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CERTAINS ASPECTS DE CONCEPTION DES VOUSSOIRS EN BÉTON RENFORCÉ DE FIBRES MÉTALLIQUES DES TUNNELS DANS LES PROJETS DE MÉTRO

SOME NEW ASPECTS FOR DESIGN OF STEEL FIBER REINFORCED CONCRETE SEGMENTAL TUNNEL LINING IN METRO PROJECTS

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Il n'y a pas plus de 15 ans que le revêtement des tunnels avec voussoirs en Béton Renforcé de Fibres Métalliques (BRFM) a attiré l'attention de nombreux Clients, Entreprises, et Bureaux d'études/Ingénieurs conseils, grâce à ses nombreux avantages, tant du point de vue technique qu'économique.

Cet article traite de certains aspects essentiels de conception des voussoirs en BRFM, avec une attention particulière sur les méthodes de calcul à long terme. Les critères de conception présentés dans cet article ont été mis au point pour un projet d'un tunnel réalisé par creusement mécanisé très difficile, où les spécifications techniques complètes et inchangeables, ainsi que les exigences de projet présentaient certains aspects critiques pour la conception des voussoirs. Ces critères importants de conception décrits permettent de suivre une règle empirique dans la conception des voussoirs, mais en tenant compte des exigences techniques du projet. Plus en détail, l'approche de conception intégrée, basée sur différentes méthodes d'analyse, a été adoptée et combinée avec des calculs de sensibilité. Par conséquent, la méthode de conception proposée est basée exclusivement sur une approche d'analyse des risques dans le but de réduire le risque initial au niveau acceptable. Les aspects de conception recommandés sont en accord avec les exigences de conception prescrites par les spécifications techniques de projet et les codes de calculs connus, les prescriptions pour l'exécution, les normes, les recommandations et les instructions en vigueur.

Not more than15 years passed that the Steel Fibre Reinforced Concrete (SFRC) segmental tunnel lining has attracted the attention of a lot of clients, contractors, and consulting engineers due to its many benefits in both technical and economical stands of view.

This paper addresses to some essential design aspects of SFRC segmental tunnel lining, with particular reference to methods of calculation for long-term state. The design criteria presented in this paper may be demanded by a very challenging mechanized tunnelling project where not only comprehensive but also unchangeable design specifications and requirements obliged to present some critical aspects in designing of segmental lining. Those significant design criteria described in this paper let designer follow a rule of thumb in designing of segmental lining, but taking into considerations the degree of design requirements of project. More in details, the integrated design approach, based on different methods of analysis, is suggested to be adopted and combined with sensitivity calculations. Therefore, the proposed design method is exclusively based on risk-analysis driven approach in such a way as to reduce the initial risk to acceptable level. The recommended design aspects are in good agreement with design requirements prescribed by any project design specifications and well-known design codes, standards, recommendations, and valid instructions.

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Résumé

Il n'y a pas plus de 15 ans que le revêtement des tunnels avec voussoirs en Béton Renforcé de Fibres Métalliques (BRFM) a attiré l'attention de nombreux Clients, Entreprises, et Bureaux d'études/Ingénieurs conseils, grâce à ses nombreux avantages, tant du point de vue technique qu'économique. Cet article traite de certains aspects essentiels de conception des voussoirs en BRFM, avec une attention particulière sur les méthodes de calcul à long terme. Les critères de conception présentés dans cet article ont été mis au point pour un projet d'un tunnel réalisé par creusement mécanisé très difficile, où les spécifications techniques complètes et inchangeables, ainsi que les exigences de projet présentaient certains aspects critiques pour la conception des voussoirs. Ces critères importants de conception décrits permettent de suivre une règle empirique dans la conception des voussoirs, mais en tenant compte des exigences techniques du projet. Plus en détail, l'approche de conception intégrée, basée sur différentes méthodes d'analyse, a été adoptée et combinée avec des calculs de sensibilité. Par conséquent, la méthode de conception proposée est basée exclusivement sur une approche d'analyse des risques dans le but de réduire le risque initial au niveau acceptable. Les aspects de conception recommandés sont en accord avec les exigences de conception prescrites par les spécifications techniques de projet et les codes de calculs connus, les prescriptions pour l'exécution, les normes, les recommandations et les instructions en vigueur.

