

Segmental Lining Design using Macro Synthetic Fibre Reinforcement

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Abstract

Fibre reinforced concrete (FRC) is becoming widely utilized in segmental linings due to the improved mechanical performance, robustness and durability of the segments. Further, significant cost savings can be achieved in segment production and by reduced repair rates during temporary loading conditions. The replacement of traditional rebar cages with fibres further allows changing a crack control governed design to a purely structural design with more freedom in detailing.

Macro synthetic fibres (MSF) are non-corrosive and thus ideal for segmental linings in critical environments. Although fibre reinforcement for segments is relatively new, recent publications such as the ITAtech “Guidance for precast FRC segments – Volume 1: Design aspects” or the British PAS 8810 “Tunnel design – Design of concrete segmental tunnel linings – Code of practice” have now given more credibility to this reinforcement type and the basis for design.

This paper presents and discusses the design methodology for precast tunnel segments and in particular the tasks associated with the use of MSF reinforcement. Temporary loadings as well as long term load behaviour will be addressed. A case history from the Santoña–Laredo General Interceptor Collector, currently under construction in northern Spain, will illustrate the specific benefits of MSF reinforcement for segmental linings.

Keywords

Macro synthetic fibre, fibre reinforced concrete, segmental lining, TBM, segment design

1 Introduction

Wide use of structural fibres in initial (temporary) and final (permanent) linings worldwide has shown the importance of fibres in underground construction, with growing interest among the designers, engineers and the referring authorities. Over the last 20 years, fibre reinforced concrete (FRC) segmental tunnel linings have been adopted in numerous projects around the world. A comprehensive overview of these projects is given in the ITA WG2 report (2015).

Structural fibres can replace or reduce ordinary rebar cages, acting as the primary structural reinforcement. Significant cost savings are often achieved by the use of fibres; mainly by the partial or entire replacement of ordinary reinforcement in the production, but also by improving the robustness, serviceability and durability and hence, reducing maintenance costs.

Macro synthetic fibre reinforced shotcrete (MSFRS) has reached maturity as an engineered material and is widely used in all forms of sprayed tunnel linings, for temporary as well as permanent ground support in both, mining and civil tunnel applications (Nitschke and Winterberg, 2016).

The application in precast tunnel segments is relatively new. However, MSF has distinct advantages over steel reinforcements, e.g. non-corrosive and doesn't suffer from matrix embrittlement and the inherent performance loss with age (Bernard, 2014). Further, continuous R&D and development yields high performing fibres that meet the particular specifications of the tunnel projects. Executed references can be found in ITAtech report no. 7 (2016).

Replacing the steel rebar cages of tunnel segments with non-corrosive fibre reinforcement not only yields an excellent durability. Moreover, the fibres near the surface reinforce the otherwise vulnerable concrete cover and provide crack control and impact resistance, minimising repair and reject rates and in turn the project costs.

The replacement of traditional rebar cages with macro synthetic fibres further allows changing a crack control governed design for durability (SLS) to a purely structural ULS design with more freedom in detailing and potential cost savings.

Although the use of MSF reinforcement for tunnel segments is relatively new, recent publications such as the ITAtech report no. 7 (2016) or the British PAS 8810 (2016) have now given more credibility to this reinforcement type and the basis for the design.

2 Segmental lining design

2.1 Introduction

There are currently no particular design standards or guidelines for macro synthetic fibre reinforced concrete (MSFRC). The regular design methodologies for steel fibre reinforced concrete (SFRC) apply. Macro synthetic fibre can be used when the project specifications and performance criteria are met: "if concrete reinforced with this fibrous synthetic reinforcement exhibits adequate post-cracking residual strengths then it can be considered suitable for structural purposes as well as SFRC" (ITA WG2, 2015).

In the past, the absence of global standards for steel fibres hasn't come in the way of their acceptance and use in various applications. Continuous developments and successfully completed projects show that the same currently applies to high performance synthetic fibres.

2.2 Fibre reinforced concrete segments

The design of FRC is based on its tensile performance, i.e. the crack-bridging capacity provided by the fibres. Experimental tests are carried out to determine the tensile characteristics. The post-cracking behaviour of fibre reinforced concrete can be determined indirectly on bending beams with displacement-controlled machines. The Model Code 2010 (2012) is today the internationally most recognized standard for the design of FRC. The post-crack performance characterisation follows the European harmonized standard EN 14651 (2005).

