STUDY OF POLYPROPYLENE FIBER-REINFORCED CONCRETE IN PRECAST TUNNEL LINING

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ABSTRACT: The underground construction industry increasingly seeks innovative alternatives to traditional steel reinforcement in concrete, especially for underground infrastructure such as tunnel linings, where mechanical behavior and durability are critical. This research investigates the application of polypropylene fiber-reinforced concrete (PPFRC) as a substitute for conventional reinforcement in tunnel lining, through a modeling of a recent Tunnel Boring Machine (TBM) project. This study examines the influence of fiber content on key mechanical properties including crack analysis, segment deformation and displacements, and overall stress distribution in TBM concrete lining. Structural modeling using DIANA will simulate the post-construction stage of a tunnel focusing on the crown, sidewalls, and inverts. Through a combination of literature review and finite element analysis (FEA), the research seeks to observe the effects of polypropylene concrete as reinforcement in precast concrete tunnel lining. Ultimately, the study will provide guidance on the effective application of PFRC in tunnel lining construction, considering design variability and construction methodologies.

1. INTRODUCTION

With infrastructure aging, urbanization and population density growing, and environmental concerns impacting infrastructure decisions, tunnel demand is expected to increase. According to global data, investment is also predicted to grow, to $107.6 billion in 2026 and $123.5 billion in 2027, on infrastructure projects with a focus on tunnelling works.

1.1 OBJECTIVE

The objective of this study is to observe the effects of polypropylene concrete as reinforcement in precast concrete tunnel lining. This research seeks to understand the current trend of polypropylene-reinforced concrete (PPFRC) tunnel linings in Tunnel Boring Machine applications.

1.2 METHODOLOGY

The Finite Element Modelling (FEM) software, Diana Interactive Environment 10.10, was used to simulate the typical conditions of TBM excavated tunnels with precast concrete lining.

Then, a comparative analysis was conducted amongst FEM results. The overarching goal is to find critical observations that better understands the mechanical properties of PPFRC.

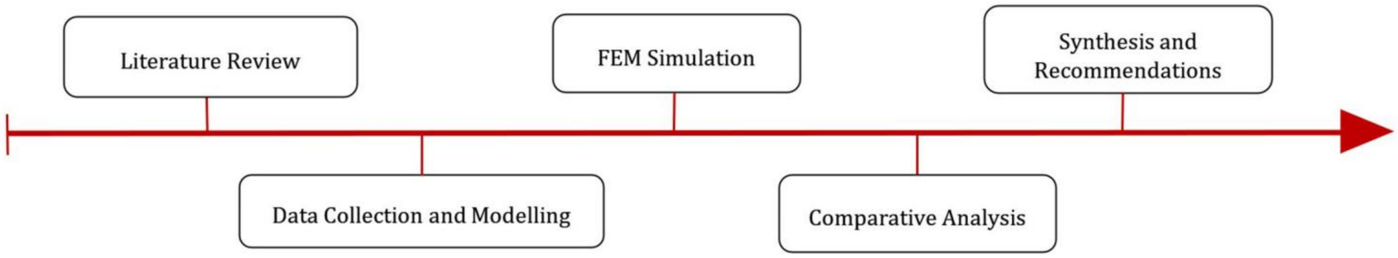

Figure 1. Timeline of methodology.

1.3 TRADITIONAL REINFORCEMENT AND FIBER-REINFORCED CONCRETE (FRC)

Nearly all TBM tunnels use reinforcement in their precast concrete lining. Traditional steel rebar is the most common method of concrete reinforcement; however, fiber-reinforced concrete (FRC), specifically synthetic fiber, has been gaining attention due to its delayed degradation, corrosion resistance, and cost-efficiency.

1.3.1 Trends.

Within the fiber reinforcement industry, steel fibers are the most utilized fiber. For example, as mentioned in Patel et al. (2023), of 78 full-scale tunnel lining FRC projects, 75% used steel fibers, and 2.5% used synthetic fibers. Although fiber reinforcement is growing in its application, there is a need for further exploration. De la Fuente et al. (2017) concludes that fiber reinforced concrete could be applied in tunnel construction, and a lack of its implementation could be due to insufficient structural understanding of its use. Patel (2023) agrees that a lack of full-scale verification tests hinder the application of polymeric fibers as primary reinforcement.