Abstract

Not more than15 years passed that the Steel Fibre Reinforced Concrete (SFRC) segmental tunnel lining has attracted the attention of a lot of clients, contractors, and consulting engineers due to its many benefits in both technical and economical stands of view. This paper addresses to some essential design aspects of SFRC segmental tunnel lining, with particular reference to methods of calculation for long-term state. The design criteria presented in this paper may be demanded by a very challenging mechanized tunnelling project where not only comprehensive but also unchangeable design specifications and requirements obliged to present some critical aspects in designing of segmental lining. Those significant design criteria described in this paper let designer follow a rule of thumb in designing of segmental lining, but taking into considerations the degree of design requirements of project. More in details, the integrated design approach, based on different methods of analysis, is suggested to be adopted and combined with sensitivity calculations. Therefore, the proposed design method is exclusively based on risk-analysis driven approach in such a way as to reduce the initial risk to acceptable level. The recommended design aspects are in good agreement with design requirements prescribed by any project design specifications and well-known design codes, standards, recommendations, and valid instructions.

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1 Introduction

Since the first usage of precast concrete segment in 1930s in tunnels instead of traditionally support using ribs and lagging, thousands kilometres of tunnels have successfully been lined with concrete segment satisfying both durability and sustainability requirements. Moreover, with advert of shielded TBMs, the segmental lining played a significant role not only to help TBM to advance by pushing rams on segments but also to speed up the tunnel construction. Such advantages cases the precast concrete segments have been the main permanent support elements in shielded-driven tunnels in soft ground.

Over last ten years, as fibre reinforced concrete has been increasingly become prevalent in precast concrete tunnel lining, so this paper addresses particularly some essential design aspects as rule of thumb to be taken into account for success of any soft ground tunnel project as presented in flow chart of Figure 1. More in details, the integrated design approach, based on different methods of analysis, has been adopted and combined with sensitivity calculations. Therefore, the proposed method is exclusively based on risk-analysis driven approach in such a way as to reduce the initial risk to acceptable level. The applicable concept of simple risk plan used for design of segmental lining is presented in Figure 2 (Guglielmetti et al. 2007).

The design aspects presented in this paper has been gained through the lessons learned over 30 years of experiences in segmental lining in world class soft ground tunnel projects and are well compatible with different design requirements. The recommended design approach is well described with reference to flow chart presented in Figure 1.

2 Design criteria and requirements

A suitable design of segmental lining should satisfy the long-term stability of the tunnels in limit state conditions. For this reason, all kind of temporary and permanent loads acting on tunnel lining must be well acknowledged and evaluated. Depending on degree of importance and relevant stage of design; namely, feasibility, concept, detailed, constructive, and as-built, several load cases and load combinations are either arbitrary analysed or obligatory evaluated in accordance with international or local codes and standards. Generally speaking, three prevailing standards, American Concrete Institute (ACI 318-08, 2008), British Standard (BS 8180, 1997), and Eurocode (EN 1992-1-1, 2004), are often applied of which the other local codes are partially adopted from.

2.1 Design loads

Tunnel lining must be designed to withstand all potential loads that may arise during construction as well as the life of the structure. While the formers are temporary or of transition stage the latter loads are of permanent should be allowed for the design life of structures. The proper evaluation of such loads is of paramount importance to assess the associated risks related to lining. Considering and examining any kind of design loads and re-checking designed concrete lining in terms of success of structural checks may reduce the initial risk of segment damage to an acceptable risk level. The lack of accurate consideration of design loads and consequent design failure will dramatically increase the cost of the project.