The segment designs typically aim at largely compressed sections with little to moderate bending moments. Additional reinforcement may be only required for temporary load cases, typically for TBM propulsion, in the form of bursting ladders at joints.

Large tunnels or tunnels in soft grounds might still require traditional steel reinforcement due to high bending moments in temporary or permanent condition. In these cases hybrid reinforcement, i.e. a combination of fibre and cage, is often the most durable and cost-efficient solution due to the partial replacement of rebar by fibres (Plizzari and Cominoli, 2005).

2.3 Ring segmentation

To better accomplish a fibre only solution, smaller segments should be adopted in order to limit the segments' aspect ratio, i.e. the ratio of developed length over thickness (see Figure 1). A larger number of smaller segments reduces the stiffness of the ring and in turn the acting bending moments on the segments. Further, the risk of damage during handling and temporary load conditions is minimized.

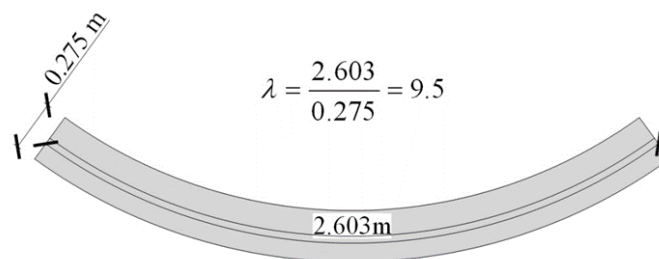


Figure 1: Definition of the segment aspect ratio

The experience of several executed FRC tunnels suggests that an aspect ratio not exceeding a value of 10 safely permits the use of FRC only (ITAtch 2016). However, other parameters such as the tunnel diameter, overburden and the ground conditions also must likewise allow replacing rebars with fibres, verified by the structural design.

2.4 SLS design

Segments reinforced with traditional steel rebar cages require tight serviceability limits in order to protect the steel reinforcement from corrosion. Crack width control given by the fibre reinforcement can change a crack control governed design (SLS) into a pure structurally

required design. This not only yields economic benefits but creates significant freedom in design and detailing. FRC without conventional reinforcement is able to limit the developing crack width where load-redistribution is possible as given in statically indeterminate elements (rotation capacity), such as tunnel segments under axial thrust (DBV 2001).

Recent research has shown that the addition of high performance macro synthetic fibres to steel rebar reinforced concrete reduces crack width and crack spacing by 30% in bending of simply supported beams (Bernard, 2018). Thus, MSF can add a significant gain of design life to steel reinforced concrete structures, such as hybrid reinforced segments.

2.5 ULS design

A typical design approach for FRC segmental linings is the use of Moment-Normal Force interaction diagrams or Moment-Thrust Capacity Limit Curves (Nitschke and Winterberg, 2016). The factored design load couples acting on the section must remain within the N-M envelope.

The FRC material properties are herein derived from the beam tests, which are eventually used as the basis to determine the stress-strain relationship of the concrete on the tension side. The idealized stress-strain diagram enables setting up the capacity limit curves, which are obtained by equilibrium iterations on a given cross-section.

3 The Santoña–Laredo Project

3.1 Project introduction

The Santoña–Laredo General Interceptor Collector is a 1.5 km subsea tunnel currently under construction in northern Spain. The tunnel is part of the Santoña Marshlands Sanitation Project. It is constructed with a 4.30 m Mixshield TBM across the Santoña bay using macro synthetic fibre reinforced concrete segments. The review of the manufacturing process and especially of the design of the tunnel segments led to the decision to replace conventional rebar cages with macro synthetic fibre (see Winterberg et al., 2018 for a detailed overview on this project).

3.2 Segmental lining design

Apart from the potential cost savings in the production, the review of the design of the tunnel segments to meet the aggressive marine environment led to the decision to replace the conventional rebar cages with EPC's BarChip macro synthetic fibre.

