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Concrete tunnel segments with combined traditional and fiber reinforcement

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ABSTRACT: The paper deals with the concrete lining behaviour at Serviceability Limit State (SLS) in order to evaluate the advantages that result from an optimized reinforcement based on the combination of rebars and fibers with respect to the crack behaviour of segmental lining. For Serviceability Limit State, an analytical model was developed to describe the tension stiffening of a concrete element reinforced with traditional rebars and fibers. A parametric study was carried out to better understand the behaviour of segmental lining with different tunnel depth projections. It is shown that fibers can substitute part of conventional reinforcement and, as additional benefit, significantly improve cracking behaviour of the segment.

1 INTRODUCTION

Fiber Reinforced Concrete (FRC) is a composite material with a cementitious matrix and fibers as discontinuos reinforcement. FRC is already widely used in structures where fiber reinforcement is inessential for integrity and safety, as in industrial pavements or as shotcrete in early stage linings of conventional tunneling (Rossi & Chanvillard, 2000; di Prisco et al. 2004).

For structural applications, steel fibers represent the traditional fiber reinforcement even though several synthetic fibers are nowadays available into the market. Steel fibers remarkably enhance concrete toughness under tensile loading; therefore, the material is able to sustain higher tensile stresses after cracking.

Among the structural applications of FRC (Ahmad et al. 2004), there is a growing interest in precast tunnel segments. FRC could be a competitive design alternative for these precast segments as it would substitute part of conventional reinforcement to allow for time reduction in handling and placing of the curved rebars.

In previous research works (Plizzari & Cominoli, 2005), it was demonstrated that a proper combination of fibers and rebars (RC + FRC) could be a competitive solution for concrete tunnel segments at Ultimate Limit State (ULS).

In the present paper, the structural behaviour of tunnel segments at Serviceability Limit State (SLS) is investigated in order to quantify the benefits in terms of crack control due to the presence of fibers. In particular, a simple analytical model is derived in order to describe the tension stiffening of a concrete element, including the fiber contribution.

The results are applied to a case study of a tunnel lining with an internal diameter of 14,9 m and a thickness of 675 mm. The tunnel design depth projection is approximately 27,4 m (measured from the center line of the lining); therefore the tunnel overburden is equal to 19,3 m (1,2 times the internal diameter D).

A parametric study was carried out by considering several reinforcement combinations and different tunnel depth projections.

2 DESIGN ASPECTS

Precast segments for tunnel lining are generally made of ordinary Reinforced Concrete. An open question for the construction companies and the designers concerns the reinforcement for these precast elements. Generally, the reinforcement should be designed according to two main loading conditions: the embedded soil pressure and the uplift pressure during grouting. In particular, previous studies (Blom, 2002) show that with the latter loading case (grout pressure) the soil support significantly influence the safety of the lining.

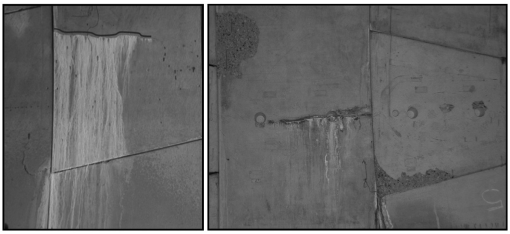


Figure 1. Cracks that typically appear in segmental tunnel linings during the construction phase.

However, other possible additional local mechanisms, which can cause cracking in the linings, should be taken into account. These mechanisms are correlated to the application of thrust jack forces or to a number of phenomena due to the trumpet shape (Blom, 2002).

Previous research works clearly evidence the beneficial effects of Steel Fiber Reinforced Concrete (SFRC) in presence of load concentrations and splitting phenomena that arise in tunnel segments because of the introduction of thrust jack forces (de Waal, 1999, Plizzari & Tiberti, 2006). Cracks often appears in the tunnel lining under the loading conditions mentioned above. Some examples of cracks that typically appear in segmental tunnel linings are shown in Figure 1. Possible causes of these cracks could be eccentricity or inclination of the thrust jacks (Burgers et al. 2007).