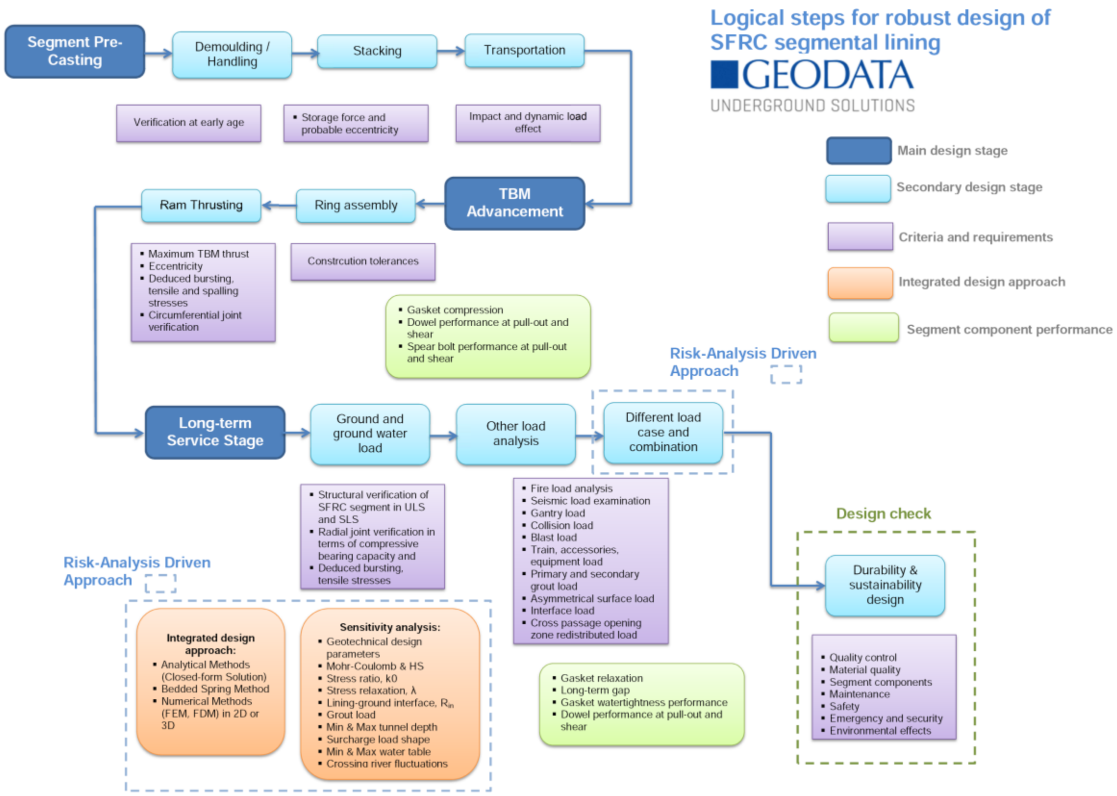


Figure 1. Logical steps for robust design of SFRC segmental lining and definition of main design loads

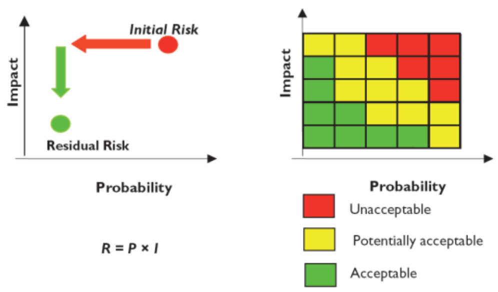


Figure 2. Principal of Risk-Analysis Driven Approach used in design of segmental tunnel lining

2.1.1 Temporary construction loads

Temporary construction loads are: (i) demoulding, (ii) stacking in curing bay and main deposit area (iii) transportation (iv) handling (v) erection during ring assembly (vi) TBM thrust ram (vii) buoyancy in fresh grout (viii) annular grout (ix) gantry load (x) gasket compression (xi) dowel or bolt tension and shear. Such loads should well be evaluated in detailed design stage so as to ensure the successful structural check in Ultimate Limit State (ULS). It should be note that a few particular load cases must be taken into consideration as obliged by project design specifications, of which the probable collision load, machinery accident, acting on temporary supporting steel frame at cross passage opening zone is significance.

2.1.2 Permanent long-term loads

On the other hand, the permanent long-term loads are: (i) ground load (ii) groundwater load (iii) surcharge loads (iv) interface structure loads (v) fire load (vi) seismic load (vii) blast load (viii) in-tunnel loads including trains, vehicles, accessories etc. (ix) gasket relaxation (x) creep effect. Seeing that the basis of these load come from interpreted geotechnical investigations, never provide perfect knowledge, so these loads cannot be known precisely. Accordingly, these loads should be re-evaluated in each design stages in parallel with progress of the project. Both ULS and SLS checks must be done for these loads in compliance with prescribed design specifications of the project and applied recommendations or standards.

2.2 Integrated design method

The integrated design method for the segmental tunnel lining relies on combination of analytical solution, structural method, numerical analysis. They are only reliable and practical means to dimension the segmental lining (Osgoui & Pescara 2014):

