Steel Fibre Reinforced Concrete Tunnel Lining Segments: Design, Construction and Sustainability Aspects

P.L. Ng & A.K.H. Kwan
The University of Hong Kong, Hong Kong, China

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ABSTRACT

In contrast to conventional reinforcing bars that form directional reinforcement in concrete elements, steel fibres form distributed reinforcement to effectively bridge across cracks at all locations and orientations. This improves the resistance to crack proliferation and propagation, ductility, energy absorption capability, and durability performance. Steel fibre reinforced concrete (SFRC) are particularly advantageous for the crack control of concrete elements under complex stress conditions, such as tunnel lining segments. In this paper, an account of the structural design, materials design, construction and sustainability aspects of precast SFRC tunnel lining segments is presented. It is remarked that regarding the fire resistance, polypropylene fibres can be incorporated in conjunction with steel fibres to form a hybrid fibre system for mitigating the risk of concrete spalling under elevated temperature.

1 INTRODUCTION

Steel fibres have offered an alternative way of reinforcement provision for reinforced concrete construction. Conventionally, reinforcing bars are installed as directional reinforcement to resist tensile stresses and control cracking. In contrast, steel fibres act as distributed reinforcement to bridge across cracks in concrete. Depending on the structural configuration and requirement, the steel fibres could be adopted solely or in combination with reinforcing bars as hybrid reinforcement. The crack-bridging capability of steel fibres enhances the resistance to crack proliferation and propagation, ductility, and toughness of concrete elements (Kovács and Balázs 2004; Singh 2017). Therefore, the post-crack flexural and shear resistances, splitting resistance, localized bearing and concentrated stress resistances, bond-slip resistance, as well as energy dissipation capacity could be improved. Moreover, being non-continuous and discrete, the fibres do not provide any mechanism for propagation of corrosion as conventional reinforcing bars do. Any chloride penetration via micro-cracks would not lead to widespread corrosion of discontinuous reinforcement, and hence the durability performance would be improved. Furthermore, in precast construction, unlike conventional reinforced concrete where there is no reinforcement in the concrete covers, the fibres would distribute themselves into the surface, edge and corner regions of the precast elements so as to prevent or reduce damages due to handling and thus minimize the subsequent concrete repair works for rectification.

In view of the above advantages, steel fibre reinforced concrete (SFRC) has been adopted for various applications such as railway sleepers (Parvez and Foster 2017), industrial flooring (Destrée and Mobasher 2022), and tunnel linings (Song and Breitenbücher 2014; Johnson et al. 2017; Kallan 2023), etc. In particular, SFRC is considered highly suitable for precast tunnel lining segments, where crack control under complex stress states during construction and long-term durability are key issues. With reference to the prevailing design practice in Hong Kong, this paper presents an account on the structural design, materials design, construction

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and sustainability aspects of SFRC tunnel lining segments. One additional aspect is the combined use of polypropylene and steel fibres to form a hybrid fibre system for fire spalling resistance.

2 STRUCTURAL DESIGN

Several structural design approaches for SFRC elements have been promulgated in a number of design codes and standards, including the *fib* Model Code 2010 (Fédération Internationale du Béton 2013), ACI Committee Report 544-18 (American Concrete Institute 2018), Singapore Standard SS 674 (Singapore Standards Council 2021), and European Standard EN 1992-1-1 (CEN 2023), etc. Furthermore, the methodologies for determination of engineering properties of SFRC have been specified in a number of testing standards, including the RILEM TC 162-TDF (RILEM 2000, 2001, 2002, 2003), European Standard EN 14651 (CEN 2005), and German DAfStb Guideline (German Committee for Structural Concrete 2012).

2.1 Flexural behaviour

It should be noted that for flexural testing of SFRC, RILEM TC 162-TDF and European Standard EN 14651 adopt the three-point bending test of SFRC notched prismatic specimens, whereas the German DAfStb Guideline recommends to use the four-point bending test of SFRC un-notched prismatic specimens.

For the three-point bending test, the crack mouth opening displacement (CMOD) across the tip of the notch is measured. The highest load level up to CMOD of 0.05 mm is denoted F_L for determining the flexural tensile strength (limit of proportionality). The load levels at other given values of CMOD are also measured (Figure 1) for determining the residual flexural tensile strength, which characterize the flexural toughness.

For the four-point bending test, the loading is exerted at third points of the specimen span, amidst of which the central portion of specimen is subjected to pure bending. The residual tensile stress-strain relationship is obtained from the load-deflection diagram of the specimen.

