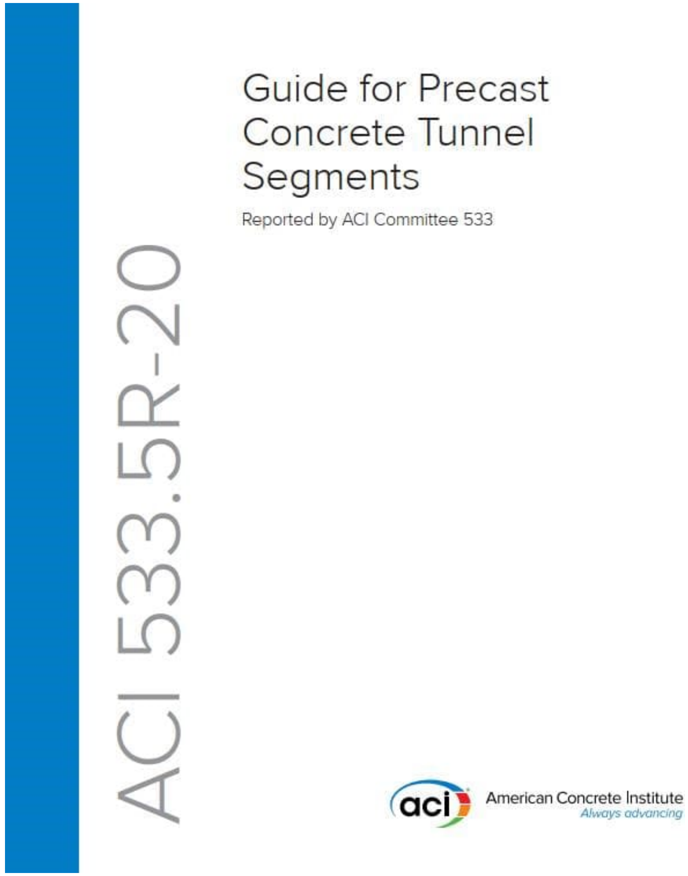
Guidelines Used for Design of Segments



World's 1st Guideline on FRC Segment (2016)

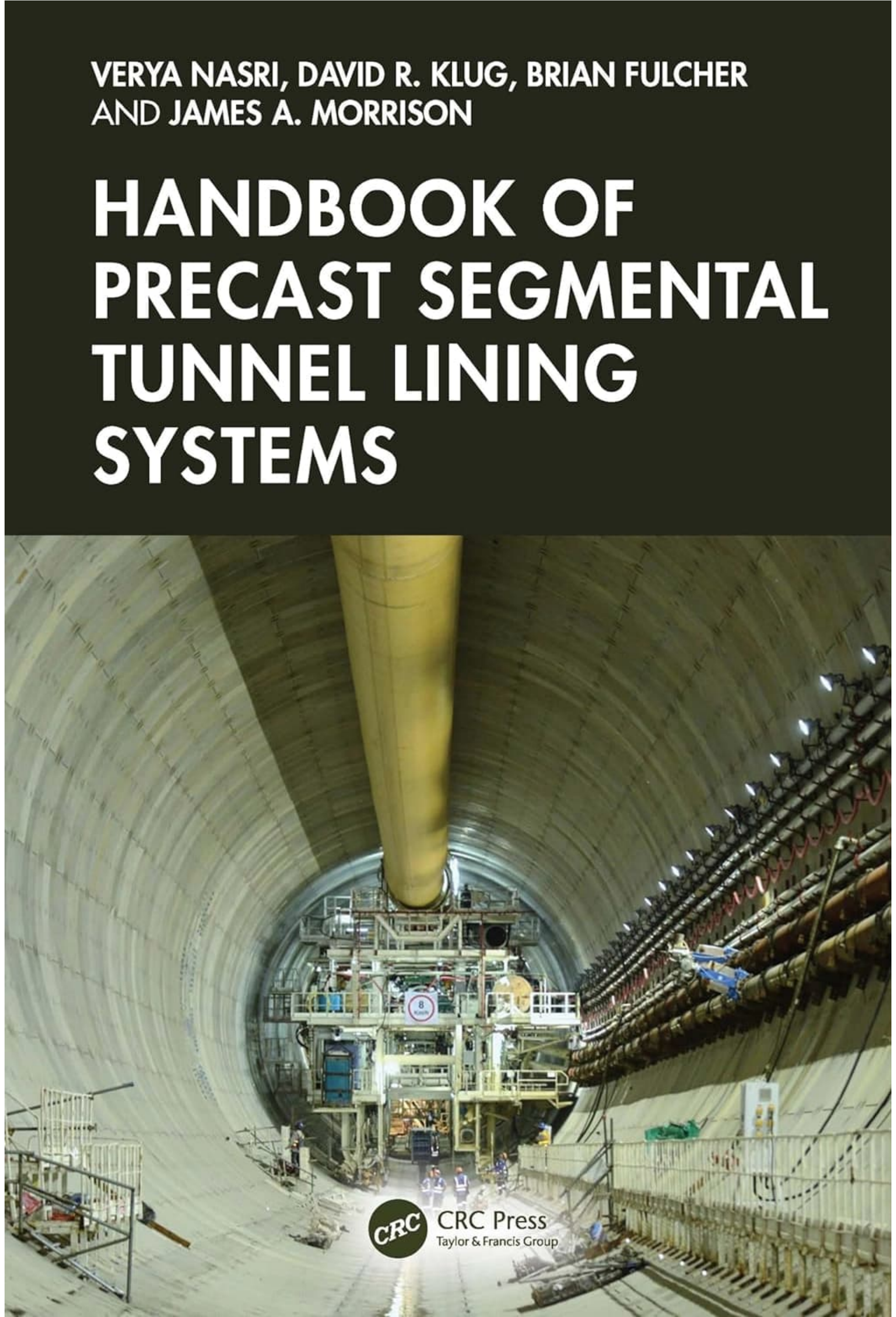


International Tunneling Association (ITA) Guidelines



1st Guideline to Cover All Aspects of Design, Manufacturing, Construction, Repair, Durability in 1 Document

Recently Published Segment Handbook



Size of Bored Tunnels and Segmental Rings

Internal Dia. Depends on Function of Tunnel:

- Roadway
- Railway/Subway
- Utilities
- Water Conveyance
- Wastewater/CSO

Spaceproofing must be done based on all required clearances and spaces for housing required equipment

Thickness of Segmental Rings:

ID > 5.5 m → ID/t = 18-25

ID: 4-5.5 m → ID/t = 15-25

ID/t = 20-23 Best Practice

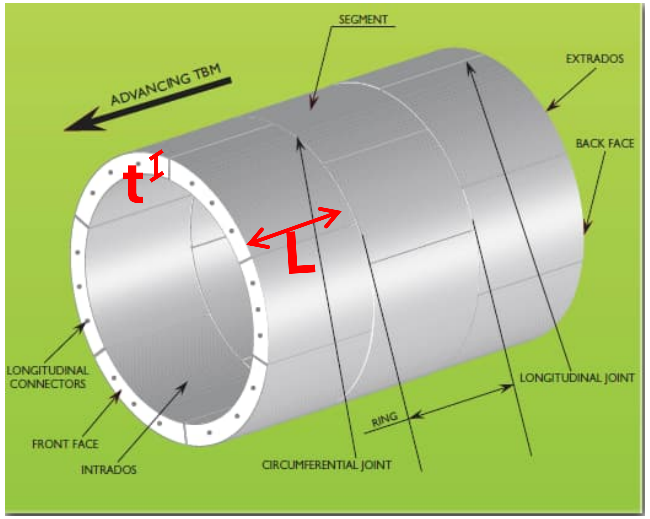
Length of Segmental Rings:

TBM Dia.: 6-7 m → L = 1.5 m

TBM Dia.: 7-9 m → L = 1.8 m

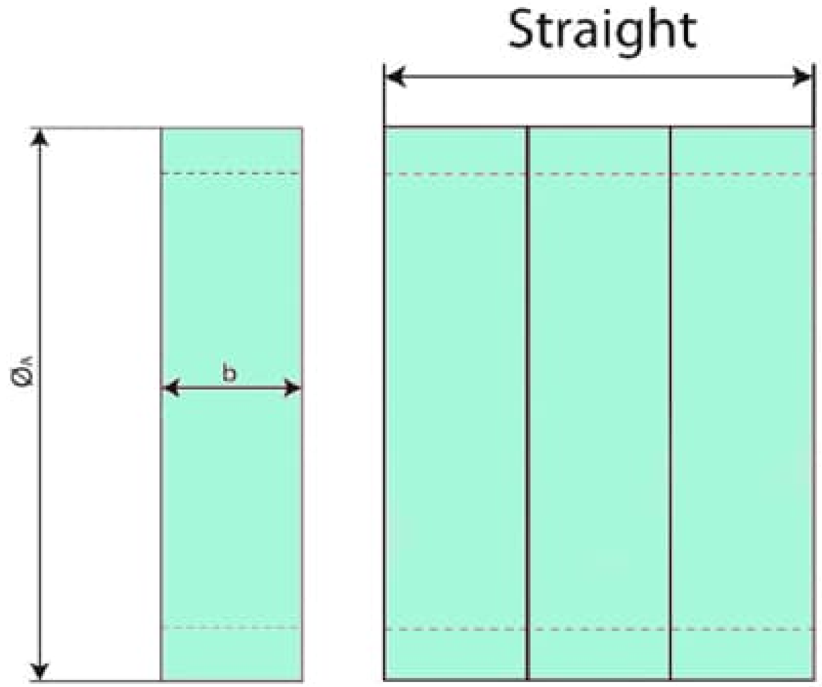
TBM Dia.: > 9 m → L = 2 m

Best Practice



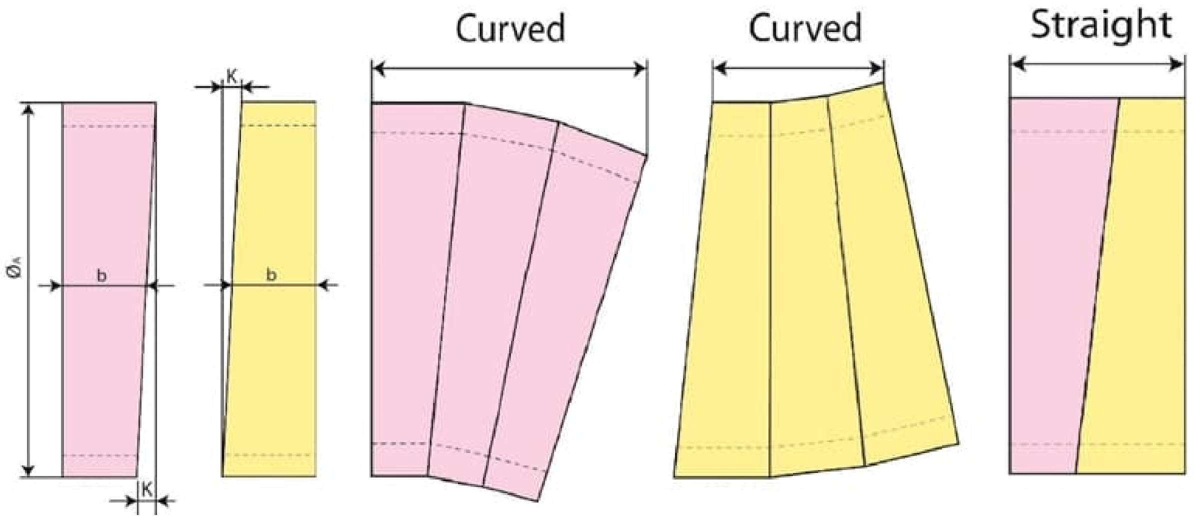
Segmental Ring Systems

Plan View of Segmental Rings



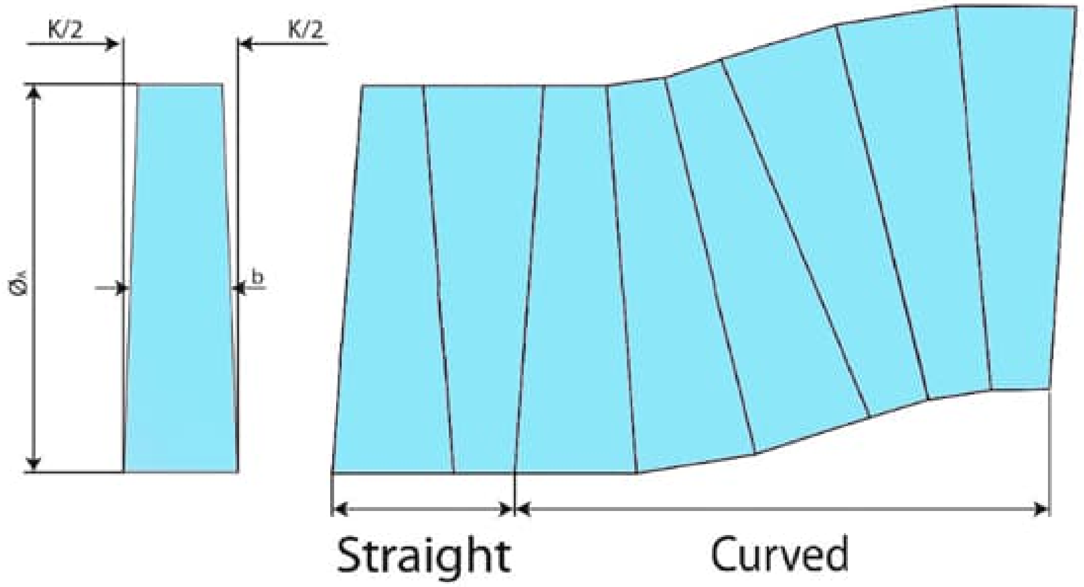
Parallel rings

Left and right rings



Universal rings

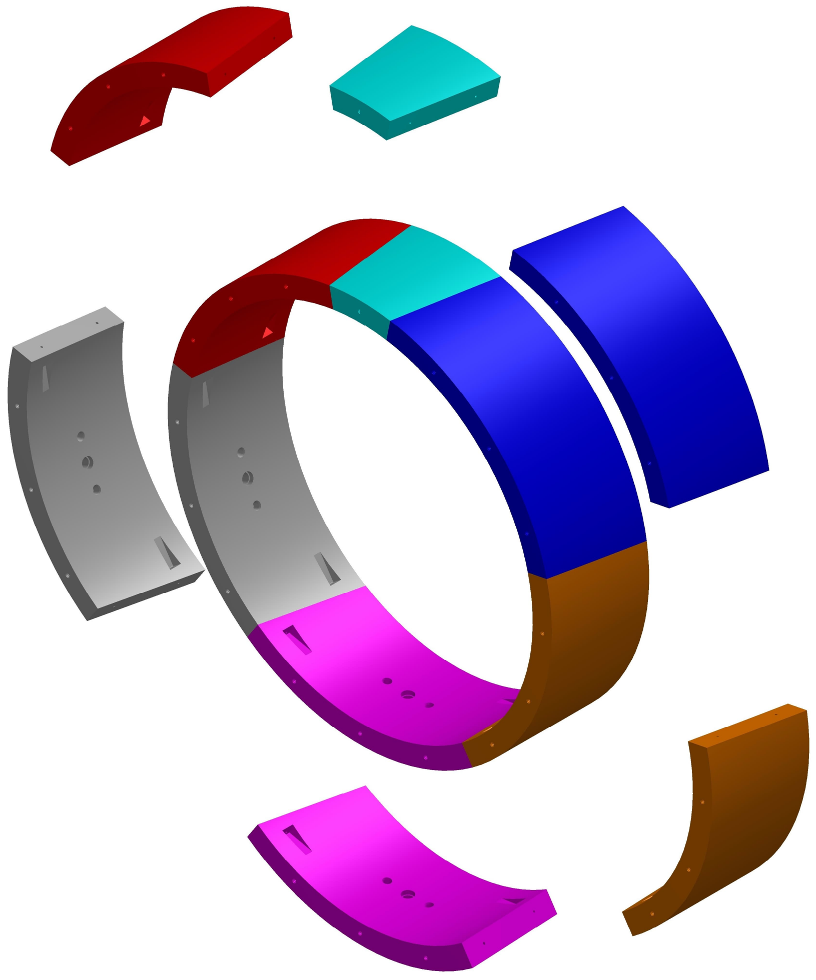
Best Practice



Ring Segmentation/Configuration

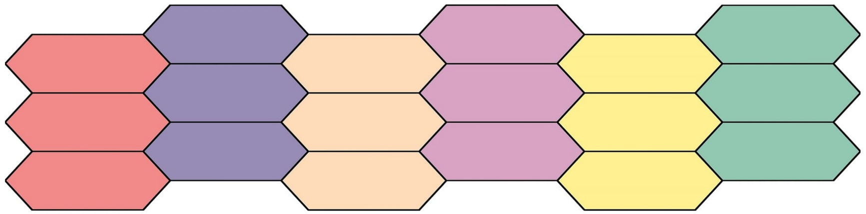
- Dia.: < 6 m → # segments = 6 (config.: **5+1**, 4+2)
- Dia.: 6-8 m → # segments = 7 (config.: **6+1**)
- Dia.: 8-11 m → # segments = 8 (config.: **7+1**, 6+2)
- Dia.: 11-14 m → # segments = 8 or 9 (config.: **8+1,** 8 equal (large key))
- Dia.: > 14 m → # segments = 10 or 12 (config.: **9+1**, 10 equal(large key))

Best Practice

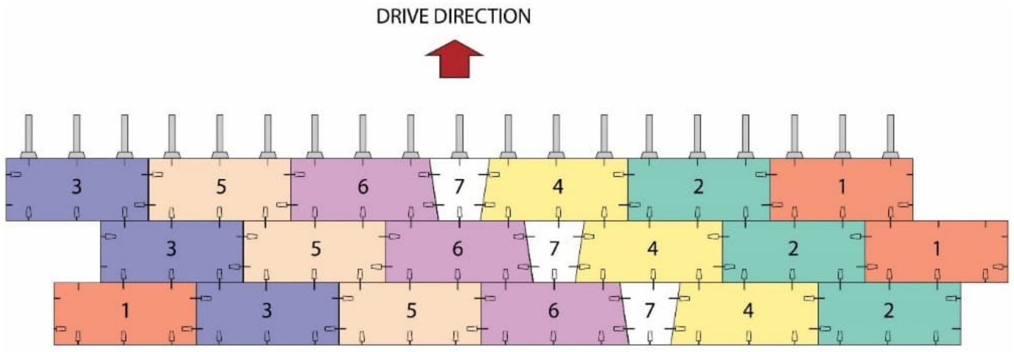


Segment Geometry

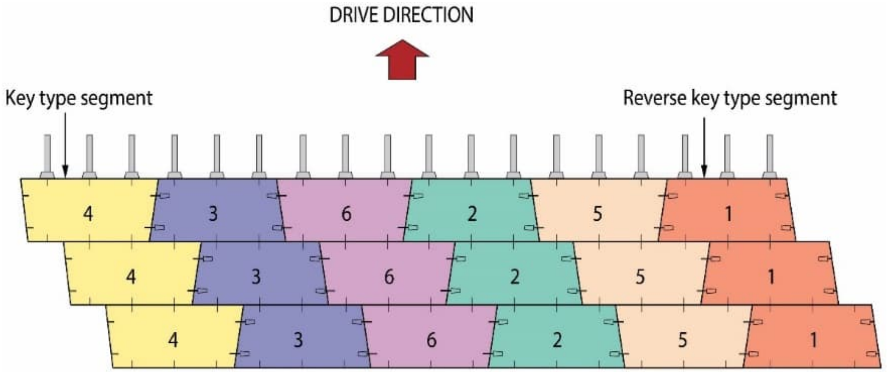
Developed Plan View of Rings



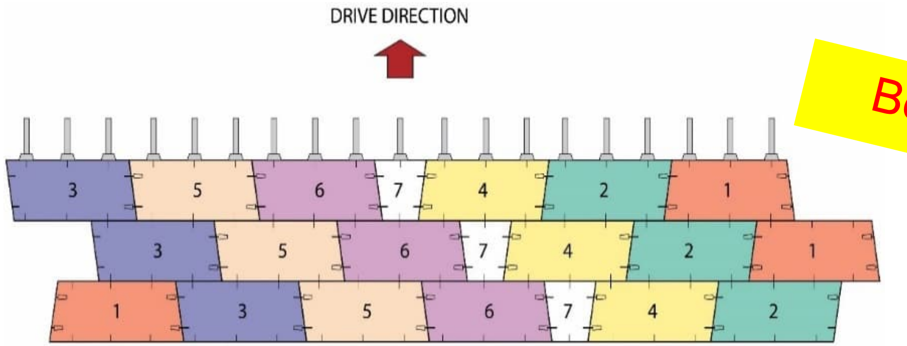
Hexagonal system
(oldest system)



Rectangular system
(has been used since 1980s)



Trapezoidal system
(has been introduced after 2000)



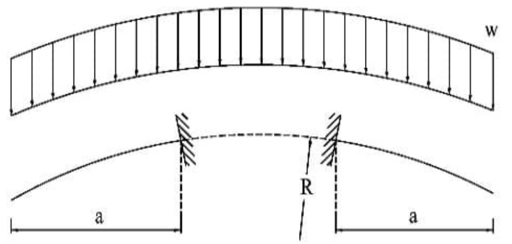
Best Practice

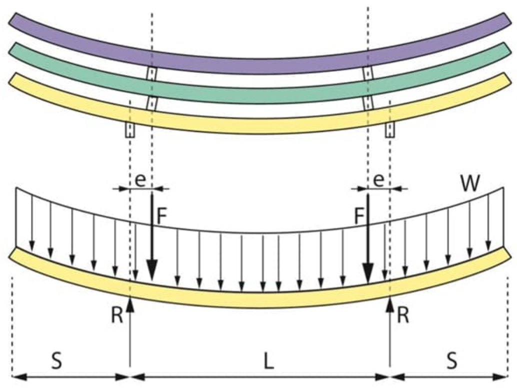
Rhomboidal system
(newest system)

Load Cases for Design of Precast Concrete Tunnel Segments Based on ACI 544.7R

Load case	**Required strength (U)**
Load case 1: stripping (demolding)	U = 1.4w
Load case 2: storage	$U = 1.4(w \pm F)$
Load case 3: handling	$U = 1.4(w \pm F)$
Load case 4: transportation	U = 1.4w
Load case 5: thrust jack forces	U = 1.0J (1.2 if max machine thrust is unknown)
Load case 6: tail skin grouting	$U = 1.25(w \pm P_{gr})$
Load case 7: secondary grouting	$U = 1.25(w \pm P_{gr})$
Load case 8: earth pressure and groundwater load	$U = 1.25(w \pm WA_p) \pm 1.35(EH + EV) \pm 1.5\ P_0$
Load case 9: longitudinal joint bursting	$U = 1.25(w \pm WA_p) \pm 1.35(EH + EV) \pm 1.5\ P_0$
Load case 10: additional distortion	$U = 1.4M_{distortion}$

Design for Production & Transient Stages

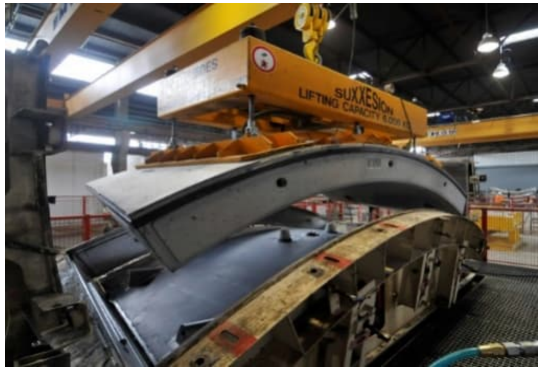




Load case number	Phase	Dynamic impact factor	Maximum unfactored bending moment
1	stripping (demolding)	-	$wa^2/2$
2	Storage	-	$w(L^2/8-S^2/2)+F_1e$ $w(S^2/2)+F_1e$
3	Handling (forklift)	2.0	$w(L^2/8-S^2/2)+F_2e$ $w(S^2/2)+F_2e$
	Handling (others)		$wa^2/2$
4	Transportation	2.0	$w(L^2/8-S^2/2)+F_2e$ $w(S^2/2)+F_2e$

Notes: F1 is self-weight of all segments completing a ring, excluding bottom segment; F2 is self-weight of all segments placed in one truck or rail car for transportation phase, excluding bottom segment.

Distances a, S and L are designed by Engineer.
Eccentricity specified by ACI 533.5R as e = 0.1m.



Stripping (demolding)

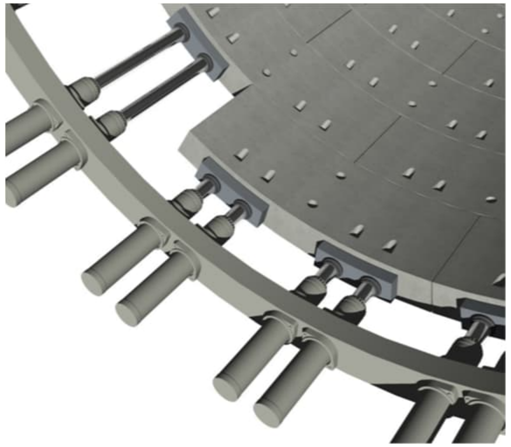
Storage

Handling (forklift)

Transportation

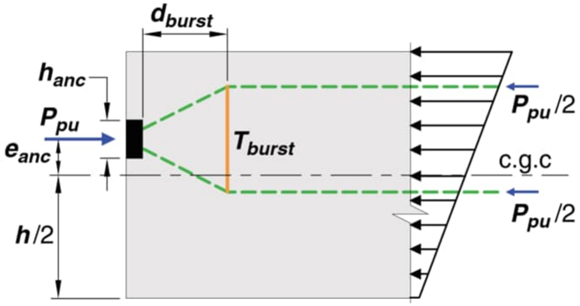
Design for Construction Stages

TBM Jack Forces

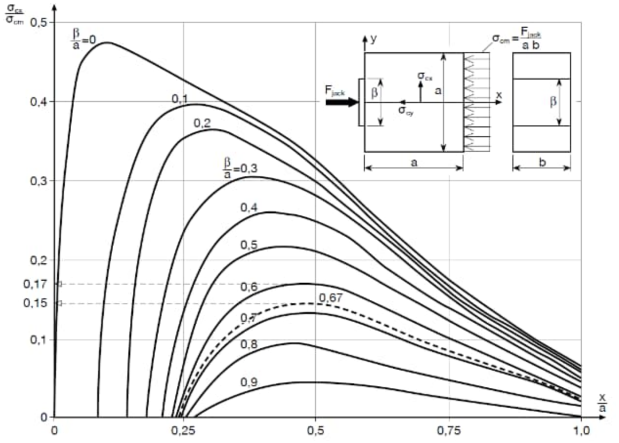


Design checks:

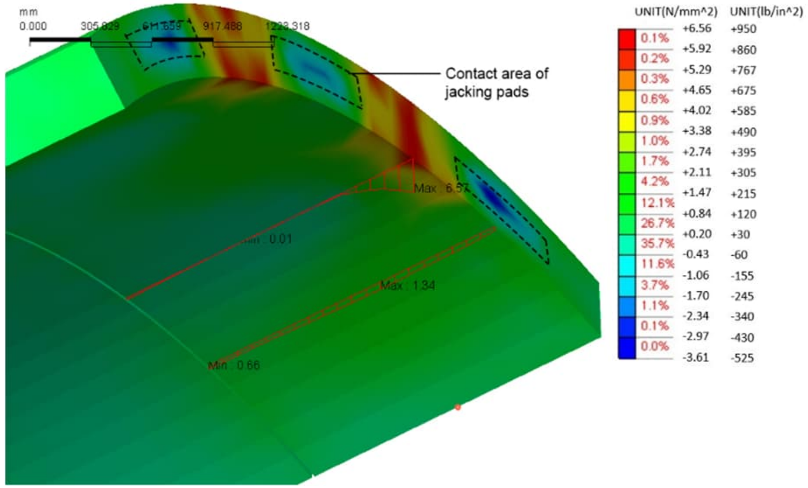
- Bursting tensile stresses
- Spalling tensile stresses
- Compressive stresses



Simplified Equations

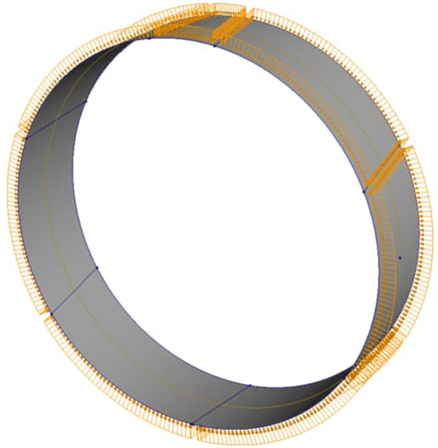


Analytical Methods (Iyengar, 1962)