To better accommodate the fibre reinforced concrete solution, smaller segments were adopted in order to limit the segments' aspect ratio. The tunnel has an internal diameter of 3.50 m with a segment thickness of 250 mm. The segmentation was selected to be "5+1", with three rectangular segments, two counter keys and a half size key stone (Figure 2). This yields a segment aspect ratio of 8.6 which is well below the before mentioned limit of 10.

The structural design of the FRC segments, employing a concrete class C45/55, is based on the Spanish EHE-08 (2008) and the fib Model Code 2010 (fib 2012). The FRC has to comply with two ductility criteria, following Annex 18 of EHE-08:

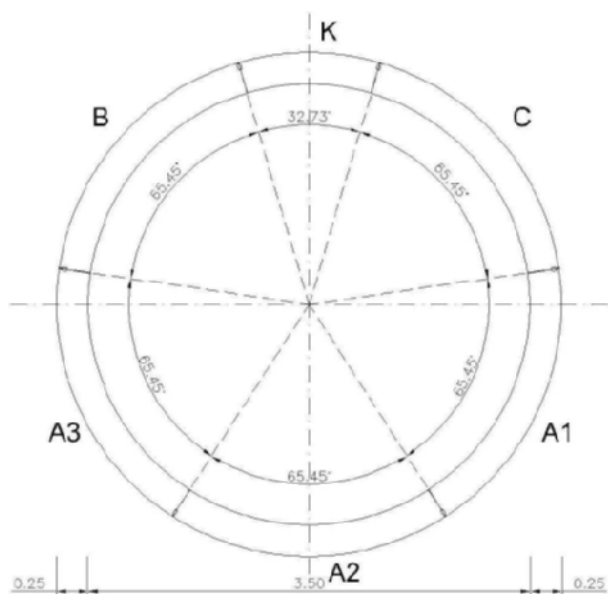


Figure 2: Ring segmentation

- $f_{R1k} \geq 0.4 f_{ctk,fl}$ and
- $f_{R3k} \geq 0.2 f_{ctk,fl}$

where the flexural performance is determined according to the European harmonised testing standard EN 14651. This means minimum ductility requirements at different displacements, retaining min. 40% of the flexural strength (cracking stress) as a residual performance in SLS (0.5 mm Crack Mouth Opening Displacement) and min. 20% in ULS (2.5 mm CMOD).

Based on experience gained from earlier projects using BarChip MSF, the following characteristic values have been determined:

$$f_{ctk,fl} = 3.60 \text{ MPa}, f_{R1k} = 1.50 \text{ MPa} \text{ and } f_{R3k} = 1.50 \text{ MPa}$$

where the residual flexural strength values can be reached with 5 kg/m³ of BarChip BC48. Testing trials were conducted at the laboratory of the Polytechnic University of Catalunya (UPC) in Barcelona, Spain, in order to corroborate the values. Apart from the standard beam tests within the frame of these trials, parallel testing was executed employing the Double Punching Test or “Barcelona Test” (UNE 83515, 2010). This test methodology uses smaller specimens and reduces the efforts related to quality control as compared to beam testing. A correlation of $R^2 = 0.9$ was attained between the two test methods so that the frequency of the complex beam tests could be reduced.

3.2.1 Design for permanent conditions

The structural analysis for permanent conditions due to geostatic loading was carried out for seven critical chainages, where the particular ground conditions were expected to yield the critical load combinations. The conditions comprise *min./max. overburden*, *max. water pressure* and *combinations thereof*.

In a slurry shield drive, assuming normal operating conditions of the machine, deformations of the terrain, which determine the loads on the ring, depend on several factors that can be summarized in:

- (a) Deformation ahead of the front;

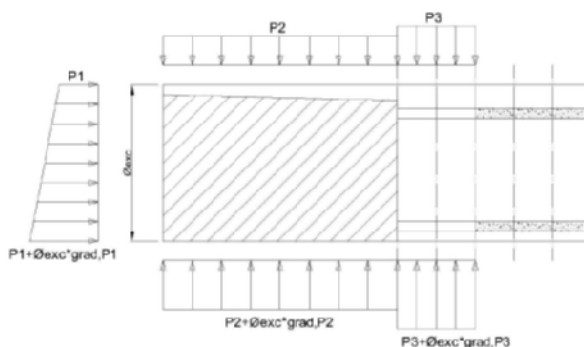


Figure 3: Load model for the face, shield, shield tail and ring

- (b) Radial deformation around the shield;
- (c) Radial deformation in the tail of the shield;
- (d) Pressure adjustment of pore and drainage in the long run.