In general, depending on the fibre content by volume (also called fibre volume or fibre dosage), fibre length, and anchorage resistance, the post-crack regime could exhibit strain softening or strain hardening behaviour. Strain hardening is not a must but would give better ductility and toughness.

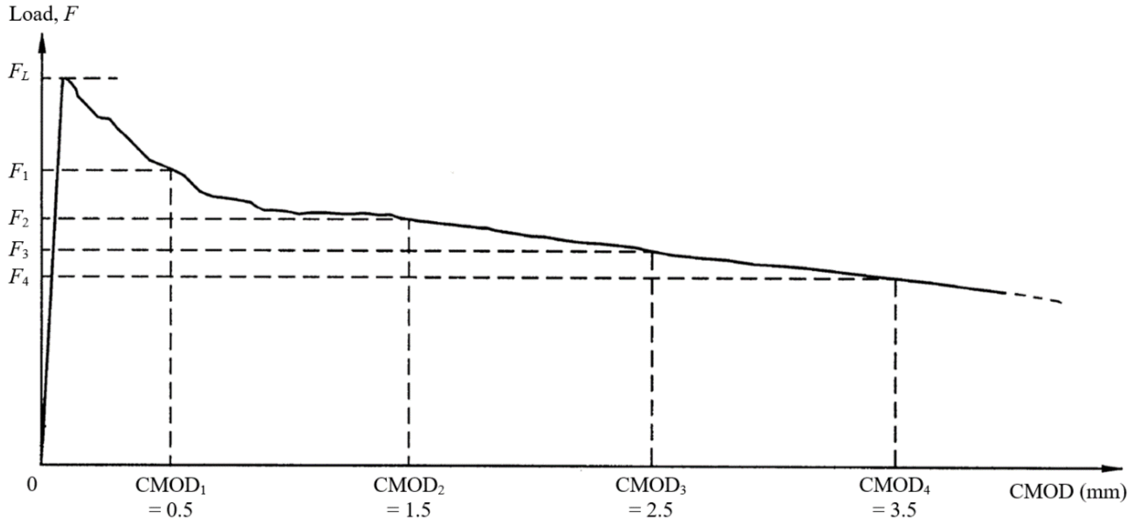

Figure 1: Load versus crack mouth opening displacement in three-point bending test

2.2 Uniaxial behaviour

Regarding uniaxial compression, the compressive strength is only little influenced by the addition of steel fibres, while it is mainly dependent on the concrete mix design parameters such as the water to cementitious ratio and incorporation of condensed silica fume. In structural design, the compressive stress block could be derived in the same manner as for conventional concrete without steel fibres.

Regarding uniaxial tension, direct tension test of SFRC specimens is seldom conducted due to the practical difficulties in performing the test. Therefore, the flexural tensile behaviour is usually referred to. In structural design, the tensile stress block could be derived from the flexural tensile strength and residual values, as further explained later.

2.3 Other mechanical behaviour

According to literature, the steel fibres would only marginally increase the elastic modulus of SFRC (Shadafza and Saleh 2016). As the effect on the elastic modulus is not significant, the elastic modulus of SFRC may be considered the same as the corresponding concrete with no steel fibres in structural design practice.

The shrinkage characteristics as well as the heat generation and thermal expansion/contraction characteristics are not affected by the provision of steel fibres. But, instead of forming a small number of shrinkage and/or thermal cracks with relatively wide crack width, the presence of steel fibres would lead to the formation of a larger number of cracks with finer crack width. Since it is the wide cracks that allow the ingress of deleterious ions and dilapidate the structural conditions, SFRC can alleviate both the shrinkage cracking and thermal cracking problems, with the degree dependent on the fibre volume.

It has been proven that steel fibres could remarkably enhance the impact resistance, fatigue resistance, and abrasion resistance of concrete (Lok and Pei 1996; Liu et al. 2020), and for this reason SFRC is desirable for use in industrial flooring and even in military applications (Zircher et al. 2017).

In particular, when applied to precast concrete tunnel lining segments, SFRC demonstrates a multitude of properties enhancement in comparison with conventional reinforced concrete tunnel lining segments, as summarized in Table 1, which provides the rationale for using SFRC.