Finite Element Methods (FEM): 2D/3D

Grouting Pressure

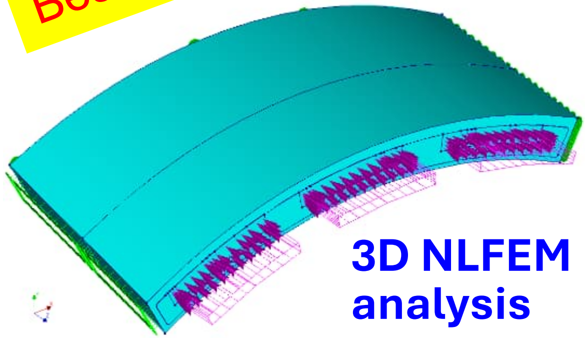


Tail Skin Grouting Pressure

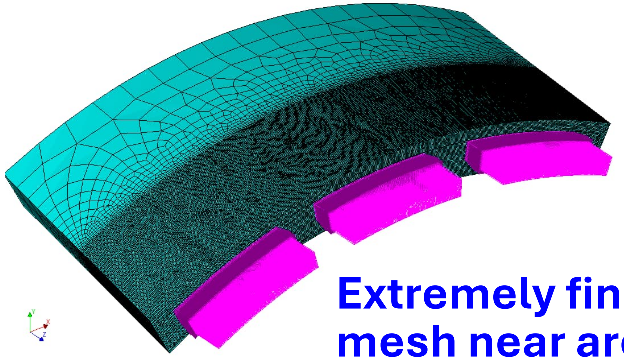
Secondary Grouting Pressure

Nonlinear Finite Element Analysis - Thrust forces

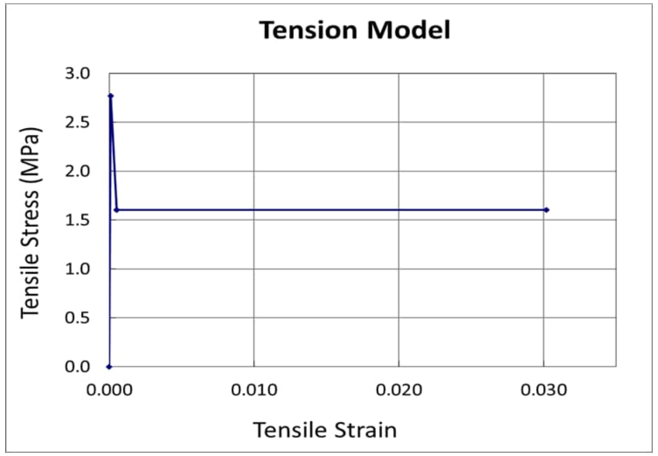
Best Practice



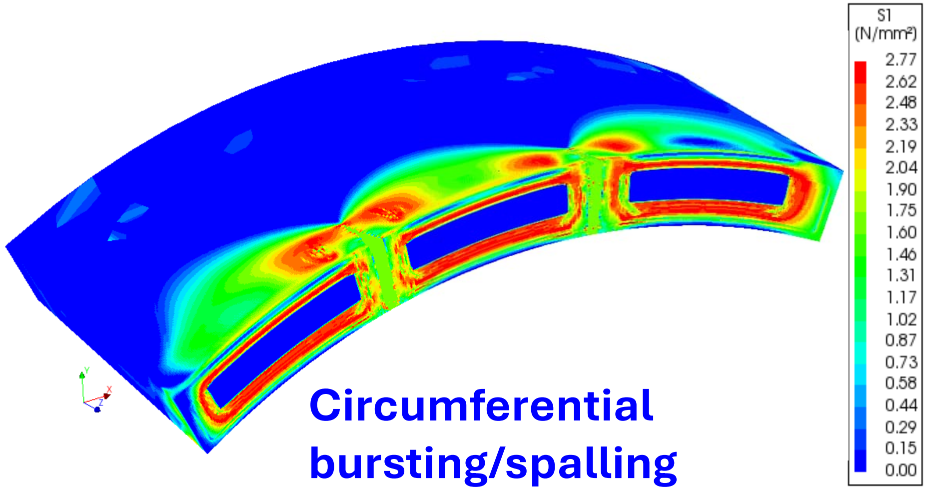
3D NLFEM analysis



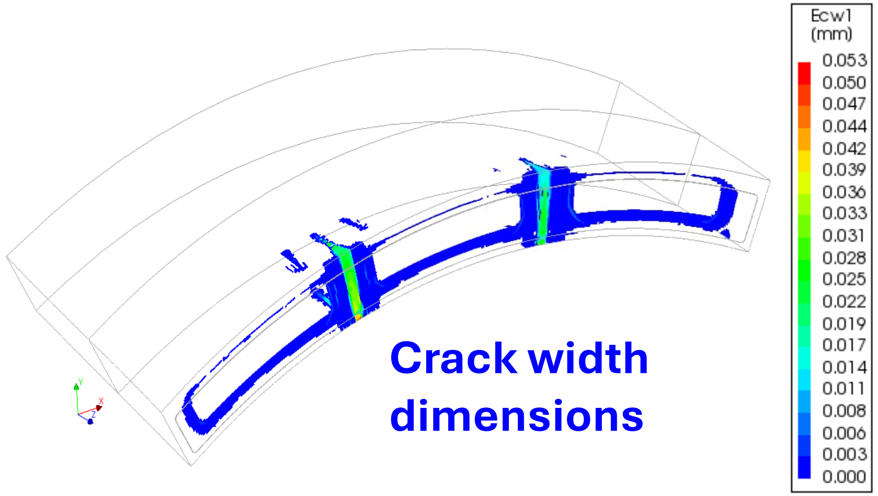
Extremely fine mesh near areas of interest



Multi-linear stress-strain FRC material model



Circumferential bursting/spalling stresses

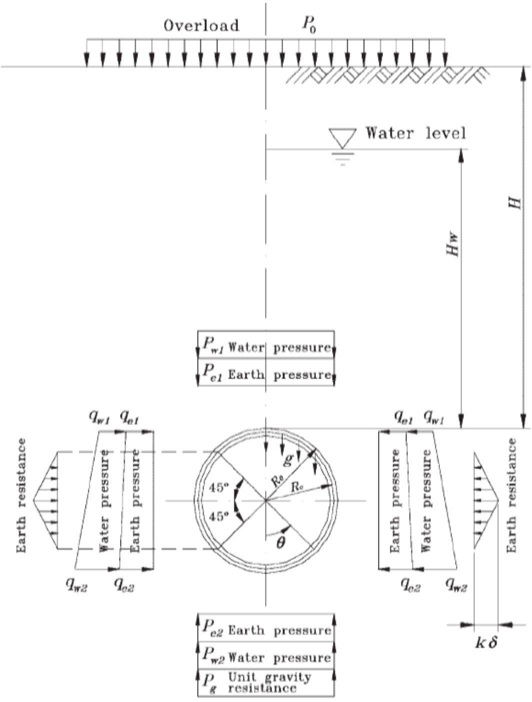


Crack width dimensions

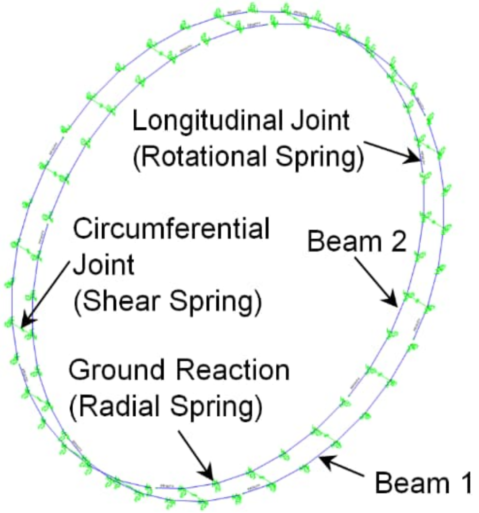
Design For Final Service Stages

Earth Pressure and Groundwater Load

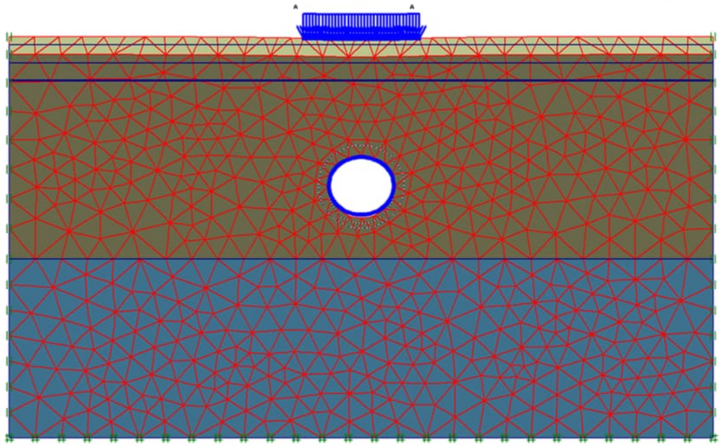
Elastic Equation Method



Beam-Spring Models

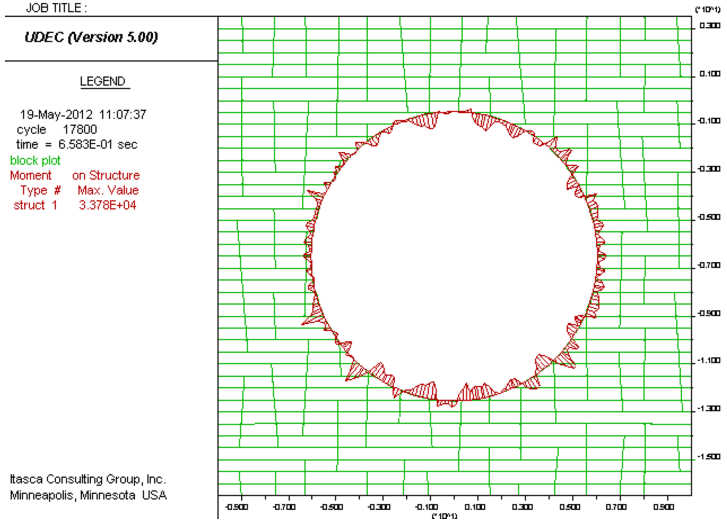


2D/3D Finite Element Methods (FEM)



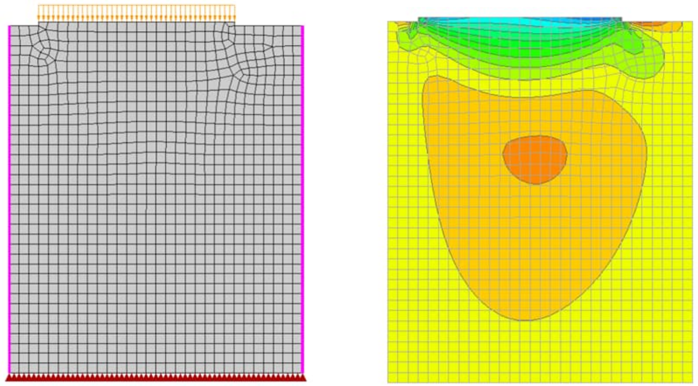
Soft Ground

2D/3D Discrete Element Methods (DEM)



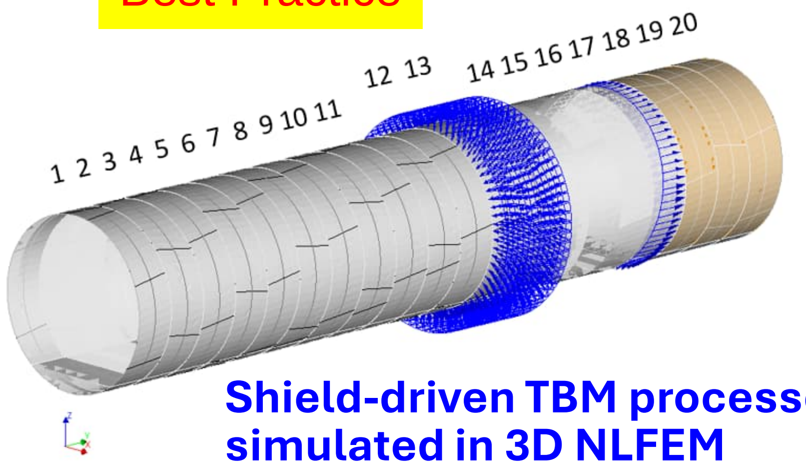
Fractured Rock

Longitudinal Joint Bursting

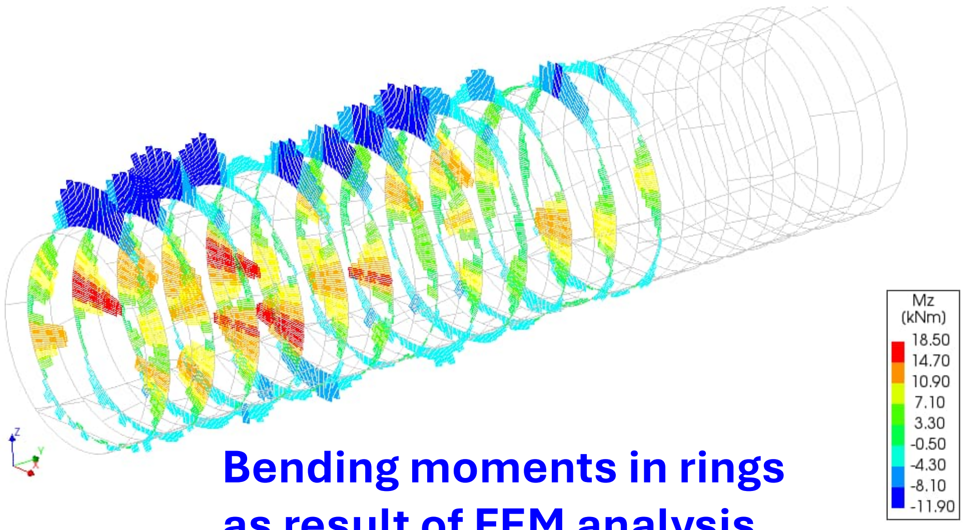


Design For Final Service Stages

Best Practice



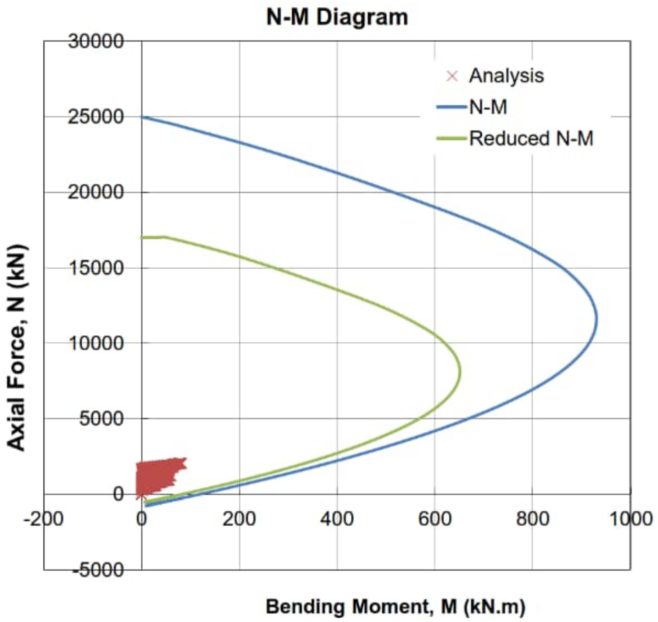
Shield-driven TBM processes simulated in 3D NLFEM