1.4 INTRODUCTION TO POLYPROPYLENE FIBER REINFORCED CONCRETE (PPFRC)

1.4.1 Elasticity: High elastic and low elastic.

Liu (2017) categorizes non-steel fibers as high elastic or low elastic. Synthetic fiber falls under the category of low elastic and is found to hold the following properties: corrosion resistance, high strengths, and low cost.

1.4.2 Diameter size: Microfiber and macrofiber.

Aldea et al. (2023) further categorizes synthetic fibers into microfiber and macrofiber. Under synthetic fibers are two categories of macro (greater than or equal to 0.3 mm) and micro (greater than or equal to 0.3 mm), which separate by diameter size. Additionally, a blend (a mix of macrofibers and microfibers) is found to exert remarkable tensile strength, compared to soley crude fiber concrete due to reduced cracks on the concrete surface meeting industry standard of < 0.2 mm.

1.4.3 Strength performance.

Kakooei et al. (2012) investigated how compressive strength changes under various polypropylene fiber concrete reinforcement amounts. This determined that the compressive strength grew proportionally with the volume of fiber due to its reduced shrinkage from reduced permeability and hindered degradation. Mohod (2015) discovered an increase in strength (compressive, tensile, and flexural) of polypropylene fiber reinforced concrete; with mechanical properties, in compressive and flexural strength, improving with an optimal fiber content of 0.5%.

1.4.4 Durability performance.

Permeability, electric resistivity changes under various polypropylene fiber concrete reinforcement amounts (Kakooei et al., 2012). Additionally, polypropylene fiber has a high melting point (165°C), is chemically neutral, and holds hydrophobic characteristics which make it a viable substitute. Mohod revealed that a low fiber fraction volume led to reduced early age shrinkage and moisture loss. Additionally, a high volume of fiber presents constructability challenges but reduces bleeding and segregation. It is believed that PFRC can effectively prevent concrete cracking, which reduces water seepage, according to Liu (2017). Aldea et al. (2023) remarks that macrofibers lead to an improved chemical, chloride, and alkali resistance. Therefore, PPF demonstrate great expectation for long-lasting and durable infrastructure.

1.3.3 PPFRC as an alternative.

With an adequate number of Tunnel Boring Machines, fiber-reinforced shotcrete allowed a useful solution to complete projects on time. Namli (2021) argues that 47% of metro station construction time and 22% whole metro construction time is reduced when using fiber reinforcements in tunnel concrete lining, specifically via shotcrete. Tiberti finds that an optimized proposed solution enables a reduction of about 30% of the total amount of fibers and rebars. Additionally, a 75% reduction of conventional rebar leads to reduced labour and storage which leads to reduced overall cost.

The partial or complete reduction of rebar has great benefits. Chiaia et al. (2009) finds that due to the presence of fibers, the area of rebars, the thickness of the segments, and the overall cost can be reduced. Tiberti et al (2014) argued that an optimized FRC design leads to decreased labor and storage, which is said to lower costs. Aldea et al. (2023) also suggests that macrofibers are safer and more affordable.

Aldea et al. also mentioned its impact on the environment. Macrofibers are more accessible and result in a smaller carbon footprint compared to traditional reinforcement. On a larger scale, the reduction of steel reinforcement will maximize durability and service life. Chiaia concludes that the addition of steel fibers lead to reduced reinforcement and when only implemented in the tensile zone of the structure, construction time can be significantly reduced as it leads to a rapid advancement of the lining structure.

2. LA METRO PURPLE LINE EXTENSION

This research project followed the conditions of the underground work of the Westside Subway Extension (WSE) in Los Angeles. The extension of the Purple Line was built for the Los Angeles County Metropolitan Transportation Authority (LA Metro). The focus of this study will be its construction of the bored tunnels in Reach 1 that extends from Wilshire/La Brea to Wilshire/Western. Pressurized close-faced TBMs were used for twin tunnel excavation.

2.1 PRECAST CONCRETE TUNNEL LINING

Under the performance criteria of precast concrete tunnel lining in the Project Technical Requirements, the provision of monofilament micro-polypropylene fibers in concrete mix is indicated. Although the participation of fibers, of dosages between 0.75 to 1.88 metric tons in the design is included, it is only for improved fire resistance and not structural. Steel fibers are mentioned but are indicated to not be used as primary concrete reinforcement.