It is desirable to mitigate or reduce these cracks as much as possible since they determine a loss of quality, leakage and high repair costs. Cracking phenomena can be limited in tunnel design by using, for example, a proper configuration of the thrust jacks and supports. Alternatively, they can be reduced by using an opportune combination of FRC and conventional reinforcement localized in proper regions of the precast tunnel segment, as shown in Figure 2 (Plizzari & Tiberti, 2007). It consists of an optimized reinforcement based on the combination of fibers and rebars which are localized on the external chords. This underlines that the optimized reinforcement of concrete structures can be obtained by combining conventional reinforcement (rebars or welded mesh) for localized stresses and structural fibers for diffused stresses.

The term “structural” fibers refers to fibers having a high elastic modulus and adopted with a dosage able to guarantee a minimum FRC performance in terms of toughness.

The concentration of rebars in the external chords of tunnel segments may be useful for practical reasons. In fact, it is expected that segments belonging to the same ring can hardly stay in a perfect plane because of the irregularities that are normally present (Fig. 3a). Therefore, the tunnel segments are not supported uniformly by the previous ring, as shown in Figure 3a and

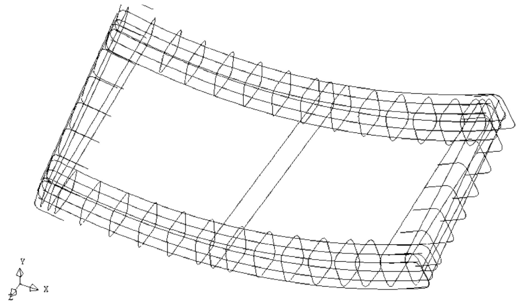
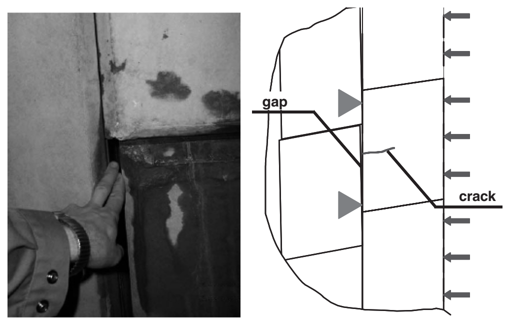


Figure 2. Optimized reinforcement proposed for tunnel segment based on a combination rebars and fibers in FRC.



(a) (b)

Figure 3. Possible gap between rings due to a no-perfect placing process (a); possible irregular support configuration (b).

a bending moment arises in the segment; this moment, in unfavorable cases (for example, when only two supports are present at the extremities) may cause the cracks shown in Figure 1 and in Figure 3b. It is clear that, in these cases, the adoption of fiber reinforcement only, can not compete with the concentrated rebars in a load condition governed by bending that produces localized stresses. However, even under very severe load condition, it was proven that the optimized reinforcement provides a better behaviour than the solution usually adopted in practice (with rebars distributed along the segment; Plizzari & Tiberti, 2007).

Moreover, it is well known that, by adding steel fibers, it is also possible to significantly reduce the amount of stirrups that are normally placed for increasing shear strength as well as the resistance to splitting stresses that are present under the jacks during the thrust phase. Since the shear forces in the final state (embedded soil load condition) are relatively small, the minimum shear reinforcement required could be replaced by fiber reinforcement (Plizzari & Tiberti, 2007).

When referring to service conditions (SLS), it should be observed that, by using FRC, the lining

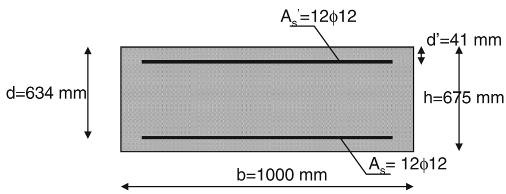


Figure 4. Tunnel lining longitudinal section considered as reference.

Table 1. Mechanical properties of concrete C45/55.