These analyses have been carried out using FLAC3D finite element analysis (FEA).

Using the Muir-Wood formula to determine the ring stiffness and an experimentally based model to determine the strength development of the injection mortar for an assumed advance rate of eight rings per day, the ruling load combinations as N–M couples acting on the segmental lining have been found. The structural design for ULS uses N–M capacity envelopes. These axial force–bending moment interaction diagrams are a common tool for the design of final linings (Nitschke and Winterberg 2016).

The FRC material properties are given as the earlier mentioned characteristic flexural values, which have been corroborated by the experimental test results. These flexural values are the basis for the stress-strain relationship of the concrete on the tension side using a simplified stress block. The idealized stress-strain diagram enables setting up the capacity limit curves, which are obtained by equilibrium iterations on a given cross-section.

Figure 4 shows the factored design load couples plotted into the N–M capacity envelope. The design is adequate for the chosen C45/55 concrete class and 5 kg/m³ of BarChip BC48 fibre as the primary reinforcement. The ring is well under axial compression due to the governing normal forces. Very moderate bending moment is acting on the ring so that tensile stresses are minimised. This shows that the ring detailing has been well designed to accommodate a fibre only solution for the given permanent load conditions. The N–M interaction diagram further shows remarkable provisions in load bearing capacity given by the fibre reinforced concrete section.

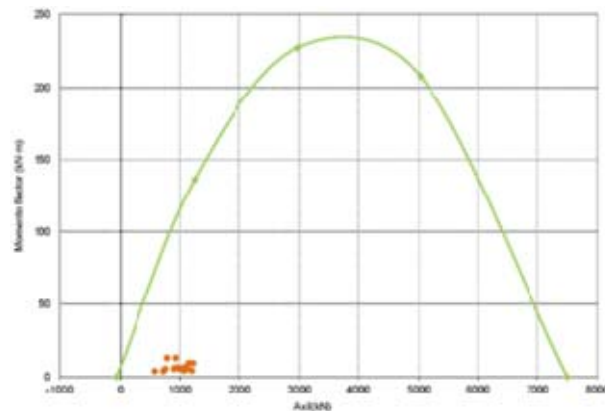


Figure 4: N–M capacity envelope for the FRC section and factored design load couples

The radial joints, i.e. the joints between the segments of a ring, have been checked against maximum compressive stress and bursting. Ground settlement was found to be minimal so that birdsmouthing due to ring ovalisation has not been considered here. Further, guiding rods in the radial joints ensure that the segments are connected with minimal offset, which in turn could produce additional eccentricity and stresses. The compressive design capacity of 5.37 MN/m of the section exceeds by far the maximum acting load, which is 1.22 MN/m. The bursting stresses were checked with FLAC3D and remained with 0.89 MPa well below the design tensile capacity of the plain concrete which is 1.77 MPa. Thus, no additional reinforcement was required.

3.2.2 Design for temporary conditions

Loads resulting from handling of the segments, i.e. demoulding, turning and stacking have also been checked against the design tensile strength of plain concrete at the referring ages. The post crack performance given by the fibre reinforcement has not been taken into account here. This is to avoid any cracking of the segments at these stages.

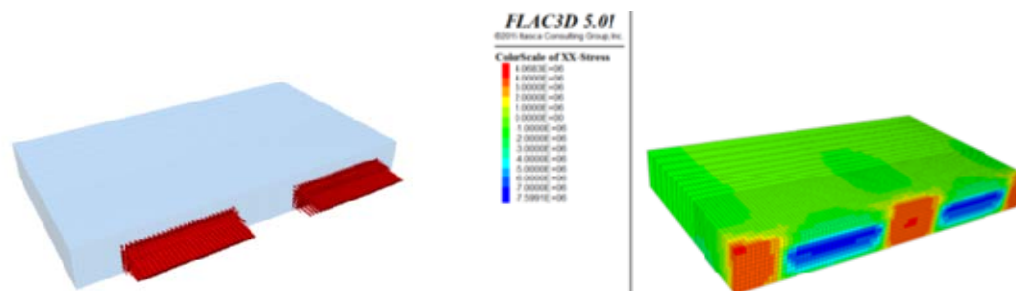


Figure 5: Model of ring joint loading during TBM propulsion (left) and resulting spalling stresses (right). Ring joint was modelled as the developed segment length