Bending moments in rings as result of FEM analysis

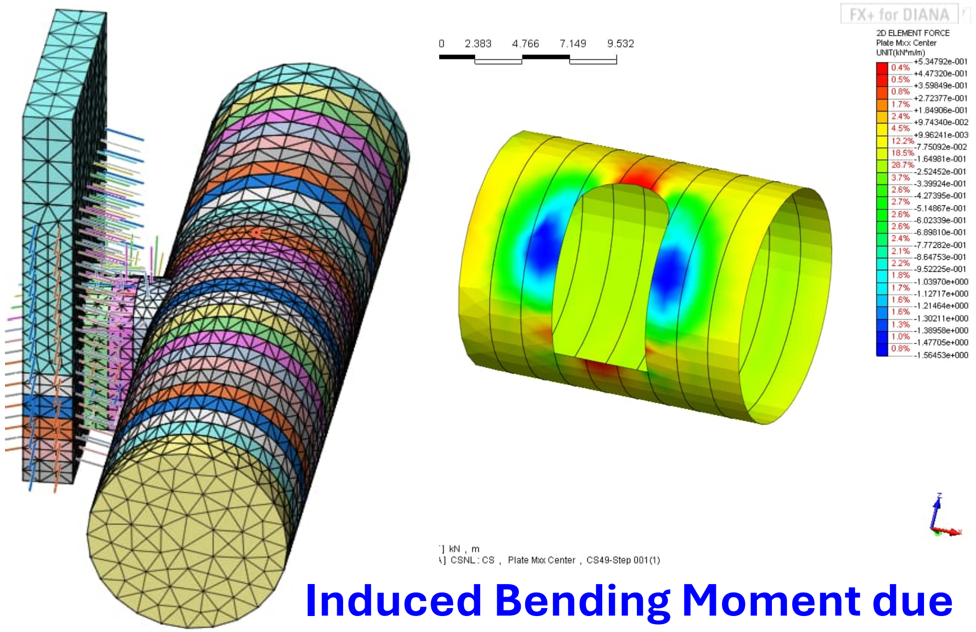
- Model rhomboidal segments w/tapered joints
- Nonlinear material model for FRC
- Janssen nonlinear line interface to simulate joints
- Staged simulation of boring in ring length
- Apply variable balancing face pressure
- Simulate conical shield w/ gap elements
- Apply variable grout pressure on most recent rings

Comparison of segment internal forces with M-N diagram

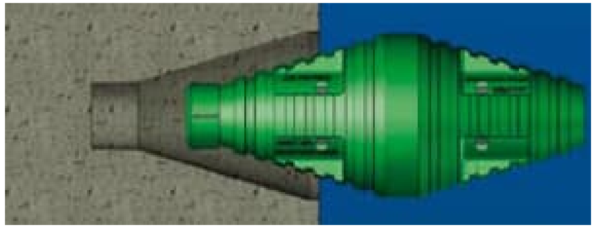


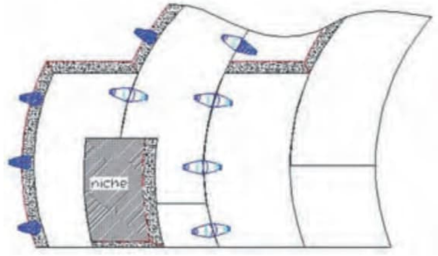
Breakouts & Additional Distortion

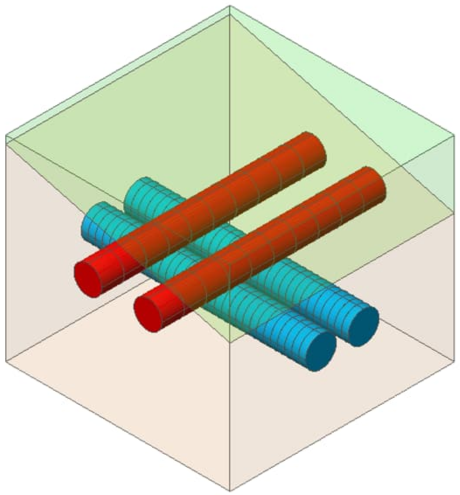
- **Tunnel in Areas of Intersection between Crosscuts and Main Tunnel**
- **External Loads due to Nearby Structures (other Tunnels /Piles)**



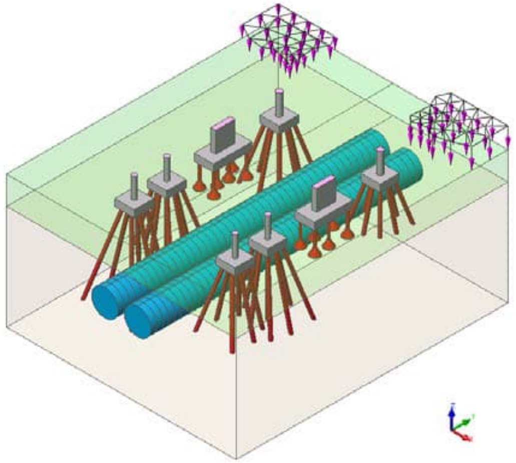
Induced Bending Moment due to Opening

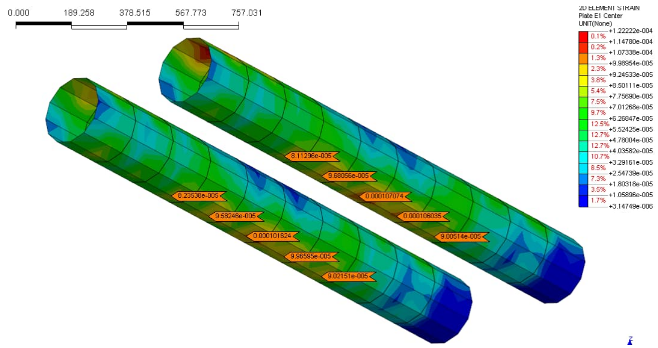






Tunnel Pile Foundation Interaction





Tensile Stress in Invert of Existing Tunnel

Detailed Design Considerations for Rebar Reinforced Segments

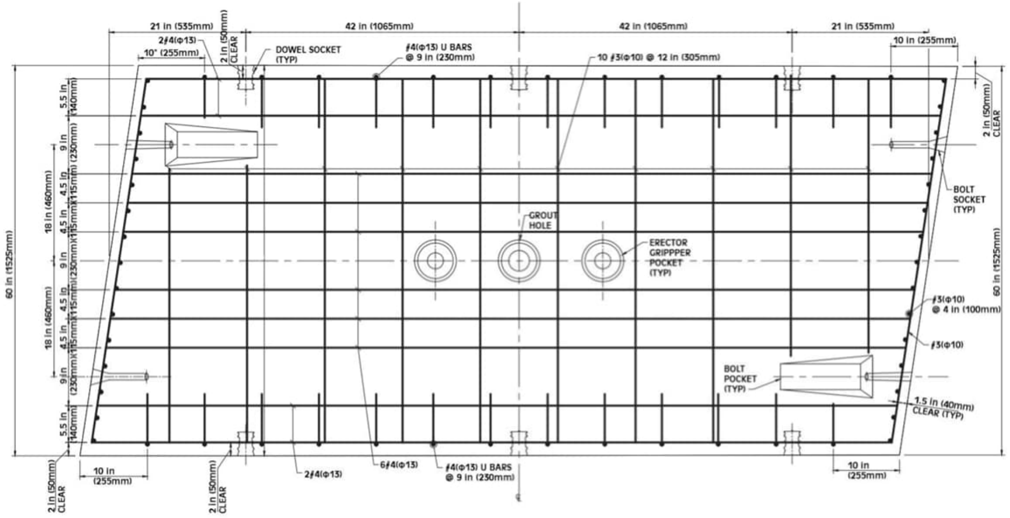
- **Reinforcement Types**
  - Rebar cage & Welded wire mesh
    main transverse bars
    longitudinal, ladders/U bars/ties

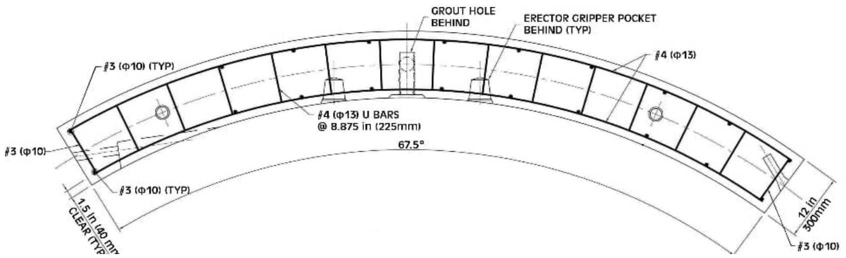
- **Concrete Cover**

	ACI 318	AFTES:2005	DAUB:2013	JSCE 2007	NEN 6720:1995	ÖVBB 2011/BS EN 1992-1-1:2004
Minimum cover, in. (mm)	1-1/2 (38)	Intrados and extrados: 1.2 (30)	Intrados and extrados: 1.6 (40)	Noncorrosive environment: 1 (25)	1.4 (35)	1 to 1.8 (25 to 45) depending on exposure conditions
		Other zones: 0.8 (20)	Joint faces and near bolt pockets: 0.8 (20)	Corrosive environment: 1.4 (35)		

- **Reinforcement Spacing**

Authority	Rebar Spacing (mm)	Comment
ACI 318 (2019)	25 457	Minimum bar spacing Maximum bar spacing
DAUB (2013)	100 to 150 90	Typical range Minimum clear bar spacing
AASHTO (2010) ÖVBB (2011) JSCE (2007)	1.25 × (max aggregate size) plus bar diameter	Minimum bar spacing





- **Concrete Compressive Strength**

Authority	Compressive Strength (Stripping)	Compressive Strength (28 day)
AASHTO DCRT-1-2010	Not provided	5000 psi to 7000 psi (34 MPa to 48 MPa)
RTRI 2008	Not provided	6000 psi to 8700 psi (42 MPa to 60 MPa)
ÖVBB 2011	1700 psi or 12 MPa (minimum)	5800 psi or 40 MPa (minimum)

Fiber Reinforcement

SFRC Segments:

- **More ductility**
- **Crack width reduction**
- **Enhanced impact resistance**
- **Reduce spalling of concrete cover**
- **Reduces steel materials**
- **Eliminate labor for rebar cage fabrication**
- **Eliminate space and time for handling and placing rebar cage**
- **Construction cost and time saving**
- **Improved durability**
- **Eliminate rebar carbonation and chloride corrosion**
- **Eliminate stray current corrosion**
- **Carbon footprint reduction**

RC

FRC

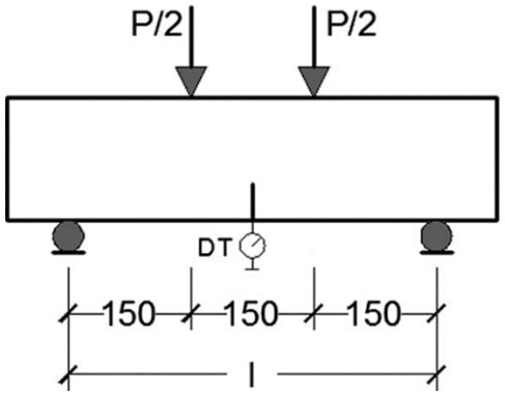
Projects with FRC Segments

- Tunnel function: water/wastewater, gas pipeline, power cable, subway, railway, and road tunnels
- Internal diameters:
  2.2-14.1m
- Thickness:
  15-40 cm
- Steel fiber dosage rates:
  25-60 kg/m^3
- Diameter-to-thickness:
  12-30

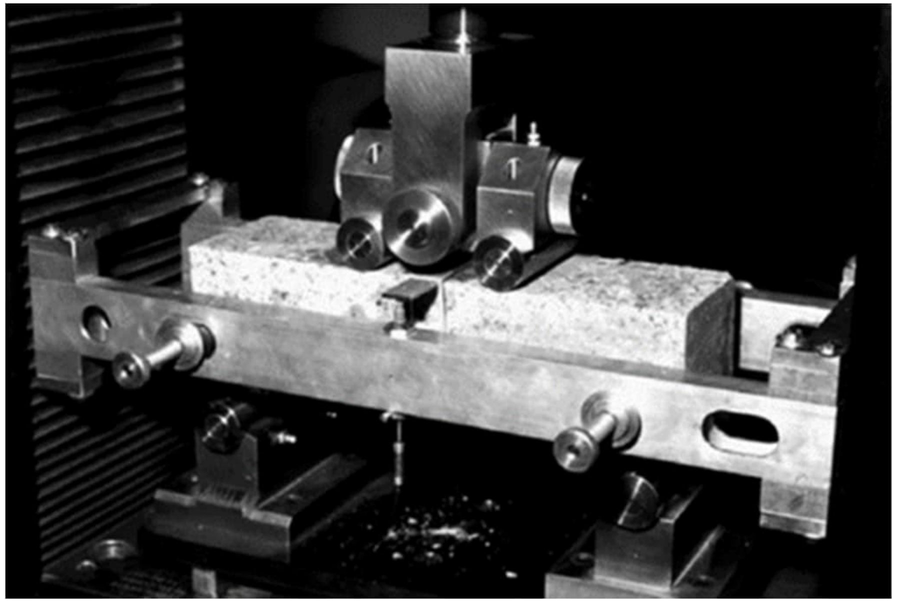
- Used in more than **100 tunnel projects**
- First FRC tunnel segments: Metrosud (**1982**)

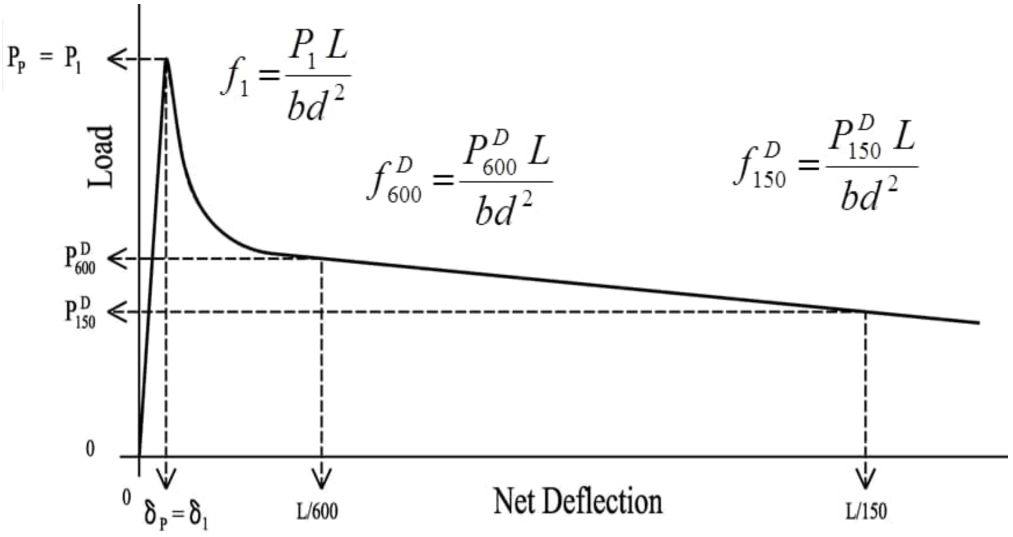
Tunnel Name	Year	Country	Function	D_i, ft (m)	h, in. (m)	D_i/h (-)	Steel Fiber Content, lb/yd³ (kg/m³)	Reinforcing bars used
Metrosud	1982	Italy	Subway	19 (5.8)	12 (0.30)	19.3	NA*	No
Fanaco	1989	Italy	Water Supply	10 (3.0)	8 (0.20)	15.0	NA*	No
Heathrow Baggage Handling	1993	England	Service	15 (4.5)	6 (0.15)	30.0	50 (30)	No
Heathrow Express	1994	England	Railway	18.7 (5.7)	9 (0.22)	25.9	50 (30)	No
Napoli metro	1995	Italy	Subway	19 (5.8)	12 (0.30)	19.3	67 (40)	No
Lesotho Highlands	1995	South Africa	Water Supply	15 (4.5)	12 (0.30)	15.0	84 (50)	No
Hachinger	1998	Germany	Water Supply	7.2 (2.2)	7 (0.18)	12.2	NA*	No
2nd Heinenoord	1999	Netherlands	Road	25 (7.6)	14 (0.35)	21.7	NA*	No
Jubilee Line	1999	England	Subway	15 (4.5)	8 (0.20)	22.3	50 (30)	No
Trasvases Manabi (La Esperanza)	2001	Ecuador	Water Supply	11.5 (3.5)	8 (0.20)	17.5	50 (30)	No
Essen	2001	Germany	Subway	24 (7.3)	14 (0.35)	20.9	NA*	No
Sorenberg	2002	Switzerland	Gas Pipeline	12.5 (3.8)	10 (0.25)	15.2	67 (40)	No
Canal de Navarra	2003	Spain	Water Supply	17.7 (5.4)	10 (0.25)	21.6	NA*	No