- Analytical closed-from solutions: mainly based on the ground-lining interaction concept and they are treated either as the simplified solution methods (Muir-Wood 1975, Curtis 1976, Einstein and Schwartz 1979, Duddeck & Erdman 1982, 1985,ITA 2000, JSCE 2006) in which the segmental lining is considered as a solid ring with equivalent flexural rigidity.
- Structural method: based on the hyperstatic reaction method (Bedded-Spring Method BSM) in presence and absence of segmental ring joints. For more sophisticated analysis, the presence of ring joints is modelled by a finite element model in which consecutive coupled rings are built using one of beam, plate, brick, and shell elements and the joints are modelled through rotational, tangential and radial springs. However, for simplified analysis, the segmental ring is modelled as a solid ring with a reduced equivalent uniform rigidity by means of Muir-Wood equation (Muir-Wood 1975) so as to stimulate the presence of the joints.
- Numerical methods, mainly based on Finite Element Method (FEM) or Finite Difference Method (FDM) in 2D and 3D, are modern methods of evaluating deduced internal forces in segmental lining capable of modelling the complex excavation stage in shield-driven tunnel even in complex soil ground condition. The finite element methods are able to model the segmental lining ring either as the solid ring with a reduced equivalent uniform rigidity or the ring in presence of the joints.

It is recommended that a tunnel be analysed with at least two methods to provide an understanding of how the method used influences the results. This is regarded a partial part of a sensitivity analysis. The comprehensive sensitivity analysis also makes it possible to take into considerations all geotechnical-geometrical variation and uncertainties in terms of applied constitutive law, normally simple Mohr-Coulomb vs Hardening-Soil Model, minimum and maximum depth of tunnel, mixed face, minimum and maximum water levels, different shape of annular grout load, crossing river fluctuation, asymmetrical surcharge loading, flood, probable future load cases due to loading or unloading the ground at vicinity of tunnel, stress ratio, ground stress relaxation λ, low overburden with low confinement pressure, ground-lining interface. In this way, the recommended design approach relies on a risk-analysis driven design.

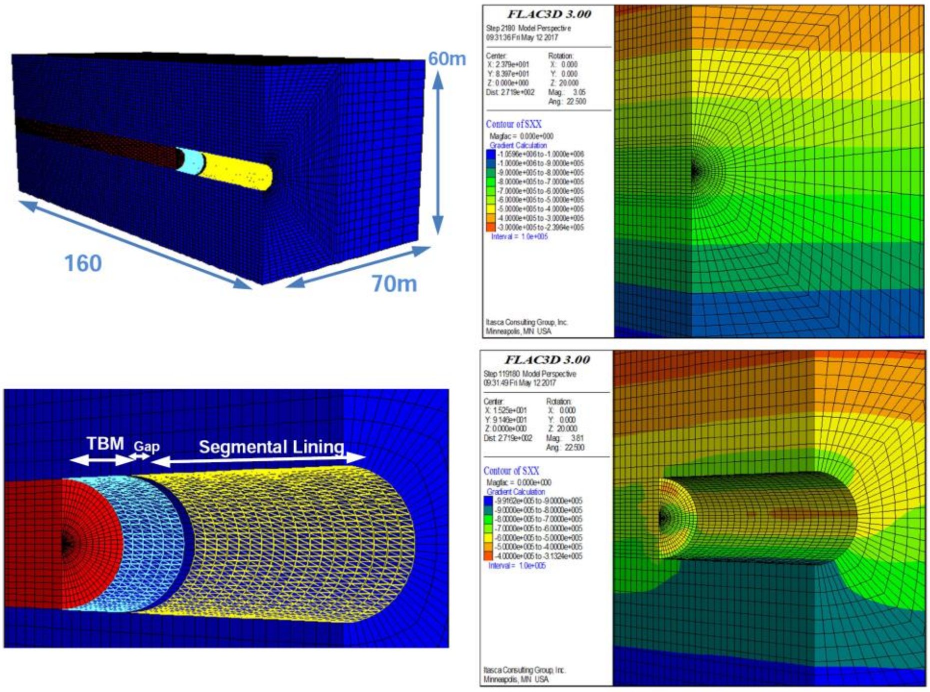
2.2.1 Estimation of stress relaxation

When segmental tunnel lining is installed behind the TBM shield, there is a relaxation of stress in the ground. Activation of lining results in a complex interaction between the ground and the lining as stresses redistribute to a new ground-lining equilibrium (Panet & Guenot 1982).