	Charact. Value			Av. Value			Des. Value (ULS)	
Class of strength	f_{ck} [MPa]	R_{ck}	f_{ctk}	f_{cm} [MPa]	f_{ctm}	E_{cm}	f_{cd} [MPa]	f_{ctd}
C45/55	45	55	2,7	53	3,8	33500	30	–

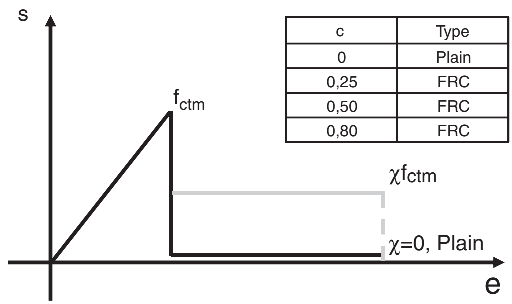


Figure 5. Post-cracking behaviour, constitutive laws adopted for FRC and Plain concrete.

behaviour will significantly improve because of the benefits in terms of crack control due to the presence of fibers.

The behaviour of the lining with combined reinforcement (rebars and fibers) at SLS will be discussed in the following Sections. It should be reminded that tunnel linings are generally structures characterized by low reinforcement ratios where the crack opening control could play a relevant role in structural design.

3 ANALYTICAL APPROACH

A simple analytical procedure to estimate the crack width expected in the lining under service loads is proposed in this Section. In particular, an analytical model was developed to evaluate the maximum bending moment achievable in the longitudinal section, without exceeding a certain maximum crack-opening (w_{max}).

For a tunnel lining, this issue implies the estimation of the bending moment under a specific axial force (N_{SLS}). The analytical model developed herein is principally based on 3 steps (Tiberti et al. 2008):

1) study of the sectional response of the tunnel lining: evaluation of the resistant bending moment-curvature diagram under a certain axial force, N_{SLS};
2) determination of the resistant bending moment (M_{SLS})-average crack opening diagram;
3) steps 1) and 2) are repeated for different normal axial forces (N_{SLS}) that correspond to different tunnel depth projections. As a result, a domain M_{SLS}^{wmax} (corresponding to a maximum crack opening w_{max}) vs. tunnel depth can be determined.

3.1 *Geometrical characteristic of the lining section*

The longitudinal section shown in Figure 4, referring to a tunnel width of 1 m, was adopted as reference for the case study considered herein. A lining thickness of 675 mm was assumed (it corresponds to 1/22 of the tunnel diameter). The longitudinal steel ratio ρ is equal to 0,21%.

3.2 *Material properties*

The study was performed by referring to a normal strength concrete C45/55. The mechanical properties of concrete were determined according to Eurocode 2 (EC2, 2005; Table 1). The concrete elastic modulus was assumed equal to 33500 MPa, since the same value was adopted by Blom et al. (2007) for determining the internal actions (axial force and bending moment), discussed in Section 5. Mechanical properties of concrete and steel refer to the average values in order to better estimate the crack openings at SLS.

The constitutive law proposed by EC2 for concrete under compression was adopted. A very simple tension softening constitutive law was assumed to describe the post-cracking behaviour of FRC under tension. In fact, after cracking, a constant branch was used to describe the residual tensile strength of FRC. This strength is obtained by multiplying the average tensile strength (f_{ctm}) for a multiplier factor χ ($\leq$1; Fig. 5). This performance law was chosen without any explicit correlation to a fiber content. In this way, designers could develop their calculations just assuming a certain FRC performance level, with respect to its post-cracking behaviour. Eventually, concrete technologists should provide an appropriate mix design to achieve the required performance for FRC post-cracking behaviour.

The following χ values were considered in order to simulate different FRC performances: $\chi = 0$ (plain concrete), $\chi = 0{,}25$, 0,50 and 0,80 (Fig. 5).