3. DATA COLLECTION AND MODELING

Geotechnical data was gathered the WSE in Los Angeles, California. Data gathered included the soil strata/profile, the approximate water table, geological conditions from the Geotechnical Data Report, Geotechnical Baseline Report, and Construction Approach Report. This data reflected the conditions of the Los Angeles Basin. Tunnel dimensions and other critical design data was found in the WSE Technical Requirements and engineering plans.

Data not explicitly mentioned in either literature reviews or reports were assumed, derived, or interpreted.

3.1.1 Model geometry.

Reach 1, Wilshire/La Brea to Wilshire/Western, of the Purple Line Extension project was selected to inform the model. The geological conditions of this region included various strata such as Artificial Fill, Lakewood, San Pedro, and Fernando. Additionally, the groundwater had a depth of approximately 10.8 m bgs and tunnel depth of 33.5 m bgs.

Twin tunnels were modelled with a 6.1 m horizontal separation. The tunnel cross section of the excavated soil included the following thicknesses: 0.1 m of grout, 0.3 m of primary precast concrete lining, and 0.2 m of secondary lining.

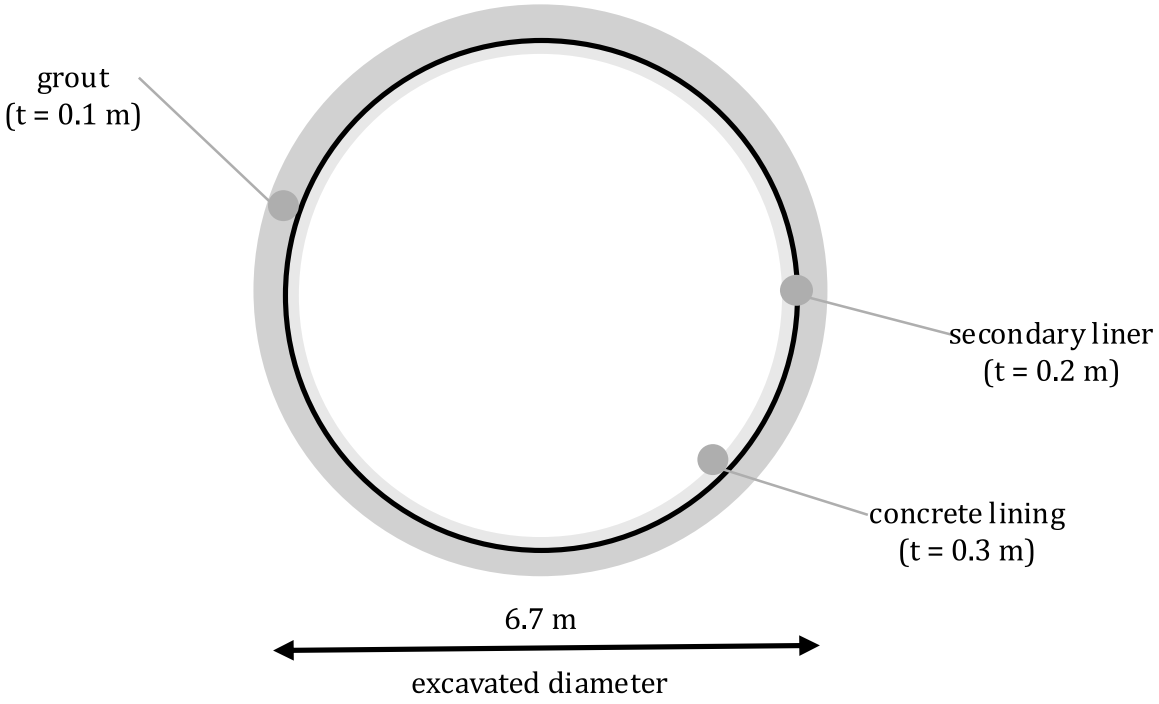

Figure 2. Cross-section of tunnel lining with marked thicknesses of each layer.

3.1.2 Material properties.

All soils were modelled using the Modified Mohr Coulomb elasticity, given that it is a robust soil model for long-term behavior. The Young Modulus was converted from the pressure meter data. The Young Modulus for Artificial Fill was an engineering assumption that is common for its soil type. The density of the soils was derived from the GDR dry density and moisture content tables. Though data was derived or interpreted, much of the data was assumed by a safe baseline value. The contact grout was also analyzed as Modified Mohr Coulomb elasticity. The grout was reflected on its material properties to be weak, as indicated on the technical requirements to have a compressive strength of approximately 345 kPa. Additionally, as the primary lining was the focus of the study, the secondary lining was represented by baseline material values.