Table 1: Properties enhancement by SFRC in precast tunnel lining segments

Property	Performance of SFRC compared to conventional reinforced concrete
Compressive strength	Unchanged
Strength to onset of cracking	Unchanged
Tensile splitting strength	Increased
Workability*	Reduced
Plastic shrinkage cracking	Unchanged
Early thermal cracking	Reduced
Drying shrinkage cracking	Reduced
Resistance to chloride attack	Increased
Resistance to spalling under fire	Slightly increased
Water permeability	Unchanged
Abrasion resistance	Increased
Fatigue resistance	Increased
Impact resistance	Largely increased
Stray current corrosion	Largely reduced

* The reduction in workability could be (partly) compensated by adopting a higher superplasticizer dosage

2.4 Structural analysis and design

The analysis of stresses in SFRC tunnel lining segments under different load combinations during the construction stage and the working stage follows the same procedures as in the structural analysis and design of conventional reinforced concrete tunnel lining segments. The loading in the construction stage encompasses loads arisen from handling, lifting, stacking, bursting, TBM (tunnel boring machine) thrust load, grouting pressure load, etc. As usual, the structural design could be an iterative procedure, depending on whether there is any previous similar design for reference. First, given a (trial) section of lining segment, the structural actions due to different load combinations are evaluated. Then, the axial force-bending moment (N-M) interaction diagram is derived from the lining section properties and the compressive and tensile stress blocks. Figure 2 illustrates the strain diagram and stress blocks of SFRC lining section. The choice between adopting SFRC lining and combining SFRC with reinforcing bars to form hybrid reinforcement lining is primarily affected by the segment sizing and has to be assessed on a case-by-case basis.

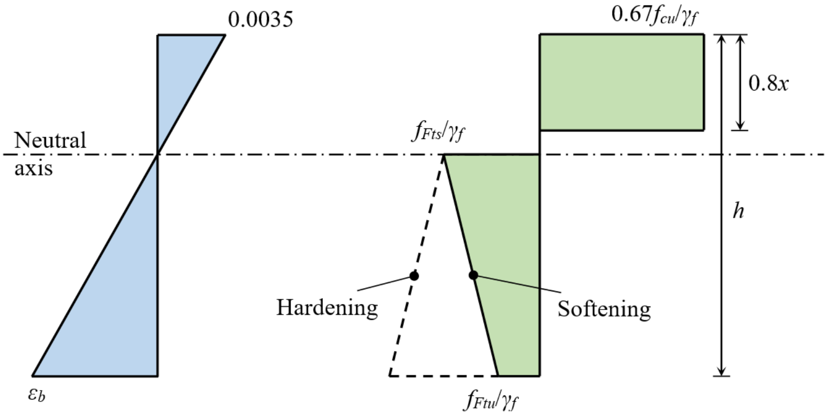

Figure 2: Strain diagram and stress blocks of SFRC

From force and moment equilibria, the following equations of axial force and bending moment can be derived:

$$N=\left[\frac{0.67f_{cu}}{\gamma_f}\cdot 0.8x+\frac{f_{Ftu}(h-x)}{\gamma_f}+\frac{0.5(f_{Fts}-f_{Ftu})(h-x)}{\gamma_f}\right]b \tag{1}$$

$$M=\left[\frac{0.67f_{cu}}{\gamma_f}\cdot\frac{0.8x(h-0.8x)}{2}-\frac{f_{Ftu}(h-x)x}{2}+\frac{(f_{Fts}-f_{Ftu})(h-x)}{2}\cdot\left(\frac{2(h-x)}{3}-\frac{h}{2}\right)\right]b \tag{2}$$

where h = depth of section, x = depth of neutral axis, b = breadth of section, f_{cu} = characteristic cube compressive strength, γ_f = concrete material factor which can be taken as 1.5, f_{Fts} and f_{Ftu} = reference values defining the tensile stress block which can be computed from the equations below:

$$f_{Fts}=0.45f_{R1} \tag{3}$$

$$f_{Ftu}=f_{Fts}-\frac{w_u}{\mathrm{CMOD}_3}\left(f_{Fts}-0.5f_{R3}+0.2f_{R1}\right)\geq 0 \tag{4}$$

in which w_u = maximum crack opening acceptable in structural design and is dependent on the required ductility (w_u could be taken as CMOD_2 or 1.5 mm), $f_{R1}=3F_1L/2b_ph_{sp}^2$ and $f_{R3}=3F_3L/2b_ph_{sp}^2$, where F_1 and F_3 are as defined in Figure 1, L = span length of notched prism specimen which is equal to 500 mm, b_p = width of notched prism specimen which is equal to 150 mm, and h_{sp} = distance between the notch tip and top of specimen which is equal to 125 mm.

