ABSTRACT: New guideline concerning the use of FRC precast segment has been recently published to provide detail state of the art (ACI, FIB, ITA) and design proposal based on Model Code 2010. This paper will provide an overview of the lessons learnt and proposed design principle. The behaviour of fibre reinforced concrete is more than a simple superposition of the characteristics of the concrete matrix and the fibres. A unique concept of fibre has been developed which combined: high tensile strength + perfect anchorage (double hook) + ductile wire. This unique post cracking behaviour has been used to design very innovative solution. Three projects will be presented in this paper: the inner lining of Lee Tunnel in UK submit to internal pressure, the Jansen Mine shaft in Canada where shaft walls are slip formed and CIP tunnel in Turkey. All the design approach has been supported by a specific testing program.

1 INTRODUCTION

Steel fibres have been used to reinforce concrete since the early 1970s. Employed initially for applications such as industrial flooring, the 1980s saw the start of underground applications, in first shotcrete and then in both precast tunnel lining segments and Cast in Place Final lining.

However, a lack of regulation and standards hampered the spread of fibre-reinforced concrete for final tunnel linings. With the publication of international design guideline, the fib Model Code for Concrete Structures 2010 (Fib Bulletins), this obstacle has been overcome and designers are gaining confidence in working with fibres. “This publication is targeted to be a source of information for updating existing codes or developing new codes for concrete structures. It specifically addresses non-traditional types of reinforcement, such as steel fibres, that have reached a status of recognition in previous years, with special attention being given to the use of fibre concrete in structural applications. At the same time, the Model Code is also intended to be an operational document for normal design situations and structures”.

2 FRC BASIC PRINCIPLE

Steel fibres come in many different sizes, shapes and qualities with each having its own effect on the concrete behaviour and quality. The dosage of fibres needed to meet the desired structural performance will vary, depending on the characteristics of the fibre itself.

The behaviour of fibre reinforced concrete is more than a simple superposition of the characteristics of the concrete matrix and the fibres. To analyse the behaviour of this composite material, the way that the loads transfer between concrete matrix and fibre also must be taken into consideration.

For efficient load transfer, three conditions must be satisfied. There must be sufficient exchange surface, governed by the number of fibres, their length and diameter; the nature of
the fibre-matrix interface allows for a proper load transfer; and the mechanical properties of the fibre such as Young’s modulus, tensile strength and anchorage strength must allow the forces to be absorbed without breaking or excessively elongating the fibre.

To analyse the performances of fibre concretes, we must consider the combination of fibre and concrete as a composite material, which means integrating the transfer of the concrete matrix charges to the fibres network. This transfer is schematically shown in three distinct steps, identified on the following typical graph corresponding to (Asquapro technical booklet):

![Figure 1. schematically graph explaining the load transfer.](image)

Felmax: Maximum strength corresponding to the elastic limit of the fibre material Fpost fissmin: Minimum force reached after cracking.

Fpost fissmax: Maximum force reached after cracking, thanks to the absorption of forces by the fibres.

In the guideline published by Asquapro the following step are described:

Step 1: Adhesion over the entire length of the fibre during the phase of elastic strain, depending on:

- the specific exchange surface area (number, length, diameter of the fibres),
- the surface quality and thus the quality of the interface fibre/matrix,
- the compactness of the concrete matrix.

Step 2: Mobilization of the fibres right under the micro cracks, depending on:

- the elasticity modulus of the fibres,
- the number of fibres,
- the profile and orientation of the fibres,
- the quality of the interface fibre/matrix (adhesion),
- the compactness of the concrete matrix.

Step 3: Full mobilization of the anchoring, which may prove to be « total » or « sliding » (in support, « sliding » is sought-after):

- the shape of the anchoring,
- the possible sliding of the fibre in its sheath (interface quality and orientation fibre/charts),
- the compactness of the concrete matrix,
- the number of fibres,
- the tensile strength of the fibre.

This transfer is efficient if the following three points are observed:

1. The exchange surface is adequate (number, length and diameter of fibres). For example, an inadequate number and length of fibres can lead to fragile behaviour even if the characteristics of the interface and of the fibres are satisfactory. Indeed, the loads then not being sufficiently transferred to the fibre network, the crack may bypass the fibres and the break becomes fragile.
2. The quality of the fibre/matrix interface allows a good transfer of loads (anchoring of the fibre in the concrete). Although the number and characteristics of the fibres are satisfactory, an inadequate anchoring of the fibres (slipping, little compact interface) causes a fragile or pseudo-fragile break; the fibres are extracted from their concrete sheath without mechanical stress or with a stress widely below resistance capacity.