Two concrete mixes for the primary tunnel lining were modelled: a plain concrete (PPFRC-0) and a polypropylene fiber reinforced concrete with 0.8% fiber volume fraction (PPFRC-8). 0.8% was selected because of its significant improvement in tensile strength compared to other dosages. The mix design proportions and mechanical properties were from Behfarnia and Behravan (2013) and specifications of the fibers were taken from BarChip.

Table 1: Mix design proportions sourced from Behfarnia and Behravan (2013).

Specimen name	**Water (kg/m^3)**	**Cement (kg/m^3)**	**Fine aggregate (kg/m^3)**	**Coarse aggregate (kg/m^3)**	**Super plasticizer (kg/m^3)**	**Fiber volume (kg/m^3)**	**PP fiber %**	**Mass density (kg/m^3)**
PPFRC-0	208.25	350	1066	848	4	0	0	2476
PPFRC-8	208.25	350	1066	848	4	7.3	0.8	2484

BarChip 48 was selected due to its design of virgin polypropylene for precast elements. According to the BarChip Product Data Sheet (PDS), this 48 mm long fiber holds a tensile strength of 640 MPa and a Young's Modulus of 12 GPa. Additionally, this Fiber Class II mix conforms to ASTM C 1116 – Type III and EN 14889 – 2.

The DIANA Total Strain crack model simulated nonlinear concrete behavior. If Behfarnia and Behravan (2013) data wasn't available, the American ACI 209R-92 code was utilized to derive some of the material parameters.

Table 2: Key material properties used in DIANA

Property	Units	PPFRC-0	PPFRC-8
Concrete model	—	ACI 209R-92 + Total Strain crack model	ACI 209R-92 + Total Strain crack model
Mean compressive strength @ 28 d	MPa (kN/m^2)	33.6 (33,600)	34.77 (34,770)
Young's modulus	GPa (kN/m^2)	27.3 (2.73E+07)	27.7 (2.77E+07)
Poisson's ratio	—	0.2	0.2
Density	T/m^3	2.476	2.484 *(includes 0.8% vol fiber mass)*
Slump of concrete slurry	mm (m)	120 (0.1)	80 (0.08)
Cement content	kg/m^3 (T/m^3)	350 (0.35)	350 (0.35)
Fine / total aggregate ratio	%	56%	56%
DIANA-derived direct tensile strength	MPa (kN/m^2)	~1.99 (~1990)	~2.03 (~2028)
Tensile curve type	—	Exponential	Exponential
Mode-I tensile fracture energy	kN/m	0.1	0.1
Crack bandwidth	m	0.3	0.3
Residual tensile strength	MPa (kN/m^2)	0 (0)	2.03 (2028)
Compression curve type	—	Parabolic	Parabolic
Compressive fracture energy	kN/m	0.02	0.02
Residual compressive strength	MPa (kN/m^2)	$0.2(f'_c) \approx 6.72$ (6720) *(~6700)*	$0.2(f'_c) \approx 6.95$ (6950)
Lateral cracking reduction	—	None	None
Confinement model	—	None	None

The normal weight concrete Young Modulus equation $E_c = 4700\sqrt{f'_c}$ (MPa) from ACI 318 was used to estimate the compressive strength. Additionally, the Poisson's ratio was taken as 0.20, which is a widely accepted value.

The tensile behaviours was modelled using the Mode-I fracture-energy based curve. Technical Requirements of Portland Cement Concrete (PCC), at 28 days the PCC mix has a residual strength of approximately 27.6 MPa at 28 days, which is practically equivalent to C30/37. BarChip's flexure performance testing of C30/37 and with a PP dosage of 6 kg/m^3 was selected, though a slight dosage under estimation. The 2.4 MPa value of L/600 was used to calculate the residual tensile strength. However, DIANA's internally computed residual tensile strength was selected since it was the minimum value computed, which best suits the tensile strength value.

3.1.3 Load conditions.

With no building directly above the tunnel and a six-lane roadway, the surface pressure was approximated to be -30 kN/m. Additionally, grout pressure was not included, as the focus of the study was on the long-term final state.

3.1.4 2D modelling.