FRC Residual Strength



ASTM C1609 or EN 14561





Designation: C1609/C1609M – 19a

Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading)[1]

EUROPEAN STANDARD **EN 14651**

NORME EUROPÉENNE

EUROPÄISCHE NORM June 2005

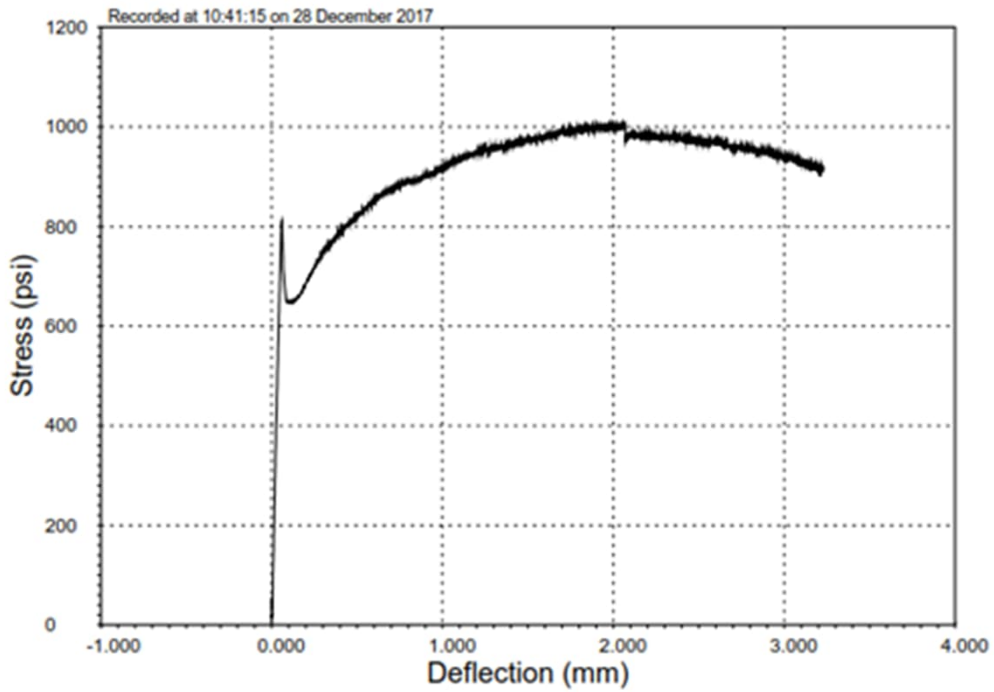
ICS 91.100.30

English version

Test method for metallic fibered concrete - Measuring the flexural tensile strength (limit of proportionality (LOP), residual)

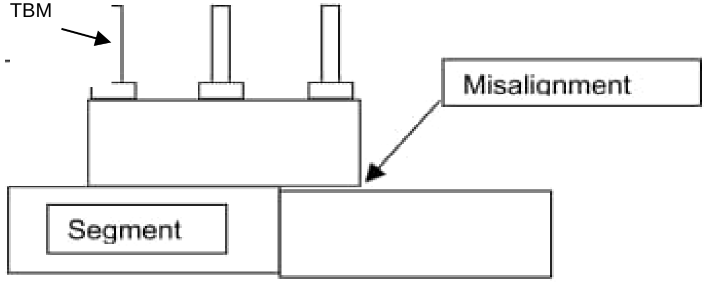
Innovative Solution: Double-Hooked End Fibers

High residual strength and low crack width



Full Scale Tests and Performance Evaluation

Full-scale bending test

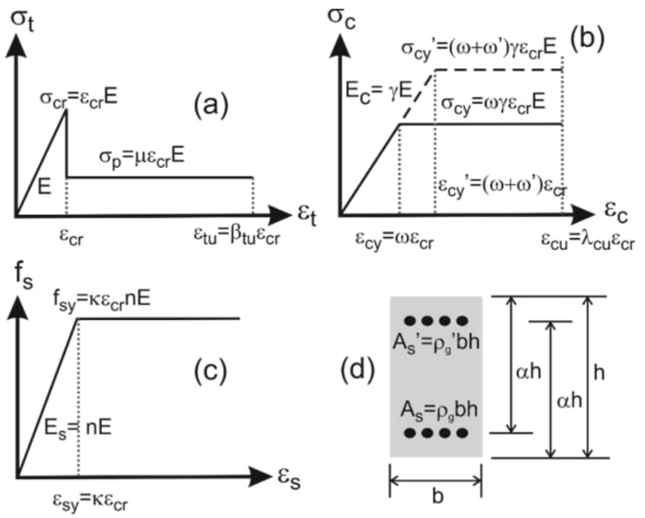


Full-scale point load test

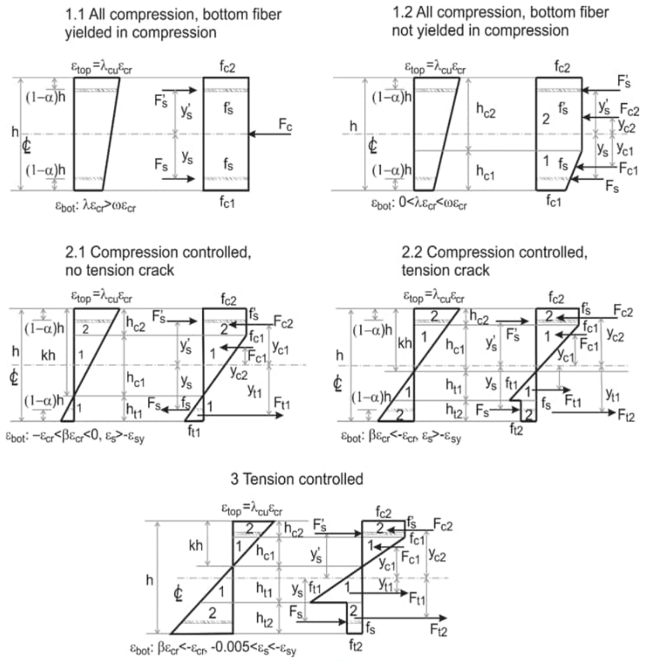
Cantilever load test

Closed-form Solutions for Interaction Diagram for Hybrid Reinforcement

Material Model



All Modes of Failure



Closed-Form Solution

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

where $k = \dfrac{\lambda_{cu}}{\beta+\lambda_{cu}}$, $C_1 = 6n\rho_g(2\alpha-1)(\chi-\kappa)$, $C_2 = 12\beta^2 n\rho_g(2\alpha+1)(\kappa-\chi) - 3\beta\gamma\omega(\omega-2\lambda_{cu})$

, $C_3 = \beta^2C_1 - \gamma\omega^2(2\omega-3\lambda_{cu})$, $C_4 = -\dfrac{\omega^3\gamma}{\lambda_{cu}^2} + \dfrac{3\omega^2\gamma}{\lambda_{cu}} - 3\omega\gamma + \beta$, $C_5 = -\dfrac{1}{2}(\dfrac{3\omega^2\gamma}{\lambda_{cu}} - 6\omega\gamma + \beta)$,

$C_6 = 3n\rho_g(2\alpha-1)(\chi-\kappa) - \dfrac{\beta}{2}$, $C_7 = -\dfrac{\omega-3\lambda_{cu}}{\lambda_{cu}^2}\gamma\omega^2 - 3(\gamma\omega+\mu) - \dfrac{6\mu-3}{\beta} + \dfrac{3\mu-2}{\beta^2}$,

$C_8 = -\dfrac{3\gamma\omega^2}{2\lambda_{cu}} + 3(\gamma\omega+\mu) + \dfrac{18\mu-9}{2\beta} + \dfrac{6\mu-4}{\beta^2}$, $C_9 = -3n\rho_g(2\alpha-1)$, $C_{10} = -\dfrac{6\mu-3}{2\beta} - \dfrac{3\mu-2}{\beta^2}$,

$C_{11} = C_{10} - C_9(\kappa+\lambda_{cu})$, $C_{12} = C_9(1-\alpha)\lambda_{cu}$

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

Interaction Diagram for Hybrid Reinforcement

Materials and Structures
February 2018, 51:35 | Cite as

Interaction diagrams for design of hybrid fiber-reinforced tunnel segments

Authors | Authors and affiliations

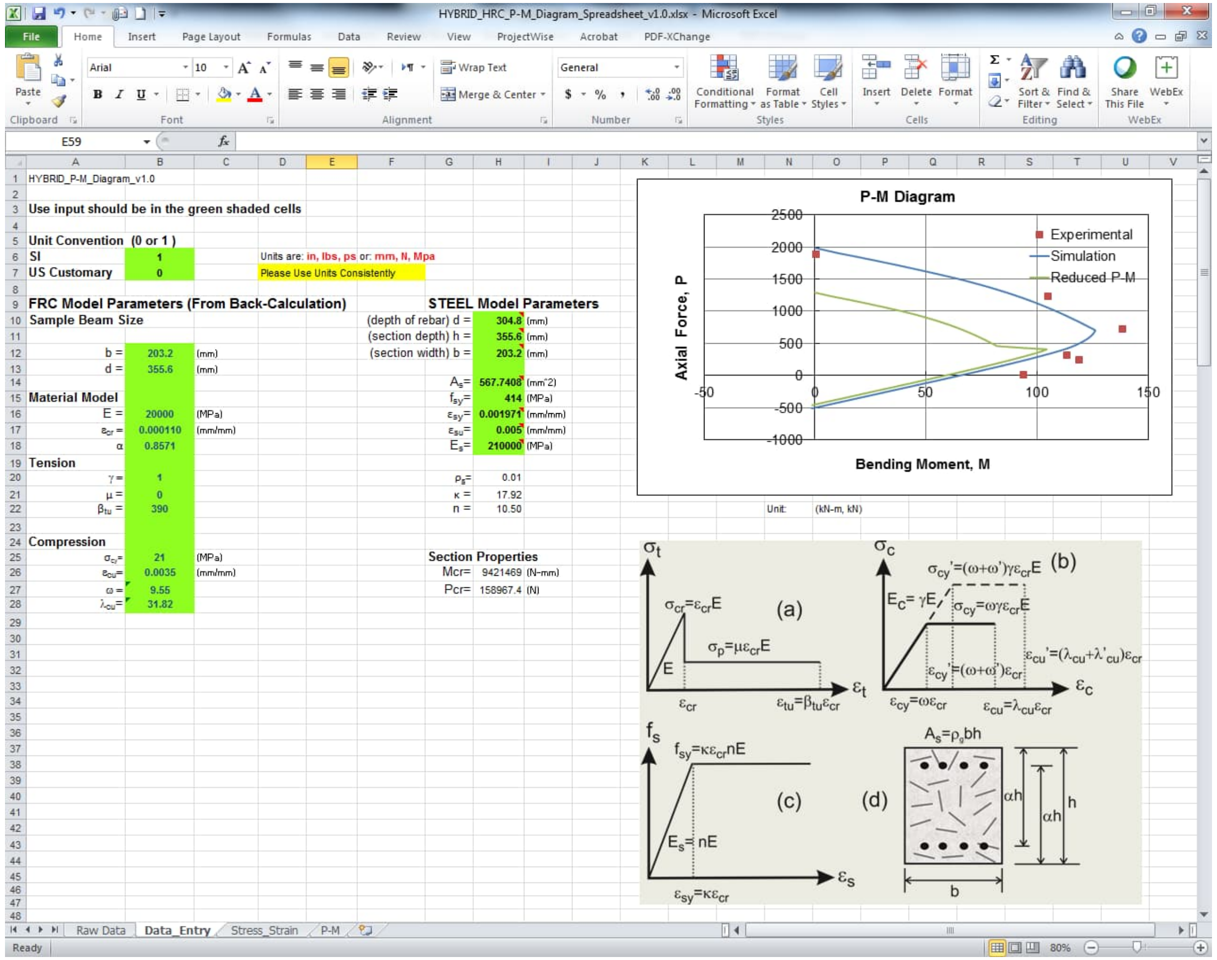
Yiming Yao, Mehdi Bakhshi, Verya Nasri, Barzin Mobasher

Original Article
First Online: 12 February 2018

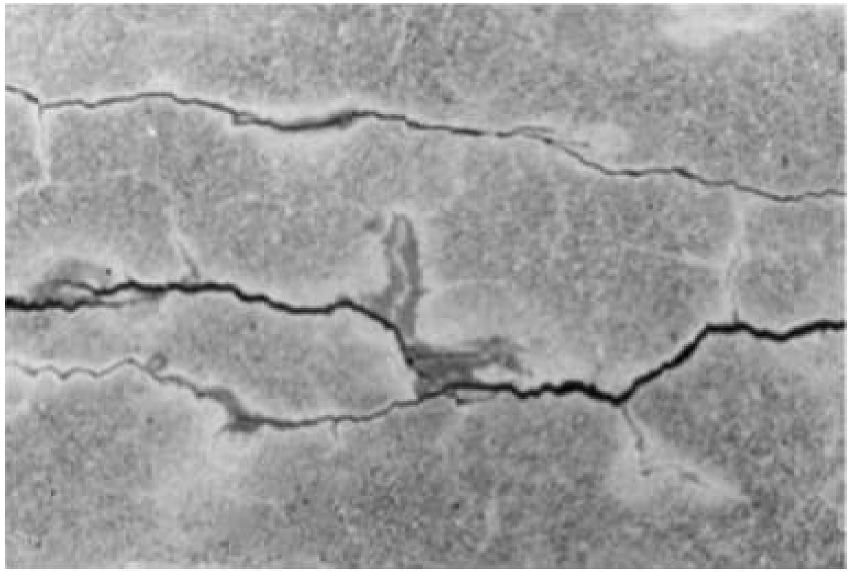
- Based on Paper an Excel Spreadsheet Developed for Easy Use by Engineers
- Available on Research Gate for Free Download: https://doi.org/10.13140/RG.2.2.14437.09440