The ring joints have been checked against the loads from jacking forces during TBM propulsion. Maximum thrust force of the Mixshield TBM is 16,275 kN, distributed over 11 jacks, i.e. two jacks per segment and one on the keystone. The compressive stress under the jacking pads remains well below the admissible stress. However, bursting stresses required special attention and were modelled and analysed with FLAC3D. Two cases need to be distinguished: tangential stresses along the ring joint face, which can lead to spalling, and stresses into the depth of the segment, which can lead to splitting. Figure 5 shows the model adopted in the FEA and the resulting tangential spalling stresses under jacking thrust.

The maximum spalling stresses were determined to be 4.07 MPa, exceeding the tensile capacity of the concrete as well as the post-crack residual tensile strength provided by the fibres. Integration of the stresses yielded a tensile force of 50.8 kN, which required 1.17 cm² additional reinforcement at the ring joints. This is provided as bursting ladders, consisting of 3 nos. dia. 8 mm that are connected with a dia. 6 mm continuous stagger bar.



Figure 6: Segment mould with bursting ladder in place (left) and a cast segment with BarChip macro synthetic fibre as primary reinforcement and (provisional) bursting ladder as secondary reinforcement (right)

Figure 6 shows the bursting ladder placed in the mould. For reasons of stiffness of the ladders and related ease of placing them in the moulds, they have been continued along the radial joints and just connected at the trailing segment edge. Note that the radial joints did not require additional reinforcement. This is a measure to ease and reduce manual handling with regards to production cycle times.

The gradient of stress distribution on the jacking face is shallow in perpendicular direction. Hence, the splitting stresses did not exceed the design tensile strength of plain concrete and thus, no additional reinforcement was required.

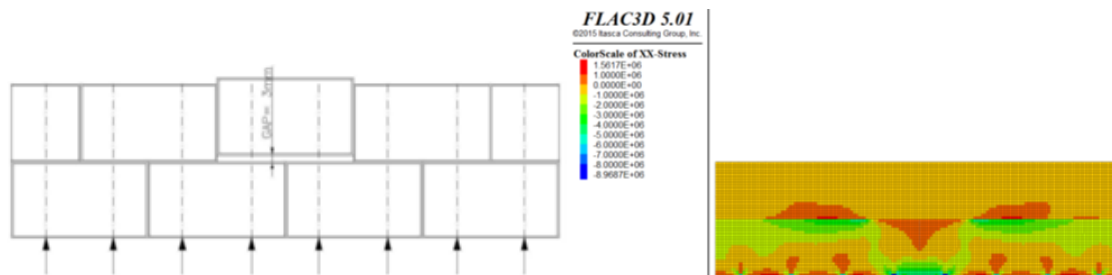


Figure 7: Model of segment gapping during thrusting (left) and resulting stresses in the segments (right)

The effect of segment gapping during TBM propulsion, due to imperfect ring build, was also verified with FLAC3D. A gap of 3 mm width between an offset segment and the lastly installed ring was analysed (Figure 7). Also in this load case the resulting stresses remained below the design tensile strength of plain concrete and no additional reinforcement was required.

3.3 Economic aspects

The initial segment design yielded a conventional steel reinforcement cage of 95 kg/m³. Regarding improvements in the precast operations and the related cost savings the main contractor Acciona Infraestructuras reviewed this design with Ingemey Consultores, the final design consultant. Switching to EPC's BarChip fibre reinforcement eliminated more than 80% of the steel reinforcement. The remaining bursting ladders (16 kg/m³) are solely for jacking forces where the synthetic fibre is the primary segment reinforcement.