In order to simulate a tunnel advancing face even with TBM in 2D, the so-called stress reduction method is commonly applied. This method allows simulating real 3D advancement through a 2D plane strain by reducing the fictitious internal pressure acting on tunnel surface (σ_r) from initial field stress (σ0). Partial closure of tunnel is taking place before the lining is installed. Throughout face advancement, internal pressure is obtained as $\sigma r = (1 - \lambda)\sigma_0$ where λ varies between 0 (no stress relaxation) to 1 (completion of stress relaxation, at almost 2~3 diameters form the tunnel face). A relaxation "λ=20%" is recommended, based on measurement of ground pressure on lining, as design reference values in 2D analysis as indicated in literature (Inokuma & Ishimura 1995, Mashimo & Ishimura 2003, Lin et al. 2015,). A series of parametric studies applying 3D models by Finite Difference Method codes of FLAC (Fast Lagrangian Analysis of Continua) have been carried out for this study for different geological conditions and geometry of the tunnels and overburden where the variable parameters were: effective cohesion of ground (c: 0-150kPa), effective friction angle (ϕ: 30°-36°), ground deformation modulus (E: 20-150MPa), ratio of tunnel depth to tunnel diameter (H/D: 1-5). The results of analyses demonstrated that the λ varies between 10%-30% in shallow TBM tunnelling in soft ground. λ is calculated as:

$$\lambda = 1 - \left(\frac{\sigma_{xx,\,final}}{\sigma_{xx,initial}} \right) \quad (1)$$

It was also observed that such a range limit the volume loss under an acceptable range lower than 1.0% as the alternative method to calculate the range of λ is volume loss calculation limiting ground surface settlement (Potts & Zdravkovic 2001).



(a) (b)

Figure 3. Calculation of stress relaxation "λ" by means of 3D FLAC (a) 3D model problem (b) Distribution of deduced stress (σ_{xx}) during TBM advancement

2.2.2 Determination of transfer ratio of bending moment (ζ) and flexural moments deduced in segment and radial joint

One of the main concerns in determining acting flexural moment on segmental rings, when using limited but fast 2D models in absence of radial joints, is to determine the transfer ratio of bending moment (ζ) and resulting bending moment acting on joints and segments. With reference to Figure 4 (JSCE 2006), the transfer ratio of bending moment (ζ) is determined as:

$$\xi = \frac{M_2}{M} \tag{2}$$

where M_2 is the bending moment that is transferred to adjacent rings, M is the bending moment calculated in the ring with uniform flexural rigidity (i.e: η.EI). The effective ratio of bending rigidity "η" is obtained by:

$$\eta = \frac{EI_e}{EI_n} \tag{3}$$

where E is the elasticity modulus of the segmental lining, I_n is area-wise moment of complete section of radial joint, I_s is area-wise moment of force transmission zone of radial joint, I_e is the equivalent area-wise moment of the section defined by Muir-Wood formulation (Muir-Wood 1975) as:

$$I_e = I_s + I_n \cdot \left(\frac{4}{n}\right)^2 \tag{4}$$

where n is the number of segment and n>4 (small key-segment not counted).

The primary BSM is able to model a staggered ring arrangement and real positions of the ring joints (two adjacent rings with rotation) with definition of rotational and shear springs and their rigidity for existing joints. Alternative structural method is, on the other hand, that of a solid ring with a reduced equivalent uniform rigidity, using Equation 4, due to presence of the joints and redistribution of the bending moments by introducing transfer ratio of bending moment "ζ". By means of this simplified method, the bending moment in the segment is added and that in the joint reduced.

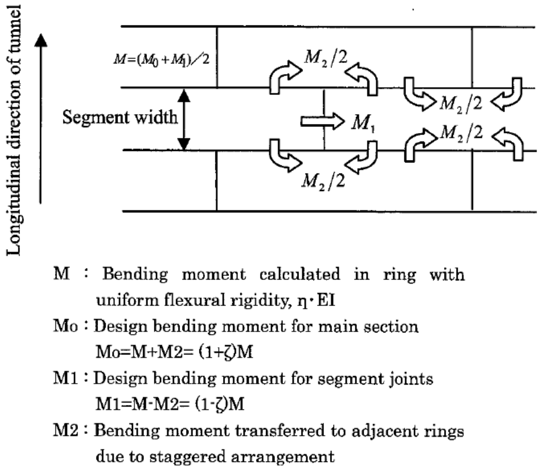
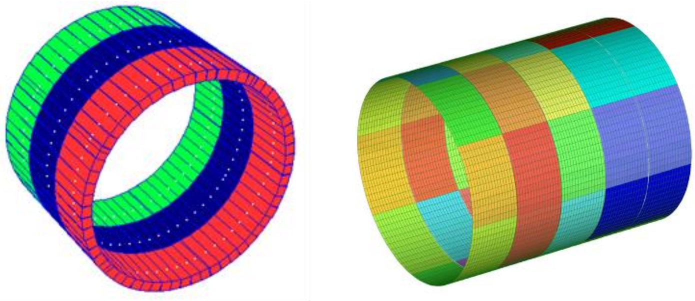


Figure 4. Flexural moments for a segmental lining and transfer of bending moment by joints (JSCE,2006, Article 48)

In order to determine a reasonable range of "ζ" for case of soft ground and shallow condition, a series of parametric BSMs (both in beam and shell elements as shown in Figure 5) have been carried out taking into consideration many variables in terms of ground properties (c, ϕ, E) and problem geometry (H/D) the same as described in 2.2.1.