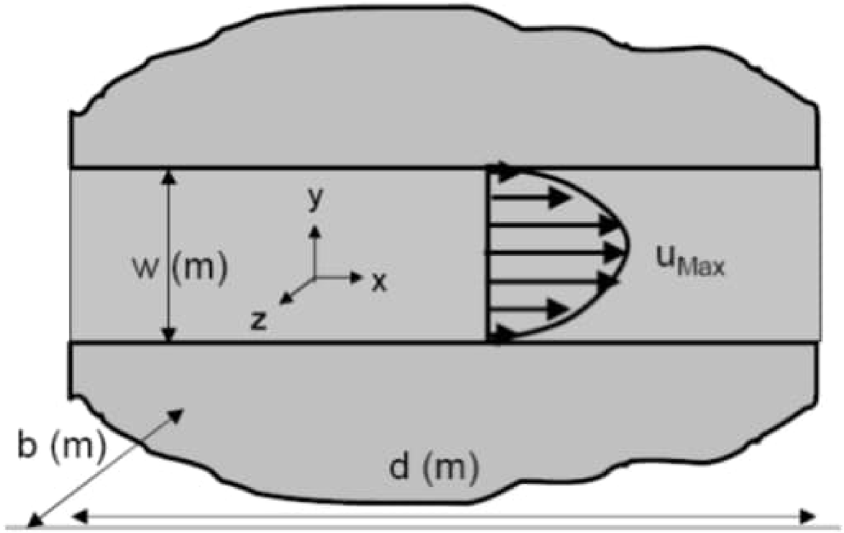
A Spreadsheet-Based Analytical Procedure for Design of Hybrid Fiber Reinforced Concrete Tunnel Lining Segments

Data · February 2018 with 56 Reads
DOI: 10.13140/RG.2.2.14437.09440



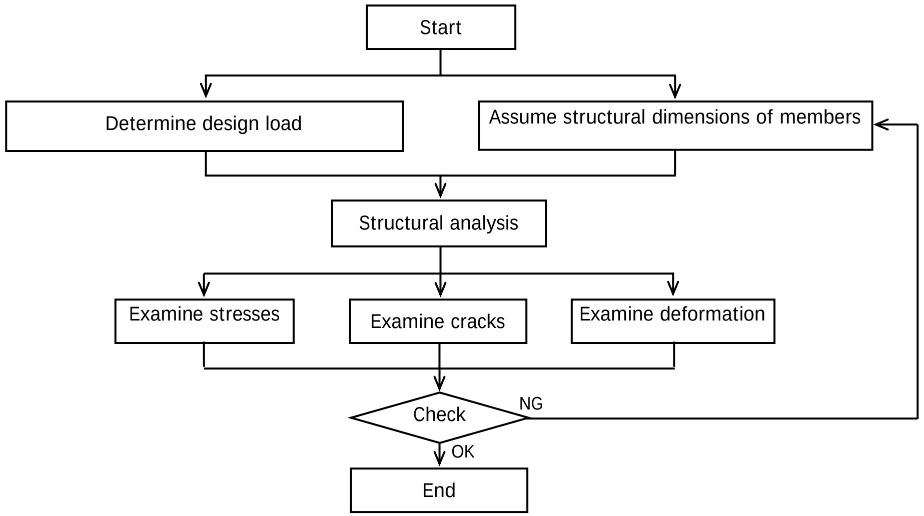
Design for Serviceability Limit State





Crack Width vs. Infiltration

SLS Checks Flowchart (JSCE 2007)



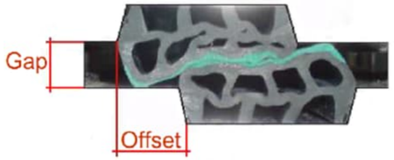
Allowable crack width for tunnel segments (ÖVBB, 2011)

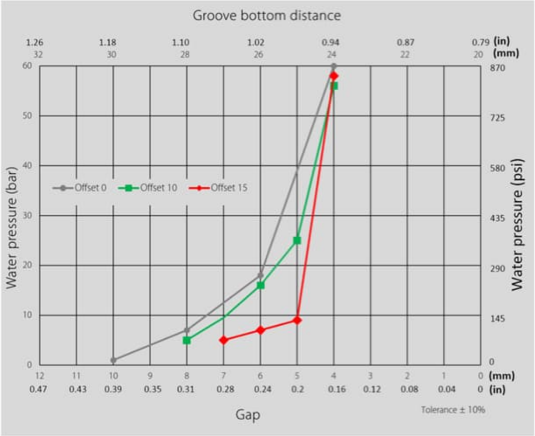
Requirement Class	Designation	Application	Requirement	Allowable Crack Width
AT1	Largely dry	- One-pass lining with very tight waterproofing requirements - Portal areas	Impermeable	0.20 mm (0.008 in)
AT2	Slightly moist	- One-pass lining for road and railway tunnels with normal waterproofing requirements (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)

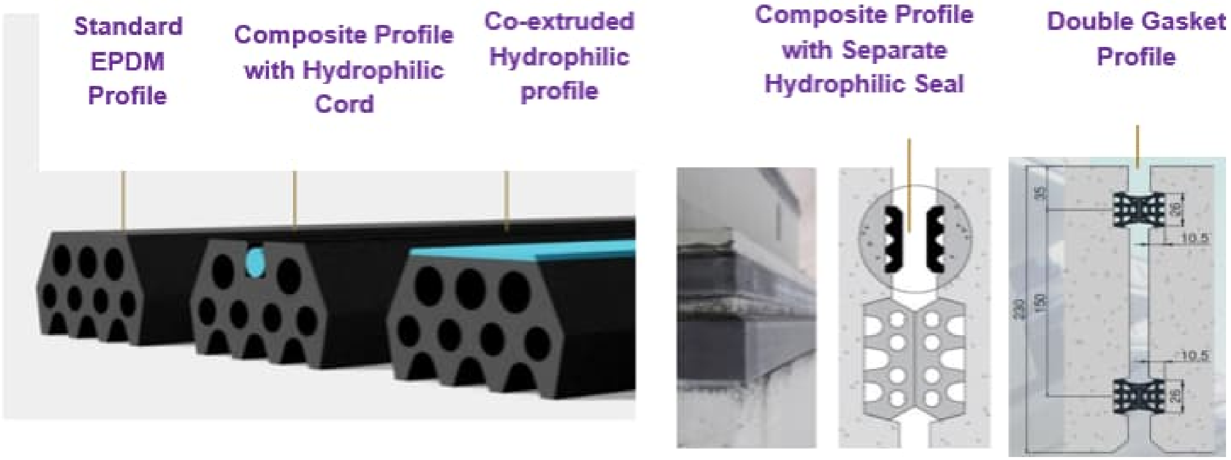
Design of Segment Gaskets

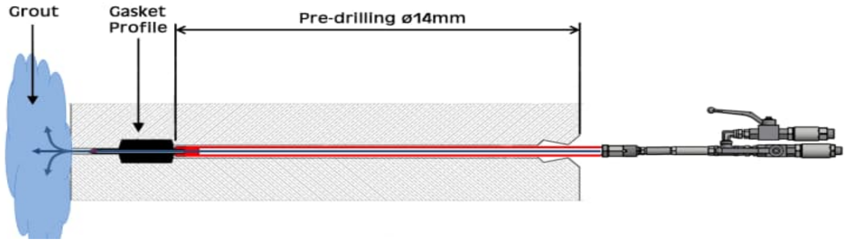
- **Materials: EPDM (ethylene propylene diene monomer)**
- **Gasket profiles for intended water pressure**
- **Gasket relaxation & factor of safety (often 2)**
- **Design acc. required tolerances (gap & offset)**
- **Load-deflection for design of connection devices**
- **New developments in gaskets & repair injection**

Designer specifies gasket









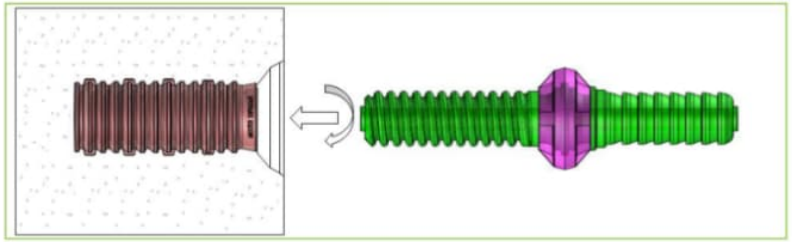
Connection Devices and Fastening Systems

Flat Joint (Most Favorable for Load Transfer and Sealing)

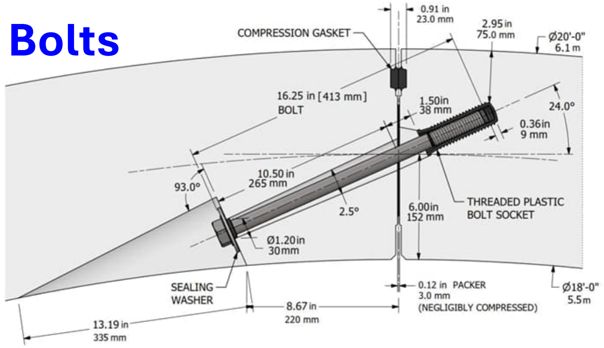
Bolts (Longitudinal Joints), Dowels (Circumferential Joints)

New dowels

The Axis with the Thread is placed by hand in the Segment to Assembly



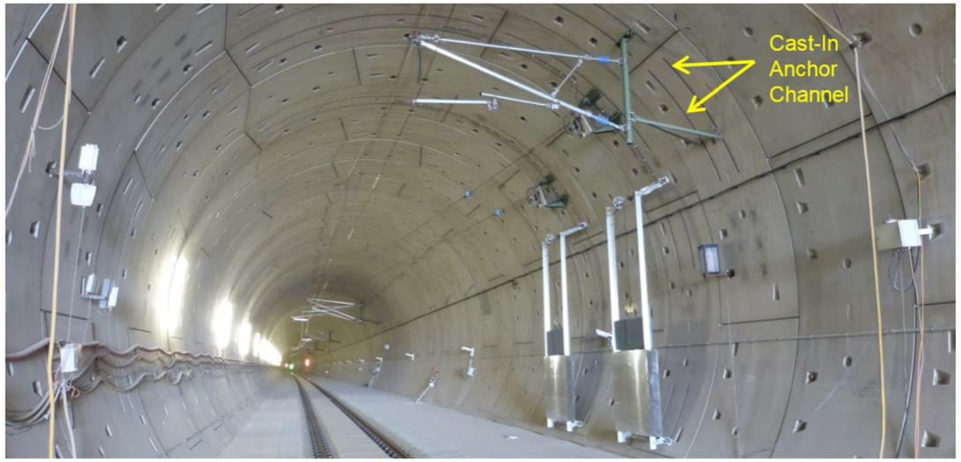
Bolts



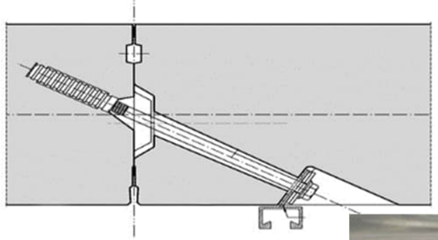
Designer specifies connections

- **Bolts**
- **Dowels**
- **Post-installed anchors without drilling**
- **Cast-in anchors**
- **Tension rods**

Cast-in anchors



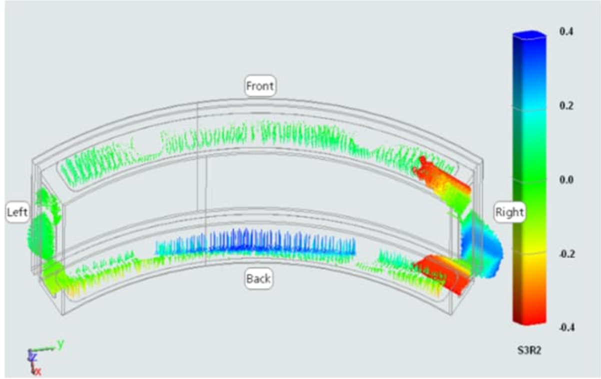
Post-installed anchors

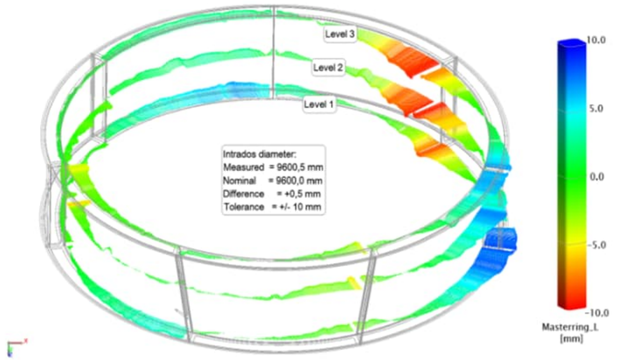


Tension rods

Tolerances, Measurements & Dimensional Control

- Tolerances are <u>extremely tight</u>.
- Production tolerances
  - segment (0.5 to 8mm)
  - formwork (0.2 to 1.5mm)
- Test ring tolerances
- Measurement & Dimensional Control: Methods & frequency
- Construction tolerances

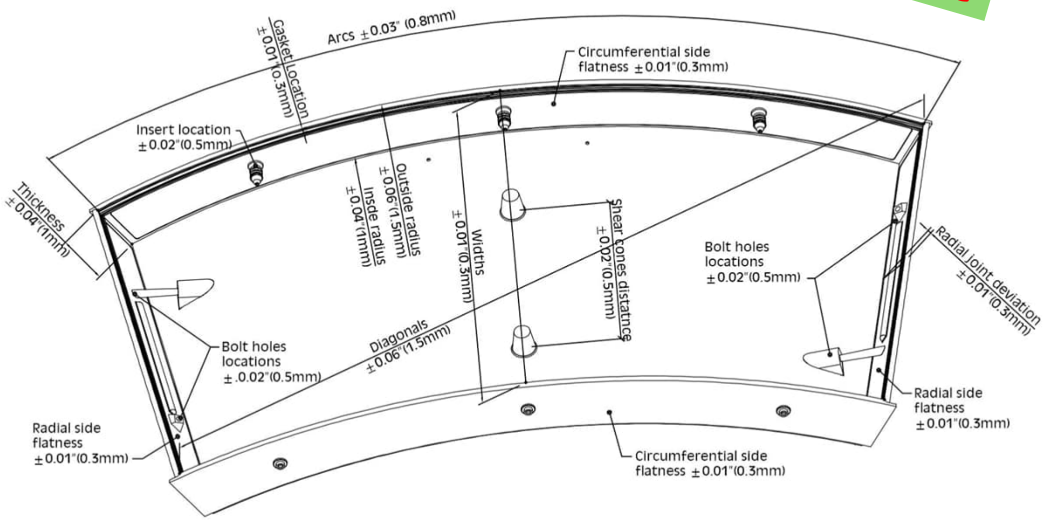




Example

laser interferometer has both speed & accuracy

Best Practice



Controlling formwork tolerances is more helpful than controlling segment tolerances

Repair of Defects

- **Classes of Damage/Defect & Description**
- **Location and Extent of Defects**
- **Remedy and Repair Procedure**

*REPAIR PROCEDURE 1

MATERIAL: Type II cement
Silica sand
Mix at the rate of 1 part cement to 2.5 parts sand, with 0.4 *w/c*.