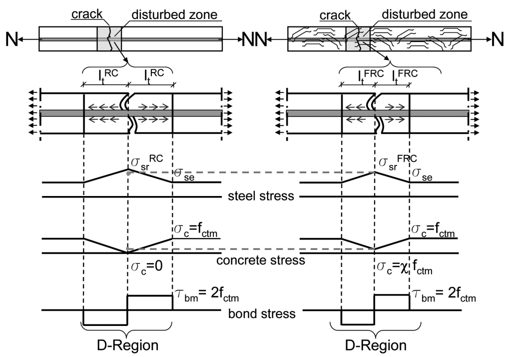


Figure 6. Scheme of the development of stresses in the transmission "disturbed" area.

The conventional reinforcement consists of two layers of rebars B500C with a diameter (Φ) equal to 12 mm whose characteristic yield strength (f_{yk}) is 500 MPa. An average yield strength, $f_{ym} = 575$ MPa and an elastic modulus of 200000 MPa were assumed. An ideal elastic-plastic law was used to describe the behaviour of steel under tension and compression.

3.3 *Tension stiffening local analytical model*

The tension stiffening concerns of the average tensile resistant contribution provided by the uncracked concrete present between two consecutive cracks.

The analytical model proposed by Walraven (1999) was adopted to properly describe the tension stiffening of a RC tunnel lining section. This model describes the behaviour of a RC tensile bar and is based on the following hypotheses:

1) a constant bond stress (τ_{bm}) is present between concrete and rebar (Fehling and Konig, 1988; Fig. 6);
2) where cracks are present, the stresses in plain concrete drop down to zero (Fig. 6).

Fibers link the cracks that exhibit a noticeable local tension softening behaviour with respect to a plain concrete (Figs. 5 and 6). In order to study the sectional response of RC+FRC tunnel lining section, it was necessary to modify the tension stiffening model, including the FRC residual tensile strength.

Figure 6 shows a scheme representing the behaviour at the location of cracks of a tensile bar in plain concrete and in a FRC concrete element; the transmission length (l_t) is evidenced.

By adopting Equation 1 that was developed by Tiberti et al. (2008), a considerable reduction of the transmission length (l_t) can be achieved. Therefore, the use of fibers in combination with conventional reinforcement allows for a reduction of the average crack spacing s_{rm} (Eq. 2), which result in a more uniform crack pattern. As a consequence a smaller crack opening is expected.

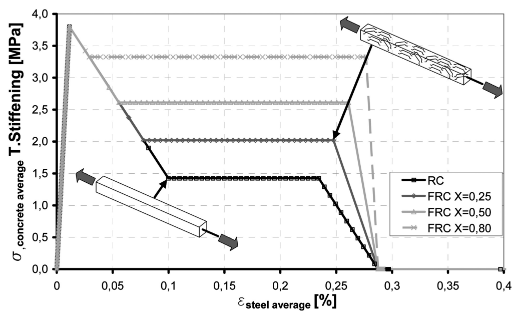


Figure 7. Tension stiffening laws adopted to describe the behaviour of RC and FRC tensile bar.

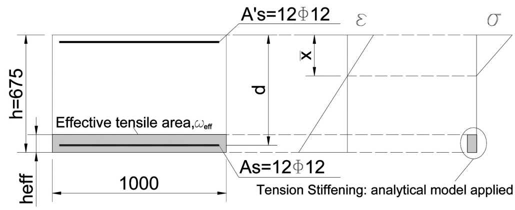


Figure 8. Scheme of the sectional response of the tunnel lining longitudinal section.

$$l_t^{FRC} = \frac{1}{4}\frac{f_{ctm}}{\tau_{bm}}\frac{\phi}{\omega_{eff}}(1-\chi) = (1-\chi)\,l_t^{RC} \quad (1)$$

$$s_{rm}^{FRC} = 1{,}5\,l_t^{FRC} = (1-\chi)\,s_{rm}^{RC} \quad (2)$$

As an example, the tension stiffening law vs. the average steel strain are plotted in Figure 7. Notice that the tension stiffening contribution was assumed to decrease progressively to zero when rebars yield at crack locations (Fig. 7).