By varying the neutral axis depth x in Equations (1) and (2), the N-M interaction curve can be obtained. This provides the basis for checking the structural adequacy of the assumed lining section, through verifying the computed structural actions being within the envelop of the N-M interaction curve.

3 MATERIALS DESIGN

3.1 Concrete materials

The concrete mix design for SFRC and conventional reinforced concrete basically follows the same principles, and the ingredients should comply with the same materials standards (except the fibres which are absent in conventional reinforced concrete). The mix proportioning parameters of water to cementitious ratio, paste volume, fine to total aggregate ratio, and replacement ratios of supplementary cementitious materials, such as pulverized fuel ash (PFA), ground granulated blastfurnace slag (GGBS) and condensed silica fume (CSF) are common to both SFRC and conventional reinforced concrete. However, appropriate adjustments of the contents of ingredients, aggregate grading, and superplasticizer dosage are necessary to accommodate the fibres in the concrete volume and to compensate the workability loss due to fibre addition. Some typical requirements on the concrete mix design of SFRC are listed in Table 2 as an indicative example.

Table 2: Typical requirements on concrete mix design of SFRC

Parameter	Requirement
Characteristic 28-day cube strength (grade strength)	50 MPa
Characteristic tensile splitting strength	3.8 MPa
Characteristic residual flexural strength	2.7 MPa
Characteristic limit of proportionality	4.2 MPa
Maximum nominal aggregate size	20 mm
Supplementary cementitious materials	min. 30% PFA or min. 60% GGBS or min. 25% PFA + 5% CSF
Total cementitious content	min. 400 kg/m^3 and max. 450 kg/m^3
Volumetric ratio of steel fibres	min. 0.5%
Volumetric ratio of polypropylene fibres	Min. 0.1%

3.2 Fibre materials

The requirements of the fibre materials vary with the project specification. Basically, the steel fibres shall comply with European Standard EN 14889-1 (CEN 2006a). They are produced from cold-drawn wire and are un-galvanised. They may have hooked ends for better anchorage in concrete compared to straight fibres. The minimum steel fibre content recommended by some manufacturers is 30 kg/m^3. Besides, polypropylene fibres that possess a relatively low melting point are required to be added to the concrete, in order to provide channels for release of vapour pressure in case of fire. The addition of polypropylene fibres is a proven method to avoid or minimize risk of concrete spalling under fire, especially in high-strength concrete with dense microstructure (Shihada 2011; Lee et al. 2012), and is preferentially adopted for tunnel lining where post-fire repair is in general difficult. The polypropylene fibres shall comply with European Standard EN 14889-2 (CEN 2006b). It is of fine monofilament type with straight geometry and is alkali resistant. Table 3 and Table 4 summarize the typical properties of commonly used steel fibres and polypropylene fibres, respectively. The co-addition of steel fibres and polypropylene fibres forms a hybrid fibre system (Qian and Stroeven 2000; Tawfik et al. 2022).

Table 3: Properties of steel fibres

Parameter	Requirement
Fibre length	60 mm
Fibre diameter	0.75 mm
Aspect ratio	80
Minimum tensile strength	1550 MPa
Elastic modulus	210 GPa

Table 4: Properties of polypropylene fibres

Parameter	Requirement
Fibre length	12 mm
Fibre diameter	0.032 mm
Aspect ratio	375
Melting point	162°C

Ignition point	593°C

3.3 SFRC concrete mix design and testing

Depending on the performance standard set in the project specification, the actual requirements on the concrete mix design of SFRC could be more stringent than those listed in Table 2. In Hong Kong, the performance standard is often set very high and much higher than in other places, and for this reason, the concrete mix design of SFRC in Hong Kong is particularly difficult. Expert advice may be needed, but first of all, we have to sort out the additional requirements on durability (such as RCPT (Rapid chloride penetration testing) and NTB (NT Build) limits (Tang et al. 2012)) and fire resistance (in terms of fire rating, polypropylene fibre content and fire tests to be carried out). The durability and fire resistance requirements are sometimes conflicting with each other and it is not easy to comply with both. For instance, the addition of CSF would improve the durability in terms of RCPT performance but would reduce the fire spalling resistance. At the end, we may have to add more polypropylene fibres than originally planned and thus increase the difficulty of concrete mixing and the cost of SFRC production.