(a) **(b)**

Figure 5. BSMs used for determining transfer ratio of bending moment- (a) Beam element model (b) shell element model

Three consecutive couple rings have been modelled taking also into consideration the rotation of key-segment as shown in Figure 6.The studied case was for a commonly used segmental ring type of 5+1, with possible rotation of 22.5° for key-segment.

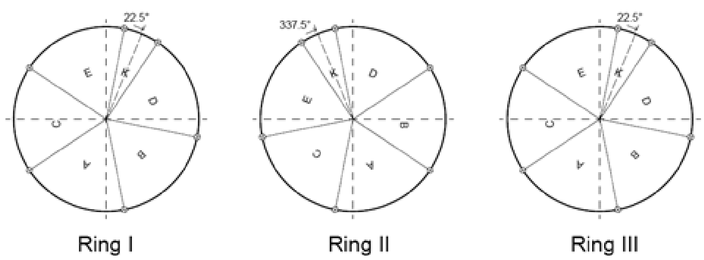
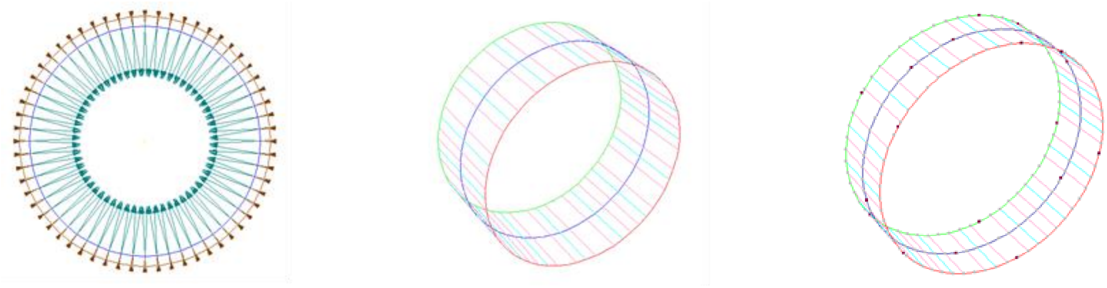


Figure 6. Possible rotation of key-segment modelled in BSM

The results of these parametric calculations have revealed that ζ=0.30 and ζ=0.45 could be used for joint and segment, respectively. This range is compatible with the ζ variation recommended by ITA (2000), Guglielmetti et al. (2007), and Osgoui & Pescara (2014) suggesting that ζ varies between 0.3 and 0.5.

With regard to integrated design method, a series of sensitivity calculations by means of BSM have also been performed for the segmental ring type of 5+1 and rotation case given in Figure 6. The sensitivity calculations were set up in terms of three model cases (1) single ring with reduced equivalent uniform rigidity by means of Muir-wood equation (2) three coupled rings in presence of joints modelled with rotational and shear spring in radial and tangential directions (3) three coupled rings in presence of joints modelled with multiple hinges as well illustrated in Figure 7.



(a) (b) (c)

Figure 7. BSMs used for the sensitivity calculations- (a) single beam model with reduced rigidity (b) coupled rings in presence of joints modelled with rotational and shear springs (c) coupled rings in presence of joints modeled with hinges

The results of the sensitivity analysis for the most critical case in terms of maximum flexural moment are presented in Table 1, giving rise to the conclusion that to achieve a risk-analysis driven approach, carrying out a sorts of sensitivity calculations is of paramount importance. The resulting internal forces (N,M) of model "a" were considered to be the reference model on which the deduced N,M of models "b" and "c" were normalized. By doing this, it makes it possible to compare the acting flexural moment in lining such that the designed lining should be structurally verified even for a worst scenario. As can be observed from Table 1, the flexural moments obtained by coupled rings model are higher than those of single beam model with reduced rigidity.