3. The intrinsic mechanical properties (Young’s modulus and tensile strength) of the fibre allow to take up the stresses without a risk to break or to stretch too much. In contrast, a fibre with insufficient properties causes a fragile behaviour despite a large number of fibres and an effective interface. A fibre with a low Young’s modulus leads to a large crack before the fibre take up the stresses. A fibre whose tensile strength is lower than the capacity of the anchoring, will break in its concrete sheath before being extracted.

3 FRC BASIC DESIGN PRINCIPLE

The existing technical guidelines/recommendations/codes provide the structural engineer advice on how to quantify the reinforcing properties of steel fibres based on the measured post crack tensile strength of SFRC.

Figure 2. Design process.

In accordance with fib CEB-FIP Model Code 2010, the structural design of SFRC elements is based on the post-cracking residual tensile strength provided by the steel fibres. Nominal values of the material properties can be determined by performing a flexural bending test: one of the most common refers to the EN 14651, which is based on a 3-point bending test on a notched beam.

Figure 3. Flexural bending test set up.

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The results can be expressed in terms of force (F) vs. Crack Mouth Opening Displacement (CMOD). In order to obtain reliable statistically results, a minimum of 6 beam tests are recommended. A typical F-CMOD curve for FRC is shown below (figure 4):

![F-CMOD curve](image)

Figure 4. F-CMOD curve.

Parameters $f_{R,j}$ representing the residual flexural tensile strengths are evaluated from the F-CMOD relationship according to the below equation (simplified linear elastic behaviour is assumed):

$$f_{R,j} = \frac{3F_{R,j}l}{2bh_{sp}^2}$$  \hspace{1cm} (1)

Where:
- $f_{R,j}$ is the residual flexural tensile strength corresponding to CMOD = CMOD$_j$
- $F_{R,j}$ is the load measured during the test [kN]
- $l$ is the span length (distance between support) = 500 mm
- $b$ is the width of the beam = 150 mm
- $h_{sp}$ is the distance between the tip of the notch and the top of the beam = 125 mm

From the above residual flexural tensile strengths, the characteristic values can be evaluated as follows:

$$f_{R,k} = f_{R,j0} - k \sigma$$  \hspace{1cm} (2)

Where:
- $k$ is the Student’s factor dependent on the number of the specimens
- $\sigma$ is the standard deviation of the test results.

For the classification of the post-cracking strength of FRC, a linear elastic behaviour can be assumed, by considering the characteristic residual flexural strength values that are significant for serviceability ($f_{R,1k}$) and ultimate ($f_{R,3k}$) conditions.

In particular two parameters, namely:

- $f_{R,1k}$ Minimum value for SLS
- $f_{R,3k}$ Minimum value for ULS

The designer has to specify these two minimum values.

Fibre reinforcement can substitute (also partially) conventional reinforcement at ultimate limit state, if the following relationships are fulfilled:

- $f_{R,1k}/f_{L,k} > 0.4$
- $f_{R,3k}/f_{R,1k} > 0.5$

In FRC design process a specific constitutive model must be considered.

A typical constitutive model used for FRC, especially at low strain level, is the rigid plastic.
4 FRC INNOVATIVE SOLUTION

4.1 Precast segment

Fibres can be used as reinforcement in precast concrete segment tunnel linings, either “fibre only” or in combination with conventional (bar) reinforcement, “combined solution”. Its state of the art is defined by a large number of reference projects, where fibre reinforced concrete (FRC) segments have been used successfully. Projects using FRC segments report the following benefits of its use:

- Excellent durability
- Handling, installing damage and repairs are minimized
- Performance in the relevant ULS and SLS can be reliably demonstrated
- Overall manufacturing costs are lower than for conventionally reinforced concrete

This year there has been a flurry of additional guidance for fibre-reinforced segments: the American Concrete Institute’s (ACI) Report of Design and Construction of Fibre-Reinforced Precast Concrete Tunnel Segments (ACI 544.7R-16); the International Tunnelling and Underground Space Association (ITA-AITES)’s Twenty Years of FRC Tunnel Segment Practice: Lessons Learned and Proposed Design Principles; BSI PAS8810:2016 Tunnel Design – Design of concrete segmental tunnel lining – Code of Practice; and ITAtech Guidance for Precast Fibre Reinforced Concrete Segments – Vol. 1 Design Aspects.