PROCEDURE:

1. Clean and wire brush off all dirt and dust from areas to be filled. Dampen repair area with water.
2. Measure and mix cement and sand with water in accordance with the instructions. Do not retemper mixture with water.
3. Fill the repair area and sack rub the finished surface immediately.

REPAIR PROCEDURES 2A & 2B

MATERIAL 2A To be used in areas less than 1½ in. (40 mm) long and 9/16 in. (15 mm) deep.
Epoxy mortar.
The properly mixed epoxy can be mixed with oven-dried silica sand as recommended by the manufacturer to obtain desired consistency. Mix until uniform consistency is achieved. Do not mix quantities larger than can be used within the work life of the material..

PROCEDURE:

1. Repair area should be dry. Remove any dust, laitance, grease, oils, or loose materials from the area to be repaired and wire brush.
2. Place mixed materials into the void, working the material by trowel or spatula to ensure bond. Strike off level to existing concrete.
3. Cure the epoxy mortar at a minimum temperature of 40°F (4°C).
4. Ensure accurate profile by removing any excess mortar by grinding.

Table 13—procedures for repair of segment defects*

Class of damage/defect	Description	Location	Extent	Remedy
Class A1 nonstructural patching	Blow holes and air voids	All locations except gasket groove, intrados, and caulking groove	Diameter > ¾ in. (20 mm) or Depth > 3.8 in. (10 mm)	Repair Procedure 2A
Class A2 nonstructural patching		Intrados, caulking groove, and gasket groove	Diameter > ¾ in. (20 mm) or Depth > 3/16 in. (5 mm)	Repair Procedure 2A
Class B nonstructural patching		Gasket groove	Depth or Diameter > 3/32 in. (2 mm)	Repair Procedure 1
Class C nonstructural cosmetics	Chipping & spalling	Gasket groove edges	Area: Length > 3/4 in. (20 mm) Depth > 3/16 in. (5 mm)	Use Procedure 2A or 2B
Class D nonstructural cosmetic		All locations except gasket groove edges	Area: Length>1½ in. (40 mm) or Depth > 9/16 in. (15 mm)	Use Procedure 2A or 2B
Class E1 surface irregularities	Local protrusions	Non-Formed surfaces	> 3/16 in. (5 mm)	Stone Rubbed or Ground
Class E2 surface irregularities		Joint faces	>0.04 in. (0.5 mm) high	Stone Rubbed or Ground, Check Mold
Class F localized surface cracking and crazing	Minor non-structural local defects	Gasket groove & extrados edge on joint faces	Cracks > 0.008 in. (0.3 mm) wide to be assessed by examination	Review for approval of repair procedure

Concrete Mixture for Precast Segments

Optimum mix design:

– **High early-age strength (15 MPa) in 5-6 hrs**

– **High performance and a durable concrete lining for 125 years intended service life**

Mix Ingredients/Characteristics	Quantity
Cement (kg/m^3)	356
Silica Fume (kg/m^3)	24
Slag or GGBFS (kg/m^3)	107
Fine Aggregate (kg/m^3)	765
Coarse Aggregate (kg/m^3)	1026
Water (kg/m^3)	160.6
Superplasticizer (liter/m^3)	3.811
Air Entraining Admixture (liter/m^3)	0.15
Steel Fiber (kg/m^3)	42
Micro Polypropylene Fiber (kg/m^3)	2.0
w/cm Ratio	0.33
Total Unit Mass (kg/m^3)	2485

- **Total cementitious material**: 485 kg/m^3
- **maximum aggregate size** as 14 mm

Durability Tests Satisfying 125yrs Service Life:

Tests	Results
Chloride ion diffusion coefficient (ASTM C1202)	213-314 coulombs
Surface electrical resistivity (AASHTO TP-95-14)	155.1-171.3 kΩ.cm
Carbonation resistance (CEN/TS 12390-10)	0mm after 120 days exposure
Shrinkage (CSA A23.2–21C-14)	0.021-0.028% at 28 days
Air void test (ASTM C457)	Air content: 5.0-5.2% Air spacing factor: 0.154-0.215 mm

Mechanical Tests

Tests	Results
Compressive strength	At 28 days: 60.2-69 MPa At demolding: 14.6-27 MPa
Tensile splitting strength	7.41-7.98 MPa
Flexural beam test	LOP: 8.0 MPa $f_{R,3}$: 7.76 MPa

Durability

- **Durability: Degradation Mechanisms**
  - Corrosion, Sulfate attack, Acid attack, Alkali-aggregate reaction, Freeze & Thaw, stray current corrosion

- **Prescriptive Approaches:**
  - ACI 318 or EN 206-1/EN 1992-1-1

- **Input to these methods:**
  - Environmental exposure classes

- **Output of these methods:**
  - Required characteristics of concrete
    - concrete strength
    - maximum w/c ratio
    - min cement content

- **Performance-Based Approaches**

Example: EN Exposure Classes for Carbonation

2 Corrosion induced by carbonation		
Where concrete containing reinforcement or other embedded metal is exposed to air and moisture, the exposure shall be classified as follows:		
XC1	Dry or permanently wet	Concrete inside buildings with low air humidity; Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact; Many foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity; External concrete sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2

EN 206-1 Required Characteristics

	Exposure classes																	
	No risk of corrosion or attack	Carbonation-induced corrosion				Chloride-induced corrosion						Freeze/thaw attack				Aggressive chemical environments		
						Sea water			Chloride other than from sea water									
	X0	XC 1	XC 2	XC 3	XC 4	XS 1	XS 2	XS 3	XD 1	XD 2	XD 3	XF 1	XF 2	XF 3	XF 4	XA 1	XA 2	XA 3
Maximum w/c[c]	-	0,65	0,60	0,55	0,50	0,50	0,45	0,45	0,55	0,55	0,45	0,55	0,55	0,50	0,45	0,55	0,50	0,45
Minimum strength class	C12/15	C20/25	C25/30	C30/37	C30/37	C30/37	C35/45	C35/45	C30/37	C30/37	C35/45	C30/37	C25/30	C30/37	C30/37	C30/37	C30/37	C35/45
Minimum cement content[c] (kg/m^3)	-	260	280	280	300	300	320	340	300	300	320	300	300	320	340	300	320	360
Minimum air content (%)	-	-	-	-	-	-	-	-	-	-	-	-	4,0[a]	4,0[a]	4,0[a]	-	-	-
Other requirements	-	-	-	-	-	-	-	-	-	-	-	Aggregate in accordance with EN 12620 with sufficient freeze/thaw resistance				-	Sulfate-resisting cement[b]	

Carbon Footprint Reduction

Concrete Mix

90 % of CO2 in the mix comes from **cement** and the **Supplementary Cementitious Materials (SCMs)**

$$Embodied\ Carbon = \sum material\ quantities \times material's\ CO_2eq\ Factor$$

Using high SCM mix* → CO_2 emission reduction of 45%

	CO_2 eq factor
Portland Cement	0.92
Portland Limestone Cement (PLC)	0.85
Slag	0.15
Fly Ash	0.093
Silica Fume	0.014

Optimizing aggregates

Traditional Aggregate Design → **ASTM standard** based on coarseness factor charts

Current Aggregate Design → **Tarantula Curve** based on all workability tests including slump, the box test, ICAR Rheometer, visual observation, and float test

↓

CO_2 emission reduction of **14%**

* A mix is considered high SCM when slag is greater than 50% of total cementitious materials or fly ash is greater than 30% of total cementitious materials or slag is greater than 40% and fly ash is greater than 20% of total cementitious materials

Carbon Footprint Reduction

Concrete Reinforcement

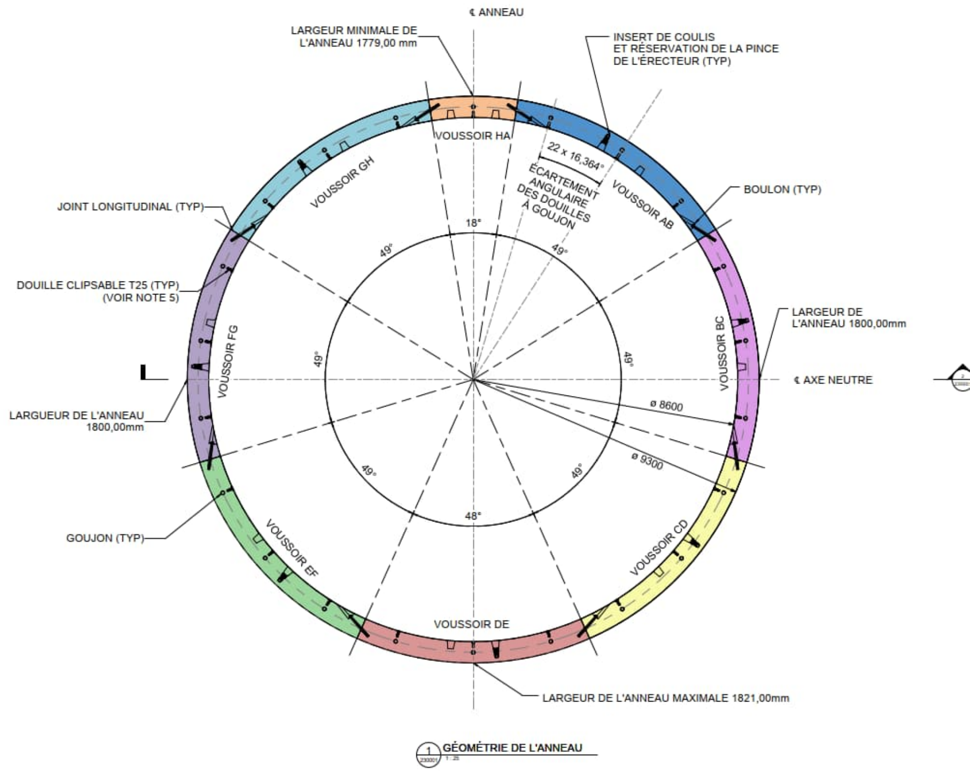
	Steel rebars	Steel fibers (Dramix 4D 80/60BGP)
Mass in unit concrete volume of tunnel segments	90 to 160 kg/m³	40 kg/m³
CO_2eq factor	1.85	0.88

Mass: 55% to 75% less

CO_2eq factor: 50% less

Carbon emission per volume	166.5 to 296 kg/m³	35.2 kg/m³

CO_2 emission reduction of **4.7 to 8.4 times**

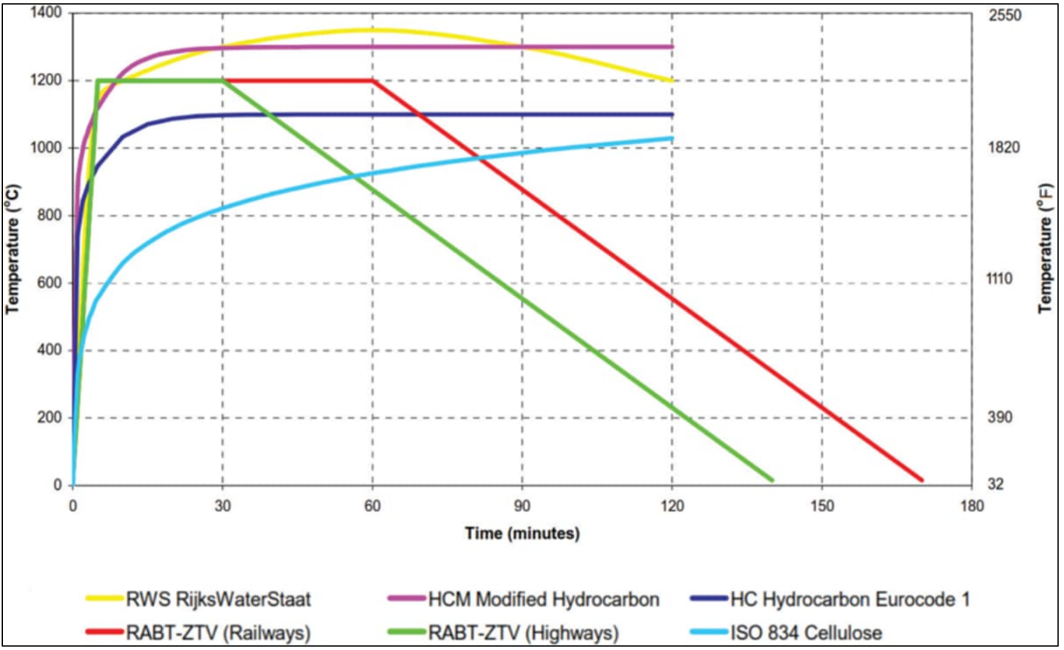


Methods to Reduce Carbon Footprint of TBM Tunnel Linings

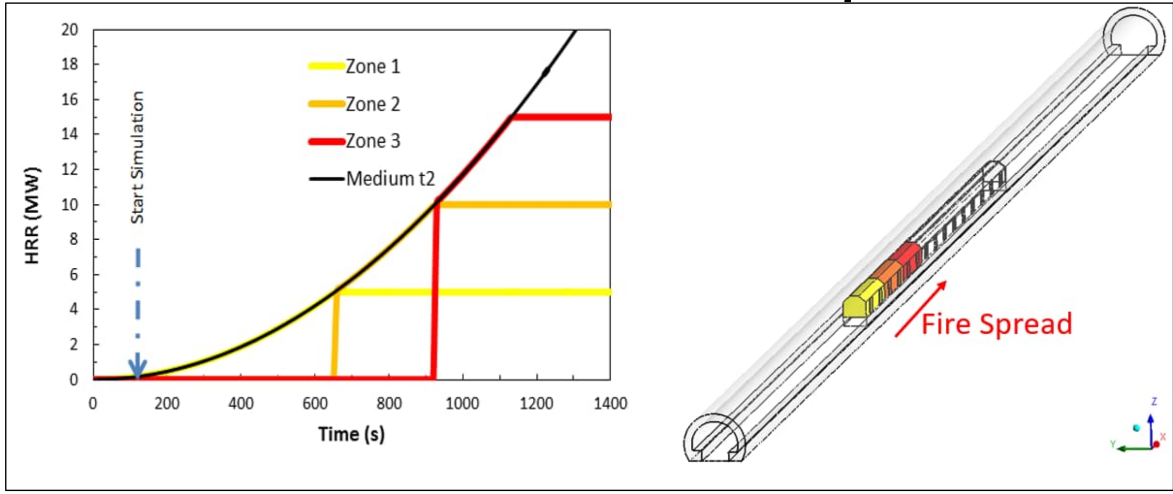
- **Optimize concrete segmental lining design by reducing the lining thickness as much as possible**
- **Reduce carbon footprint of concrete by optimizing mix design through:**
  - **Replacing Portland Cement in the mix as much as possible with Portland Lime Cement (PLC) and Supplementary Cementitious Materials (SCMs)**
  - **Reducing total cementitious materials and paste by aggregate optimization (Tarantula Curve)**
- **Use of fiber for concrete reinforcement instead of rebar**
- **Optimize other materials used in segments such as bolts, dowels, inserts, gaskets, etc.**
- **Optimize cementitious backfill grout behind the segments.**
- **Optimize production lines and consumed energy in precast plants.**
- **TBM operation optimization through; optimized design of machine to reduce energy consumption during operation and increase TBM advance rate to reduce operation hours.**