Table 1. Comparison of the deduced normalized N, M by sensitivity calculations for BSMs

Model: a		Model: b		Model: c	
Single ring model with reduced rigidity by Muir-Wood equation		Coupled ring model with joints modelled as the springs		Coupled ring model with joints modelled as the hinges	
N (kN)	M(kN.m)	N (kN)	M(kN.m)	N (kN)	M(kN.m)
1.0 (1.0)	*1.002* (1.45, ζ=0.45)	1.003	1.7	1.0	1.9

Note: Italic numbers are reference for model "a"

2.3 Design aspects for SFRC segmental lining

SFRC segmental lining has become very popular over the past 15 years because of cost saving arising from eliminating steel rebar cages. In addition, segment damage during construction is reduced. However, the bending capacity of SFRC segment is significantly lower than segments with steel rebars, which limits their use to situations where only moderate flexural moment stress arise. This drawback is compensated using steel ladders at the edge surfaces of concrete segment which is regarded as the combined or hybrid reinforced segment. A good indication for applicability range of SFRC in terms of deduced eccentricity in lining is presented in Figure 8.

Some project design specifications require to uses such hybrid solutions in any bending stress conditions. However, significant benefits of SFRC segment arise from increased impact capacity during construction and increased bearing capacity under TBM ram loads. This makes SFRC segments suitable for use with pressurized-face TBMs.

Regarding metro projects, it is well known that the segmental lining is generally subjected to high value of axial force and low value of bending moment which is ideal for the application of the SFRC. However, special attention should be paid for conditions where the low overburden results in low confinement, which in most case cause unsuccessful structural verifications of SFRC. This state often takes place at inlet and outlet ramp area where only few meters of soil layers cover tunnel. In addition, SFRC might not be a suitable solution at the stress concentrated zone around tunnel where an asymmetrical load affects the tunnels, often happen at cross passage opening area inside the line tunnels. In such a case, the usage of steel segment or a heavier segment reinforced by both steel rebars and steel fibres might be an optimum solution.

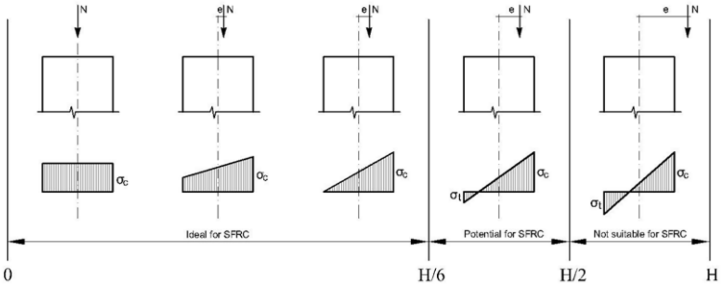


Figure 8. Applicability range for SFRC segmental lining- H stands for section height, e defines eccentricity, N acting load (Smith, 2011)

Ever since the advent of application of steel fibre in concrete segmental tunnel lining, a large number of international and local recommendations have been offered (DBV 2001, RILEM TC 162-TDF 2003, CNR DT 204, 2006, *fib* Model Code 2010, ITAtech 2016, ACI 544.7R-16 2016, ITA-AITES 2016, BTS PAS8810, 2016), of which the recommendations of *fib* Model Code (2010) have intuitively become very prevalent among designers and internationally accepted by consulting firms.

Steel fibres provide a dramatic improvement in the post-cracking behaviour (post-failure behaviour) with a considerable increase in the toughness of concrete. The steel fibres also supply an improvement in the behaviour post-peak compression of the concrete in terms of increasing the ductility. According to *fib* Model Code (2010) and EN 14651 (2003), the residual flexural tensile strength values for different values of Crack Mouth Opening Displacement (CMOD) could be constructed for a given fibre-reinforced concrete beam with specified strength class. The typical curve of residual flexural strength vs CMOD, associated with the ultimate state is demonstrated in Figure 9.

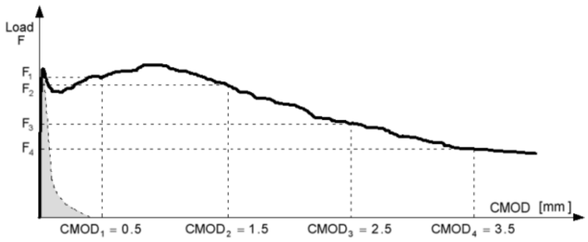


Figure 9. Typical Load F-CMOD curve for SFRC (EN 14651,2003)

It is imperative that, according to EN 14651, beam tests be performed to meet the design requirements. At least nine specimens (SFRC segments) are recommended for the bending test in order to obtain the mean values of residual tensile strength.