A minimum performance class as C40/50 4c for the FRC as described by Model Code 2010 is recommended.

The use of fibre as Dramix 4D 80/60BG with the following properties are recommended as:

- $l/D = 80$
- Tensile strength $> 1800$ Mpa
- Optimum anchorage

Figure 5. Simplified rigid-plastic constitutive relationship for FRC tensile behaviour.

Figure 6. EN 14 651 test result with 4D 80/60BG.
• Glued for easy mixing and homogeneous reinforcement

The goal is to guaranty with the lowest dosage as possible a clear hardening post crack behaviour on beam and confirm on test scale 1 realized on segment.

4.2 Permanent spray concrete lining

Fibre reinforcement in the secondary linings of Sprayed Concrete Lining (SCL) designs, such as those used for Crossrail’s station and platform tunnels, is also becoming more commonplace. And, as this article demonstrates, designers now have the option of fibre-reinforced concrete for cast-in-situ final linings too.

This application will be also structural reinforcement and could be design using the same process. Shorter fibre length 35mm and 0.55mm are commonly used to ensure with 20kg/m$^3$ already a network of 10 000ml/m$^3$. Glued and high tensile strength (> 1800Mpa) are recommended to meet project requirement. The typical Dramix 4D 65/35BG will be used for this application

4.3 Cast in place final lining

Bekaert spent five years developing the 5D fibre, trying many combinations of hook design and wire strengths to optimise the performance and the cost. The goal was to create a fibre that could be used in structural applications such as foundations slabs, rafts, suspended structures – and the final linings of tunnels.

Dramix 3D – the name for the Bekaert Maccaferri’s original steel fibre – and the Dramix 4D, which uses higher-strength wire both work in the same way. The kinked ends provide ductility to the concrete by the slowly deforming as the wire is pulled out of the concrete. This is the mechanism that generates concrete ductility and post-crack strength.

The Dramix 5D fibre, with four kinks at either end rather than two or three respectively, actually works in a totally different way to its siblings the 3D and 4D: a revolution rather than evolution. Rather than relying on the pull-out mechanism of the fibres to provide ductility, the 5D does not pull out but remains anchored, lengthening itself - as rebar does - to provide ductility.

The tensile strength of a steel fibre has to increase with the strength of its anchorage, otherwise it would snap causing the concrete to become more brittle. So, the 4D, for example, with its stronger anchorage is made of stronger wire than the 3D. The 5D uses wire with a tensile strength of 2.2N/mm$^2$ and ductility of more than 6 percent.

Figure 7. Dramix 5D a unique combination.
Very soon after the launch of Dramix 5D fibres in 2013, UnPS became one of the first designers to take advantage of the fibres’ superior properties on London’s multi-million-pound Lee Tunnel (Psomas et al 2014).

The decision to use the fibres was driven by the need to reduce crack widths – although it yielded other The Lee Tunnel in Beckton, London is the first tunnel to be nominated and to win the prestigious UK Concrete Society Award. Built as part of the Thames Tideway CSO project, the tunnel is lined with an innovative Dramix 5D steel fibre reinforced concrete.

Generally inner linings that are reinforced are done so when tension is induced into the lining. For example, hydro and/or sewer tunnels with a high internal head pressure places the inner lining into tension and therefore requires reinforcement to resist the tension in the lining and control cracking.

The design and fabrication of the traditional reinforcement in such a tunnel as the Lee Tunnel would have been a major logistical challenge to the construction team at the jobsite – an estimated 17000 tons of reinforcing bar would have had to have been delivered, stored, transported underground and fixed into position – with iron workers working at height off work platforms of some description in what is technically a confined space and consuming valuable time within the program. One may argue that this operation would have been undertaken as the concrete pours progressed. However, the logistics of moving the high volume of bar reinforcement through the tunnel is a high-risk operation and places additional numbers of operatives and equipment underground and in the immediate vicinity of the concrete works.

MVB JV decided after much research over the last year or so to use the relatively new 5D Dramix steel fibre: this has a double hooked end and a much higher wire tensile strength than the 3D standard Dramix steel fibres previously used. These changes to the fibre geometry and technical characteristics provides the 5D fibre concrete with strain hardening in bending properties that enabled the designer (MS UnPS) of the secondary inner lining to verify the governing design situation for structural crack control.

Figure 8. BRE testing – multi cracking.