Structural Fire Resistance

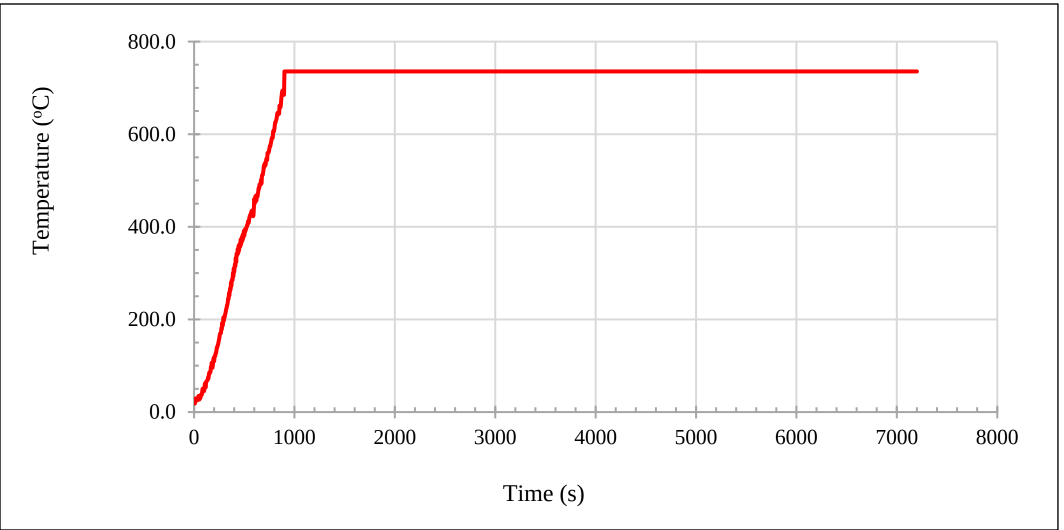
Standard Fire Curves, Prescriptive



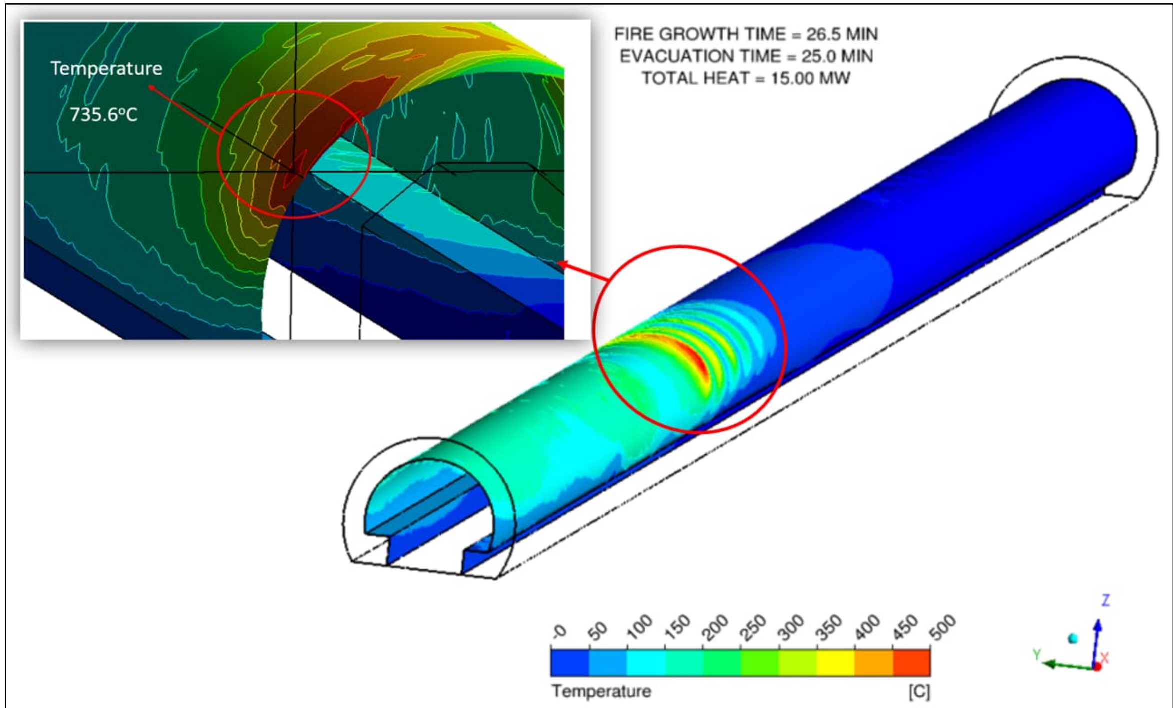
Fire Growth Curve, Medium Time-Squared



Project Fire Curve

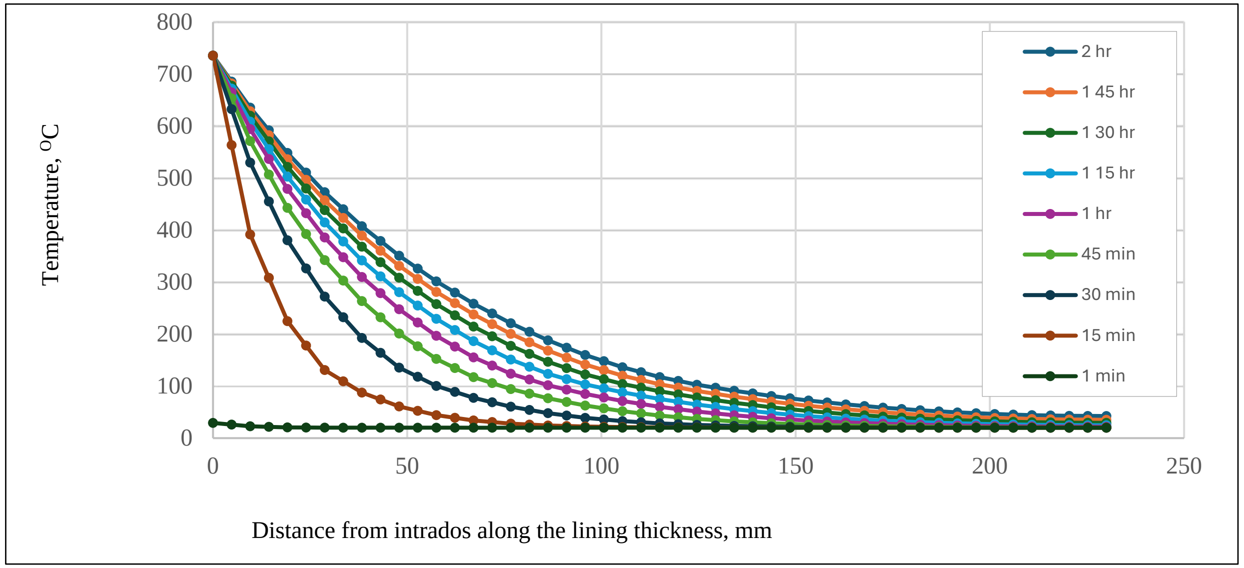


CFD Results, Temperature Contours at Intrados

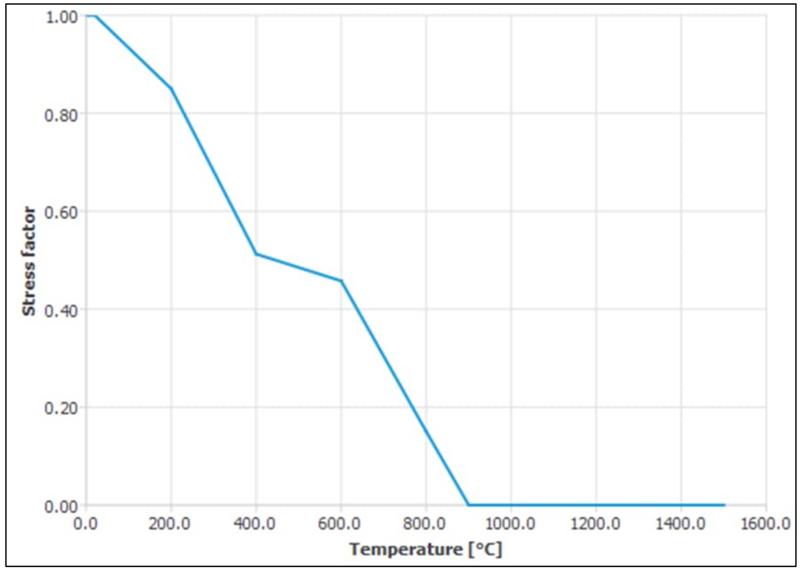


Structural Fire Resistance

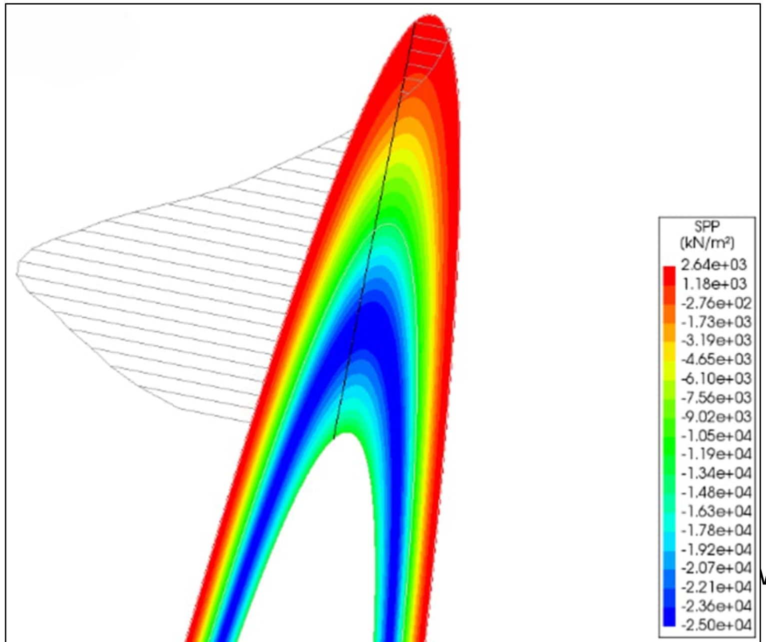
Temperature in Segment Thickness at different Times



Residual Tensile Strength Decayed Factor

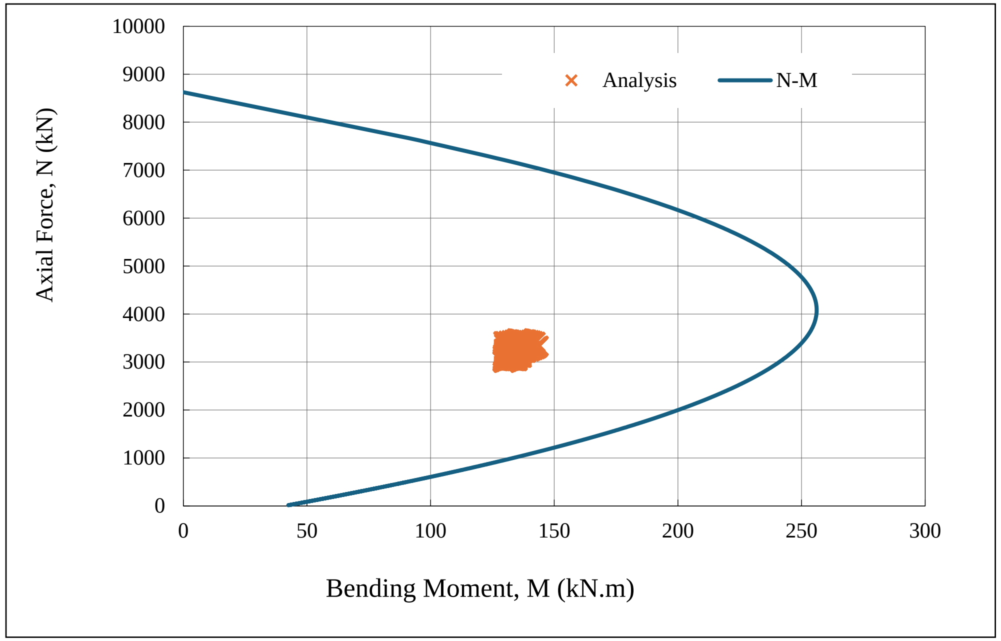


Hoop Stresses in Segment Thickness



VARSAW

Decayed Lining Capacity versus Demand



Conclusions

- **Segment Handbook, ITA, ACI 544 and 533 Guidelines consolidate most recent developments, international best practices, and state-of-the-art information on all aspects of design and construction of precast segments.**
- **These documents are useful for experienced tunnel engineers for addressing specific needs of each project, as well as for students/entry-level engineers for understanding major design and construction concepts.**
- **They are the state of the practice at the current time on a continuously evolving technology field which makes future updates and revisions to these documents inevitable.**

Useful Publications on This Topic

- **Nasri, V., Klug, D., Fulcher, B., and Morrison, J. (2024), Handbook of Precast Segmental Tunnel Lining Systems. Taylor & Francis, pp. 840, ISBN 9781032453309.**

- **Guide for Precast Concrete Tunnel Segments. American Concrete Institute, Committee 533, Report 533.5R-20, USA, April 2020, 84 pages.**

- **Report on Design and Construction of Fiber-Reinforced Precast Concrete Tunnel Segments. American Concrete Institute, Committee 544, Report 544.7R-16, USA, January 2016, 36 pages.**

- **International Tunneling Association Working Group 2 – Research, (2019), Guidelines for the Design of Segmental Tunnel Linings. ITA Report N°22 - April 2019, pp. 60, N° ISBN: 978-2-9701242-1-4**

- **Bakhshi, M., Nasri, V. (2019), New ACI 533 Guide on General Design and Construction Aspects of Precast Concrete Tunnel Segments. Geomechanics and Tunneling Journal, October 2019, pp. 478-483.**

- **Yao, Y., Bakhshi, M., Nasri, V., & Mobasher, B. (2018). Interaction diagrams for design of hybrid fiber-reinforced tunnel segments. Journal of Materials and Structures, 51(1), 35.**

- **Patel D., Pleesudjai C., Bakhshi M., Nasri V., Mobasher B. (2025), Back-calculation of mechanical properties of fiber-reinforced concrete in tunnel lining segments. Structural Concrete Journal of the fib, April 2025, https://doi.org/10.1002/suco.70052.**

AECOM

Thank you!

Warsaw University of Technology
Faculty of Civil Engineering

ITA AITES

ITACET Foundation

Bekaert