The creation of the geometry included the various strata and the tunnel lining components. As displayed in Figure 3, the cross section measured to have a vertical span of 65.5 m by 46.0 m to include enough soil for accurate analysis.

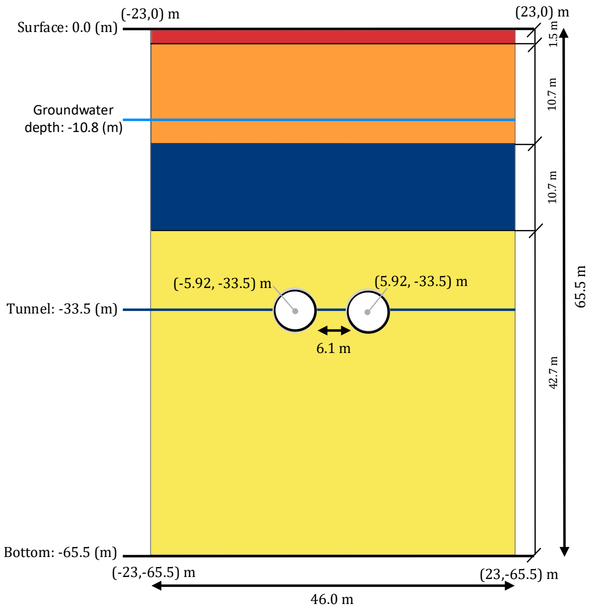

Figure 3. Cross-section of model, showcasing the various strata and twin tunnels.

Following, properties were assigned to their respective shapes. Boundary conditions were created through vertical and lateral constraints. Lateral boundaries were modeled with roller supports (Ux = 0, Uy free). After the water level was added, the mesh was generated. Following, analysis was run with four different stages as described in Table 1.

Table 3: Geomechanical staged construction analysis

Stage number	Stage name
0	Initial/geostatic
1	Excavation + primary lining installed
2	Secondary lining installed
3	Long-term

4. RESULTS

Simulations were run with polypropylene fiber dosages of 0% and 0.8%. The outputs analyzed were Displacements, Cauchy Effective Stresses, Cauchy Total Stresses, and Pore Pressure. The following figures showcase the various results:

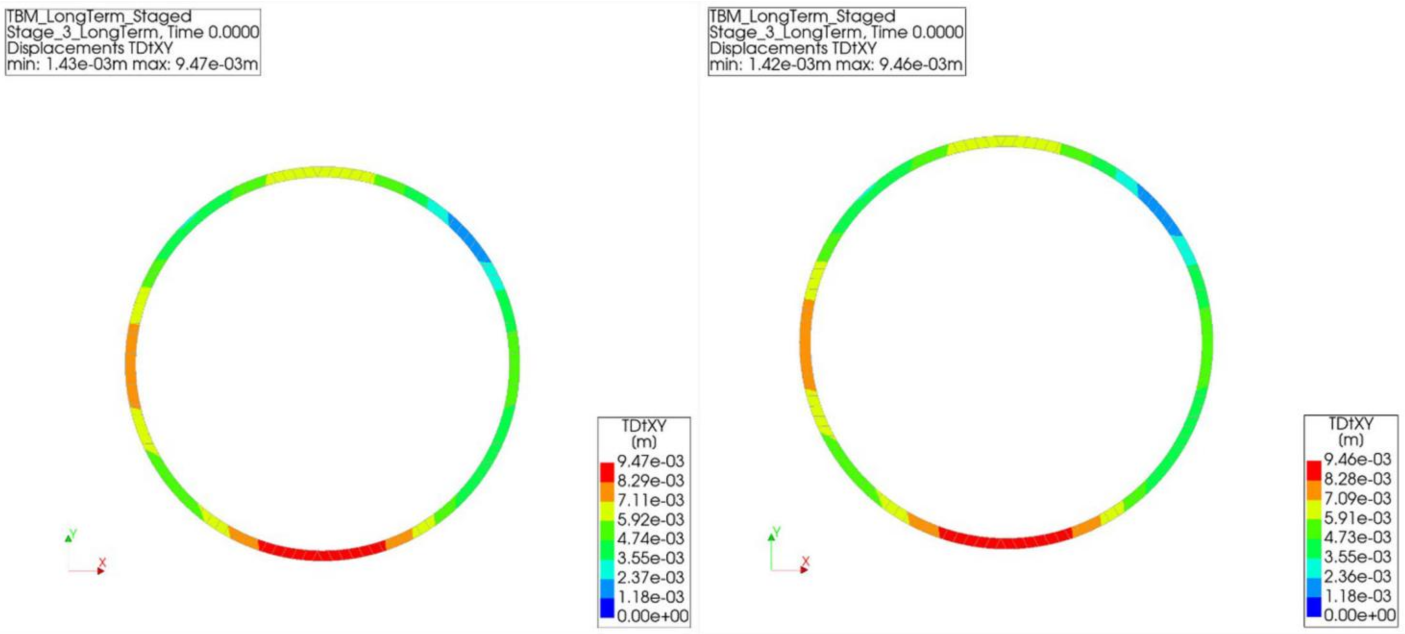

Figure 4. Stage 3 Long-term Displacements (TDtXY). PPFRC-0 on the left and PPFRC-8 on the right.

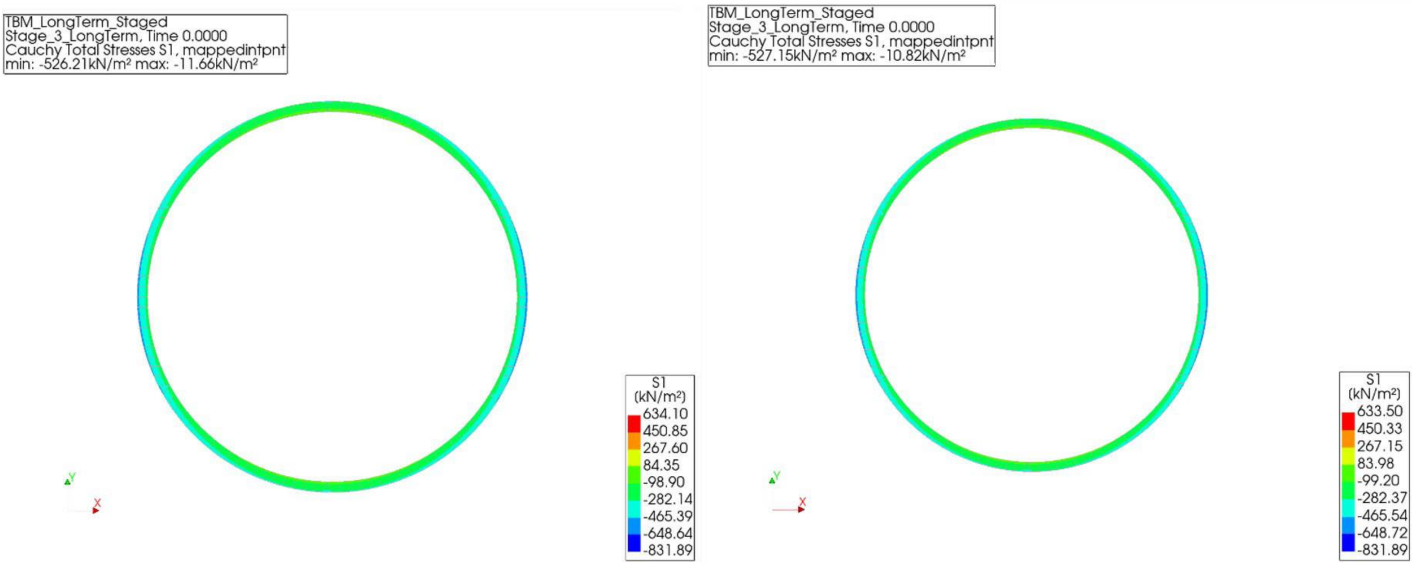

Figure 5. Stage 3 Long-term Cauchy total stresses (S1). PPFRC-0 on the left and PPFRC-8 on the right.