The stress-crack opening law in uniaxial tension is defined for the post-cracking range. Two simplified stress-crack opening constitutive laws may be deduced from the bending test results. A plastic rigid behaviour, or a linear post-cracking behaviour (hardening or softening) as schematically shown in Figure 10, where f_{Fts} represents the serviceability residual strength, defined as the post-cracking strength for serviceability crack opening, and f_{Ftu} stands for the ultimate residual strength.

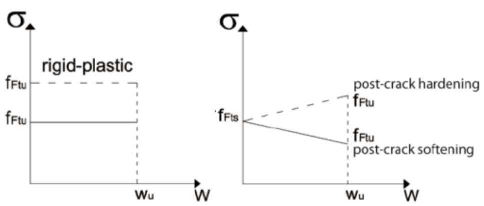


Figure 10. Simplified post-crack constitutive laws: stress-crack opening (fib Model Code, 2010)

The rigid-plastic model identifies a unique reference value, f_{Ftu}, based on the ultimate behaviour. Such a value is determined as:

$$f_{Ftu,k} = \frac{f_{R3,k}}{3} \quad (5)$$

1 On the other hand, the linear model identifies two reference values, f_{Fts} and f_{Ftu}. They have to be defined through residual values of flexural strength by using the following equations:

$$f_{Fts,k} = 0.45 f_{R1,k} \quad (6)$$

$$f_{Ftu} = f_{Fts} - \frac{w_u}{CMOD_3} \cdot (f_{Fts} - 0.5 f_{fR3} + 0.2 f_{R1}) \geq 0 \quad (7)$$

Where w_u is the maximum crack opening accepted in structural design as referred to applied codes.

2.4 Structural verification in ultimate state

Both Ultimate Limit State (ULS) and Serviceability Limit State (SLS) verifications should be made based on *fib* Model Code (2010), where the verification of the bending capacity of the lining cross section is based on a stress-strain relationship as presented in Figure 11. A procedure has been implemented into the Visual Basic to determine the M-N failure envelope by means of systematic variations of the strain distributions within the admissible range. The verification for SLS is carried out in terms of flexural bending-curvature diagram (M-ϕ) where both micro and macro crack formation levels were calculated to be compared with acting bending moment and crack opening width. Depending on class of applied concrete, the flexural moment related to micro crack formation corresponds to the attainment of limit $0.9f_{ctk}$ equal to a relevant deformation in tension side of the section whereas the flexural moment related to macro crack is associated with the attainment of limit of f_{ctk} equal to a relevant deformation in tension side of the section and the occurrence of a macro-crack.

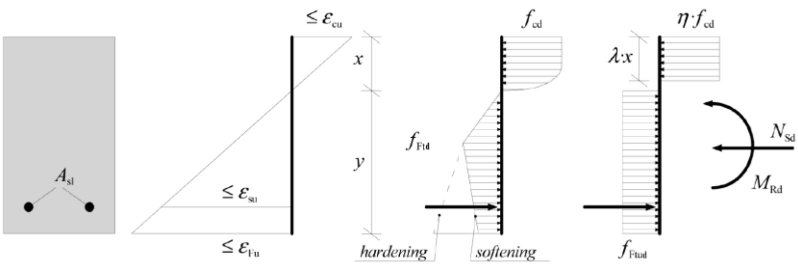


Figure 11. Assumed cross-sectional strains and stress for use in the ULS. ε_{su} is maximum strain in the steel reinforcement and ε_{Fu} is maximum strain in the FRC material. The coefficients η and λ in accordance with Equations 7.2.15 to 7.2.18 of *fib* Model Code (2010)

3 Conclusion

The design aspects for SFRC segmental tunnel lining presented in this paper mainly focused on integrated design approach based on different analysis methods, different load cases and combinations. Such a method is combined with sensitivity calculations, making it possible to turn out a risk-analysis driven method in design of segmental tunnel lining.

This comprehensive method has been demanded by very restrict design specifications found in different mechanized tunnelling projects. Depending on degree of importance of the project and also on design requirements, the design aspects presented in this paper are recommended to achieve any project goal. The recommended design aspects are believed to successfully be applied for any segmental lining project in metro projects.

4 Acknowledgements

The authors of this paper would like to express invaluable appreciation to Mrs. Roberta Agazzoni for her extreme effort in carrying out a large number of numerical calculations, Mr. Diego Neri and El-Amrani for their valuable efforts in implementing Bedded Spring Models. Without their support and assistance, this paper would never have been presented.

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