Trial concrete mixing in a laboratory is required to determine the content of each ingredient material and the optimum concrete mix proportions. Trial concrete mixing in the production plant is also required because the mixing method, time of adding fibres and total mixing time could affect the performance of the SFRC produced. Generally, excessively rigorous mixing in a high rotation speed stirrer type mixer should be avoided because this could cause kinking of the steel fibres and/or balling of the polypropylene fibres. Moreover, a somewhat longer mixing time may be needed to achieve thorough and uniform mixing especially when high dosages of steel fibres, polypropylene fibres and CSF are added. For precast concrete construction, a high slump is not needed and in fact not preferred because a high slump achieved by adding a high dosage of superplasticizer may cause bleeding and segregation.

Lastly, due to the presence of rigid steel fibres up to 60 mm long, the concrete cube specimens for testing the cube strength of the SFRC produced should be 150 mm in size instead of 100 mm in size because the use of small cube moulds would affect the fibre distribution and orientation in the concrete cube specimen. And, when carrying out the RCPT for checking compliance with the durability requirement in terms of RCPT total coulomb passed, the SFRC should have the steel fibres removed because the steel fibres are electrically conductive and thus would affect the total coulomb passed (an alternative is to produce the concrete mix without steel fibres added solely for the RCPT test).

4 CONSTRUCTION ASPECT

Fibre entanglement of the steel fibres hampers the uniform dispersion of steel fibres throughout the concrete matrix and thus could adversely affect the performance of the SFRC produced. Fibre entanglement is sometimes described as fibre balling but actually the fibre entanglement of rigid fibres is not the same as the fibre balling of flexible fibres. To reduce fibre entanglement of the steel fibres, the 20 mm coarse aggregate content should be reduced because the steel fibres also entangle with the coarse aggregate particles, and the paste volume of the SFRC may need to be increased so as to provide more paste to wrap around the steel fibres and fill into the space between the steel fibres. In addition, it is recommended to first add all the ingredients except the steel fibres into the mixer for mixing until the mixture becomes uniform and then add the steel fibres in an uncollated manner into the plain concrete mixture without steel fibres in the mixer for mixing.

The steel fibres may be added using an automatic motorized fibre doser equipped with feeder coil and mesh screen (Figure 3) as well as conveyor belt (Figure 4). Basically, the steel fibres are initially filled into the feeder coil, the motor of the fibre doser operates at a controlled fibre feed rate which is synchronized with the conveyor belt by an automatic feedback control system. The steel fibres are then added to the mixer for thorough mixing with the plain concrete mixture in the mixer. This would help to disperse the steel fibres while dosing into the mixer to avoid the formation of clumps due to fibre entanglement.

More recently, it has become quite popular to add the steel fibres to the concrete mixture in the form of glued bundles (Figure 5). The glued bundles each has a fixed weight and a fixed number of steel fibres, and thus no weighing is needed for batching. What is needed is just to add the required number of bundles according to the concrete mix design. The glue would dissolve in the concrete mixture for the steel fibres to get free and disperse in the concrete mixture during mixing. Experience indicates that such method of adding and mixing steel fibres would ensure homogeneous distribution of the steel fibres throughout the concrete mixture to avoid fibre entanglement and formation of clumps, provided of course the mixing time is sufficiently long for the steel fibres to disperse throughout the concrete mixture.

Figure 3: Automatic fibre doser

Figure 4: Conveyor belt for steel fibres

Figure 5: Steel fibres in the form of glued bundles

5 SUSTAINABILITY

The use of SFRC would significantly improve the durability of precast tunnel lining segments by mitigating steel corrosion of continuous reinforcement and by reducing shock damages during installation which could adversely affect the durability of the installed lining segments. With the improved durability and extended service life taken into account, the carbon footprint per year of service would be dramatically reduced. In fact, depending on the structural design, the use of SFRC may help to reduce the thickness of the tunnel lining segments for further reduction of the carbon footprint.

Moreover, the use of recycled steel fibres could provide a great potential of low-carbon construction for circular economy (Soltanzadeh et al. 2022; Shahzad et al. 2023).

6 CONCLUSIONS

SFRC has already been used in many parts of the world for diverse applications. It is particularly advantageous when used in precast tunnel lining segments. It may take time to learn the structural design, materials design, construction and sustainability aspects of SFRC but Hong Kong engineers are smart and fast learners and perhaps in a few years of time, we shall become a world leader in SFRC construction.

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