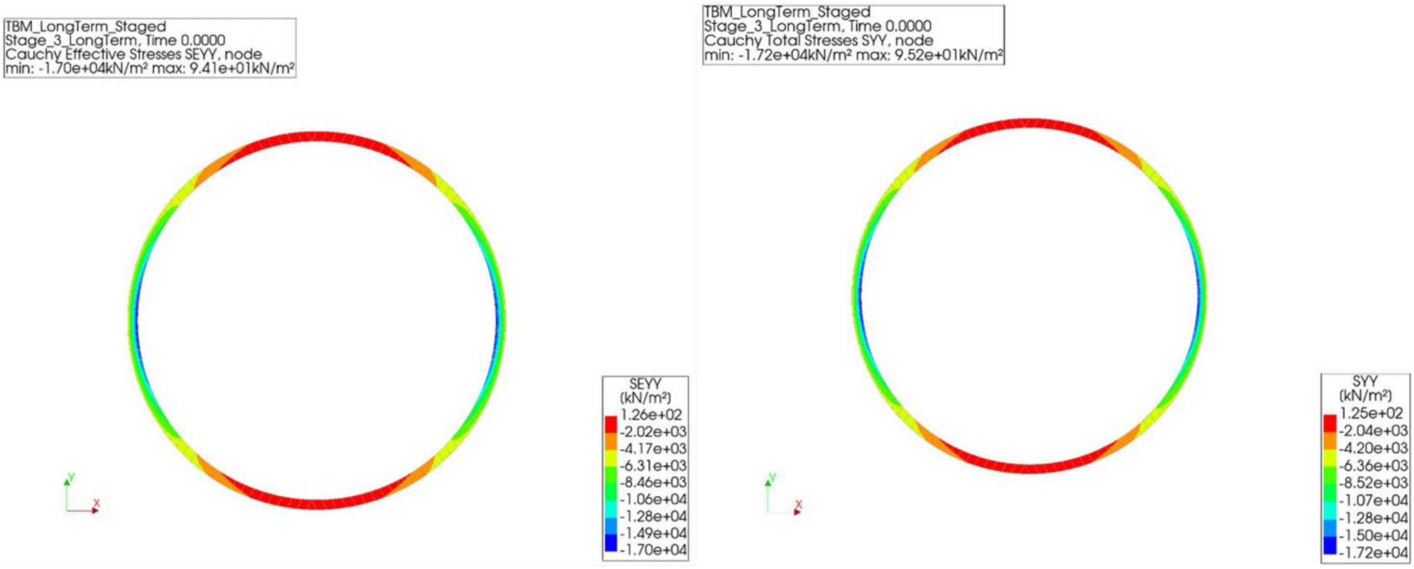

Figure 6. Stage 3 Long-term Cauchy effective stresses (SEYY). PPFRC-0 on the left and PPFRC-8 on the right.

TDtXY showcases the displacement magnitude which helps showcase any pattern of deformation. The overall displacements of the various stages are inspected and reveal only a minimal difference, with the locations of displacements being the same.

As revealed in Figure 5, the Cauchy total stresses show the lining compressive capacity. The mean for PPFRC-8 is -323.85 kN/m^2, which reveals that the graph dominates in compression and doesn't indicate tension.

Table 4: Cauchy total stress (S1) comparative results

	PPFRC-0	**PPFRC-8**	**Location (m)**
Peak tensile S1 value (kN/m^2)	634.10	633.50	(-5.51, -30.89)
Peak compressive S1 value (kN/m^2)	-837.38	-837.38	(0.00, -65.50)
Mean (kN/m^2)	-323.82	-323.85	
Range (kN/m^2)	1471.47	1470.88	

They share the same peak tensile S1 value of -837.38 kN/m^2, but they are hold different peak tensile values. PPFRC-0 has tensile value of 634.10 kN/m^2, while PPFRC-8 holds a peak tensile value of 633.50 kN/m^2. The percent different is 0.095%, which shows no meaningful change.

5. CONCLUSIONS AND FUTURE CONSIDERATIONS

Overall, the model reveals that there is not significant change between PPFRC-0 and PPFRC-8. This can be due to model misrepresentation or genuine lack of change in mechanical properties caused by the fiber reinforcement.

Still, the application of BarChip 48 fibers encourages sustainability and, according to the Infrastructure Sustainability Council, and may allow projects to be IS 14025 and EN 15804 certified by gaining points in ISv2.1 or ISv2.0 Rso-6, or ISv1.2 Mat-1. As industry seeks to grow in sustainable infrastructure, the evolution of PPFRC is expected to grow in importance and the value of its application on projects may grow also.

This model did not consider all factors that impact real-world construction. However, this model did include the general process of mechanized TBM construction through its staging process. Full scale testing is needed to confirm the validity and accuracy of the model. Additionally, analysis on the predicted lifetime of the concrete segments should be conducted to see if it reaches 100 year design life of the Project.

6. ACKNOWLEDGEMENTS

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