Aside from the direct cost advantages, the switch to macro synthetic fibre eliminated the rebar cage and its inherent labour and reduced production cycle times by nearly 50%.

A cost assessment including segment manufacture and reduced repair or reject rate, due to significantly improved robustness of the FRC segments, revealed a total cost saving of nearly 40% for the rings, compared to the traditional rebar cage design.

4 Conclusions

Ongoing research and continuous developments on macro synthetic fibre and macro synthetic fibre reinforced concrete have made it today being a modern and cost-efficient construction material.

Eliminating durability issues with regard to corrosion of the primary reinforcement yields significant advantages for the design, since it is no longer governed by serviceability limits.

Substantial time and cost savings can be attained using fibres by reducing the cost-intensive labour to prepare, place and control standard rebar reinforcement. This applies especially to the complex reinforcement cages of precast tunnel segments. Furthermore, costs related to maintenance by replacing rejected or by repairing damaged segments can be significantly reduced.

The experience gained in the Santoña-Laredo project shows that macro synthetic fibre reinforced segments perform very robust and satisfactory even under difficult conditions (Winterberg et al. 2018).

These types of utility tunnelling projects (sewage, power, irrigation or hydropower underground pipelines) are widely present in the world market and they can raise a huge opportunity for macro synthetic fibre reinforced concrete segmental linings, profiting from the given advantages.

The successful completion of this project will build further confidence in macro synthetic fibre reinforced segmental linings. The success and gained experience of this project will lead to the implementation of this technology in other tunnel projects.

5 References

- Bernard, E.S. 2014. Age-dependent changes in post-cracking performance of fibre reinforced concrete for tunnel segments. Proceedings of the 15th Australian Tunnelling Conference 2014, Sydney, 17-19 September
- Bernard, E.S. 2018. Reduction of Flexural Crack Widths Using Synthetic Fibres in Reinforced Concrete. Proceedings FRC 2018, Fibre Reinforced Concrete: from Design to Structural Applications, Desenzano, Italy, 28–30 June 2018
- DBV 2001. Merkblatt Stahlfaserbeton, Ausgabe Oktober 2001 (Guide to good practice Steel fiber reinforced concrete, German Concrete Association, final edition October 2001)
- EHE-08 2008. Instrucción de Hormigón Estructural. Anejo 14 “Hormigón con fibras”, Spanish Concrete Design Code
- EN 14651 2005. Test method for metallic fibered concrete - Measuring the flexural tensile strength (limit of proportionality (LOP), residual)
- fib 2012. fib Model Code 2010 for Concrete Structures. International Federation for Structural Concrete, Lausanne, Switzerland
- ITA WG2 2015. Twenty years of FRC tunnel segments practice: lessons learnt and proposed design procedure. Report from ITA/AITES Working Group 2 Research, www.ita-aites.org
- ITAtch 2016. ITAtch Guidance for Precast Fibre Reinforced Concrete Segments – Vol. 1 Design Aspects. ITAtch Activity Group Support, ITAtch Report No. 7, April 2016, www.ita-aites.org
- Nitschke, A. and Winterberg, R. 2016. Performance of Macro Synthetic Fiber Reinforced Tunnel Linings. Proceedings of the World Tunnel Congress 2016, San Francisco, USA, 22–28 April 2016
- PAS 8810 2016. Tunnel design – Design of concrete segmental tunnel linings – Code of practice. The British Standards Institution, BSI Standards Ltd

- Plizzari G.A. and Cominoli L. 2005. Numerical Simulations of SFRC Precast Tunnel Segments. In Proceedings of ITA-AITES 2005, Underground space use: Analysis of the past and lessons for the future, Erdem Y. and Solak T. Eds., Istanbul (Turkey), May 7-12, pp. 1105-1111.
- UNE 83515 2010. Fibre reinforced concrete. Determination of cracking strength, ductility and residual tensile strength. Barcelona test. Spanish Standard
- Winterberg, R., Justa Cámara, R. and Sualdea Abad, D. 2018. Santoña-Laredo General Interceptor Collector – Challenges and Solutions. Proceedings FRC 2018, Fibre Reinforced Concrete: from Design to Structural Applications, Desenzano, Italy, 28–30 June 2018