In all the derivations it was assumed that the reinforcing steel was uniformly distributed over the cross section (Tiberti et al. 2008). In order to study the sectional response of a tunnel lining, the behaviour of the tensile bar was adopted for simulating an effective tensile area (around the main reinforcement) of a beam (Leonhardt 1976; Fig. 8).

The approach introduced by Fehling & Konig (1988) was used in order to estimate the height of the effective tensile area, h_{eff} (Fig. 8) that is equal to:

$$h_{eff} = smallest:\ 2{,}5(h-d);\ (h-\bar{x})/3 \quad (3)$$

The tunnel lining sectional response at SLS was calculated by applying the proposed local tension stiffening law (for plain and FRC concrete) over the effective tensile area, as shown in Figure 8.

4 LINING BEHAVIOUR AT SLS

Results presented in this paragraph refers to a shallow tunnel depth configuration with a tunnel overburden of 19,3 m (1,2 times the internal diameter).

The following types of reinforcement were adopted: RC (reference design solution), RC + FRC by adopting the following χ values: 0,25–0,50–0,80. The longitudinal steel ratio ($\rho = 0{,}21\%$) was the same for all the configurations.

The comparison of the resistant bending moment vs. crack opening, determined with the proposed model for the different reinforcement combinations adopted, is presented in Figure 9. The diagrams clearly evidence the benefits provided by fibers in combination with regular rebars at SLS. In fact, the RC + FRC configurations exhibit higher resistant bending moments for the same crack opening. As expected, fibers provide a better crack control. The results are also plotted in the same figure in term of percentage of increment. The increment of the resistant moment (ΔM, expressed as a percentage) was calculated according to the following relationship:

$$\Delta M = \frac{M_{w_{\max}}^{RC+FRC} - M_{w_{\max}}^{RC}}{M_{w_{\max}}^{RC}} 100 \qquad (4)$$

Notice that the RC + FRC solution with a χ value of 0,8 is able to guarantee, for a crack opening of about 0,1 mm, the maximum increment of resistant bending moment (about 45%). The RC + FRC with $\chi = 0{,}5$ configuration exhibits an increment of 25% for a crack opening of 0,2 mm.

The reinforcement types adopted were also checked at ULS; as expected, the RC + FRC ($\chi = 0{,}80$) configuration exhibits a maximum bending moment only 5,3% higher than the one with rebars only. Since at ULS the main issue is the ultimate bearing capacity, it turns out that the rebars play the major role while the fiber resistant contribution at that limit state is negligible.

Figure 9 also shows that it is possible to estimate the range of crack opening where a certain fiber content could be effective at SLS. In fact, for crack openings from 0,2 to 0,3 mm, it turns out that the RC + FRC with $\chi = 0{,}50$ shows an average increment percentage (ΔM) similar to the one with $\chi = 0{,}80$, although the fiber content is lower.

A parametric study considering several tunnel depth projections (range of tunnel overburden from 0,4D to 4,51D) was performed. It was possible to carry out the domain M_{SLS}^{wmax} vs. tunnel depth projection, for a specified maximum crack opening, w_{max} (the RC solution was adopted as reference). In the domain, the tunnel depth is measured from the center line of the lining.

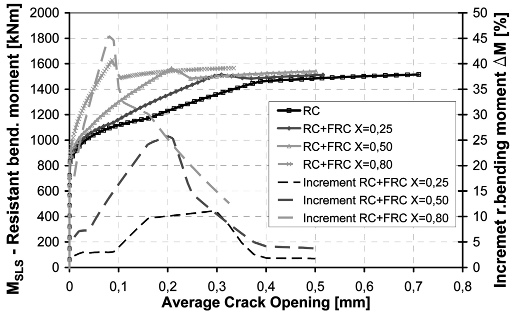


Figure 9. Comparison between different reinforcement combinations: resistant bending moment vs. average crack opening. Diagrams are referred to the design tunnel depth projection.