Figure 9. BRE testing – multi cracking over loading span 1.645m.
All hook ended steel fibres, when under loading tend to deform/straighten out by pulling out of the concrete and so a controlled deformation occurs providing the energy absorption that can be measured by beam and plate testing, however the Dramix 5D steel fibre has these double hooked ends and these remain anchored in the concrete, the wire itself is some 2300MPa and this elongates some 7% just as traditional reinforcement behaves and this is what provides the steel fibre concrete element with the bending hardening properties and therefore provide designers with more opportunities to design steel fibre concrete structures both underground and surface structures.

By researching on a large scale seen above and by careful examination and analysis of the results the Designer (MS UnPS) & MVB JV decided to replace the standard traditional reinforcement with the 5D Dramix steel wire fibres – so removing some 17000 tons of bar with >2000 tons of the 5D Dramix steel fibre and eliminating the very large and difficult logistical challenge that would have been placed before the contractors underground team.

However, before work could start underground with the secondary lining, much work was required to establish a suitable concrete mix design that would pump up to 250m and virtually self-compact itself in the enclosed shutter within the tunnel lining. The concrete mix design (and final refinement) has taken almost 6 months to be able to work well and maintain its performance after pumping such distances and while not a great distance compared to some projects it still has to be able to almost self-compact with very little vibration. It isn’t designed as a self-compacting concrete – the contractor wished to avoid any risk of the steel fibre segregating, fibre distribution was checked on the early pours and the indications showed there is excellent fibre distribution based on retrieved cores from the first pours in the works that suggest that the two principal orientations are in hoop and longitudinal direction, further analysis is being considered using X-ray photography.

The Riva Tunnel is another underground project to use the new Dramix 5D series fibres which can be used to create a material which has a far greater residual strength after cracking than other fibre-reinforced concretes, behaving more like traditionally reinforced concrete. In each of the three cases, designers and constructors faced challenges around constructability or durability – or both – of the final lining which have been solved with the help of this new breed of fibre.

When contractor IC Ictas-Astaldi came to fix the rebar for the secondary lining of the Riva Tunnel in Istanbul, it ran into some problems. The 22m-wide tunnel required reinforcing bars up to 12m long to be fixed; this was proving difficult to do, introducing safety risks and causing damage to the sheet waterproofing membrane which sits between primary and secondary lining.

The solution was a bold and unusual one for Turkey: using fibre-reinforced concrete to create the permanent secondary lining. Following careful evaluation and tests at Istanbul Technical University, designer EMAY International was able to demonstrate that by using high-performance steel fibres a fibre-reinforced concrete lining would be just as good as one reinforced using steel reinforcing bars.

The latest project to make use of 5D’s characteristics is the Jansen project, the development of a new potash mine in east-central Saskatchewan, Canada. Contractor DMC Mining is slip-forming the walls of two 1000m-deep shafts, aiming for production rates of 3m a day.

The future will see more use of 5D fibres in the permanent linings of tunnels and shafts. Several projects are already being designed using the fibre and others are considering its use as an alternative to traditional reinforcement for the final lining. Other underground applications have included track slab inside rail tunnels and free-spanning slabs in car parks.

5 CONCLUSION

The possibility of adopting fibre reinforced concrete, without traditional steel reinforcement for precast tunnel segments and cast in place final lining is herein analysed, with reference to test scale 1 and some project realized worldwide.
A minimum performance class or the FRC as described by Model Code 2010 should be defined according to the project requirement. Fibre materials with a Young’s modulus which is significantly affected by:

- time and/or
- thermo-hydrometrical phenomena

are not covered by this Model Code.

Steel fibres are suitable reinforcement material for concrete because they possess a thermal expansion coefficient equal to that of concrete, their Young’s Modulus is at least 5 times higher than that of concrete and the creep of regular carbon steel fibres can only occur above 370 °C (ISO 13270).

FRC has proven over the years to be a reliable construction material. State of the art concerning steel fibre is complete and validate by the scientific community through many standards and guideline. After 30 years of experience, the first Rilem design guidelines for steel fibre concrete were edited in October 2003 and Model Code 2010 published by fib in 21012 is now recognized as the reference design standard.

Nevertheless, in order to obtain the desired results, it is worth noting the necessity to develop an accurate study of the material, i.e. the fibre typology suitable to a peculiar matrix.

In order to optimize the FRC solution some investigation should be conducted at early age of the design process with all actors involved in the project.

There is no good and bad fibre but just the right fibre for the right application using the Relevant testing method to determine engineering properties and for quality control.

The use of the finished material should be considered along with the test and performance criteria, post-crack behaviour, match crack widths and deformation in the test to expectations in the project and durability requirement.

REFERENCES

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