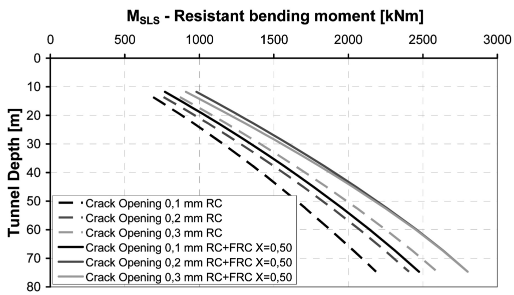


Figure 10. Resistant bending moments achievable for different required crack opening, according to different tunnel depth projections. RC + FRC ($\chi = 0{,}50$) and RC tunnel lining section.

A comparison of the proposed domains (for RC + FRC with $\chi = 0{,}50$ and RC) is presented in Figure 10. Notice that, by considering a certain tunnel depth and a required crack opening, the RC+FRC solution always guarantee higher resistant bending moments.

The percentage of bending moment increment (ΔM) vs. the tunnel depth projection is plotted in Figure 11 for the RC + FRC $\chi = 0, 50$ solution, referring to different maximum crack openings. It can be observed that the RC+FRC configuration is more effective for shallow depths. As an example, by considering a crack opening of 0,2 mm and a tunnel depth of 19,3 m (0,7 D), it is possible to achieve a noticeable increment of about 32%. For deep tunnels, the increment drops to about 16%. This phenomenon is correlated to the significant normal ring (axial) forces acting on the tunnel lining at high depths. When the normal ring force is high, the tunnel lining section behaves like as a pre-stress concrete structure. Therefore, the lining section is already able to exhibit a considerable

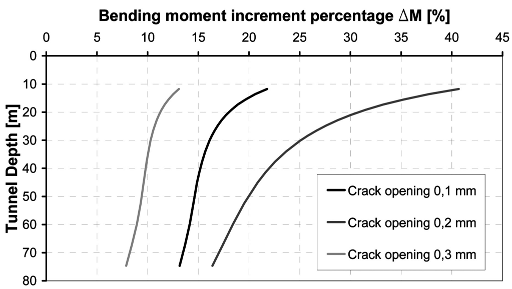


Figure 11. Percentage of increment of the resistant bending moment vs. fiber content for different required crack openings and according to different tunnel depths. RC + FRC with $\chi = 0, 50$.

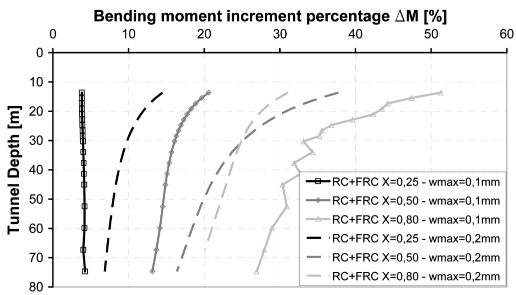


Figure 12. Increment of the resistant bending moment as a function of the tunnel depths for a specified maximum crack opening (0,1 mm and 0,2 mm): comparison between the different reinforcement types adopted.

bending moment bearing capacity without exceeding a required crack opening.

A final comparison of the reinforcement combinations adopted is presented in Figure 12 that exhibits the moment increment for different tunnel depths. The maximum crack openings adopted were 0,1 mm (continuous line) and 0,2 mm (dashed line). The curves help to estimate the most convenient fiber content (χ) to be combined with rebars (whose percentage was fixed to $\rho = 0{,}21\%$ in this example). This allows to find the minimum fiber content which can provide approximately the maximum increment of resistant bending moment. It turns out that, by assuming a maximum crack opening of 0,2 mm, the use of high fiber content (RC + FRC with $\chi = 0{,}80$) combined with rebars tends to be useless. High fiber content (e.g. $\chi = 0{,}80$) are convenient for very low crack openings (less than 0,1 mm) which are usually not of main interest for designers. Therefore, a RC + FRC with $\chi = 0{,}50$ seems to be preferable.

The previous results aims to provide a general trend since they are strictly correlated to the longitudinal steel ratio (ρ) adopted. In fact, by assuming a lower value of ρ, the range of average crack openings where fiber are more effective (at the moment around 0,1–0,2 mm) moves to higher values. On the other hand, by increasing the value of ρ, that range will move to very low values, determining fiber contribution useless because, generally, the maximum crack openings adopted in design are around 0,2–0,3 mm.

5 CONCLUDING REMARKS

The present paper concerns design consideration for segmental tunnel linings, by proposed an optimized reinforcement for both Ultimate (ULS) and Serviceability (SLS) Limit States.

The combination of traditional reinforcement (rebars) and fiber reinforcement was investigated by means of an analytical approach based on the tension stiffening.

The analytical approach adopted enables to quantify the significant benefits provided by fibers in combination with regular rebars at SLS. It has been proven that it is possible to estimate approximately the range of crack opening where a certain fiber content could be of great benefit. At ultimate Limit State, fiber contribution to bending resistance is negligible since the localized stresses (due to bending moment) are better contrasted by rebars.

A parametric study of different tunnel depth projections according to several reinforcement combinations was carried out. It turns out that, by increasing the tunnel depth, fiber becomes less effective and can be used only as minimum reinforcement.

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REFERENCES

Ahmad A., di Prisco M., Meyer C., Plizzari G.A. and Shah S. 2004. "Proceedings of the International Workshop Fiber Reinforced Concrete: From theory to practice", Bergamo, 24–25 September 2004, Starrylink, 222 pp.

Blom C.B.M. 2002. "Design philosophy of concrete linings in soft soils", ISBN 90-407-2366-4, Delft University of Technology.

Blom C.B.M. and Groeneweg T.W. 2007. "Shield driven tunnels in ultra high strength concrete, reduction of the tunnel lining thickness", Delft University of Technology.

Burgers R., Walraven J., Plizzari, G.A. and e Tiberti, G., 2007. "Structural behaviour of SFRC tunnel segments during TBM operations", in World Tunnel Congress ITA-AITES 2007, Praga.

di Prisco M., Felicetti R. and Plizzari G.A. 2004. "Proceedings of the 6th RILEM Symposium on Fibre Reinforced Concretes (FRC)", BEFIB 2004, RILEM PRO 39, 1514 pp.

Fehling, E. and König. 1988. "Zur Risbreitenbeschränkung im Stahlbetonbau, Beton – und Stahlbetonbau", Vol. 83, Nos. 6/7, pp. 161–167, 199–204.

Leonhardt, F. 1976. "F., Rissebeschränkung, Beton und Stahlbetonbau", Vol. 71, pp.14.

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.

Plizzari, G.A. and Tiberti, G. 2006. "Steel fibers as a reinforcement for precast tunnel segments", in the World Tunnel Congress ITA AITES 2006, Seoul, Corea, April 22–27.

Plizzari, G.A. and Tiberti, G. 2007. "Structural behaviour of SFRC tunnel segments", In Proceedings FraMCos 6th, Catania (Italy), June 17–22.

Rossi, P. and Chanvillard, G. 2000. "5th RILEM Symposium on Fibre Reinforced Concretes", BEFIB 2000, RILEM Publications, Cachan France.

Tiberti, G., Blom, C.B.M. and Walraven, J.C. 2008. "Concrete tunnel segments with combined traditional and fiber reinforcement", Technical Report, Delft.

UNI EN 1992 1-1. 2005. "Eurocode 2 – Design of concrete structures – Part 1-1: General rules and rules for buildings".

Waal, R.G.A. de. 1999. "Steel fibre reinforced tunnel segments", Delft, ISBN 90-407-1965-9, Delft.

Walraven, J. C. 1999. "Tension stiffening", Textbook on behaviour, design and performance. Update knowledge of CEB/FIB Model Code 1990, Volume 1 – pp. 189–205, Lausanne, ISBN 2-89394-041-X.