The use of steel fibre reinforcement in Lee Tunnel Project

Model Code New design perspective
Precast segment and shaft slip formed inner lining

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Abstract

The Thames Water Lee Tunnel is the first stage of an enhancement to London's sewer system which will remove the discharge of combined storm water and sewage to the River Thames and lower River Lee. This paper will provide project description, main test result realized for this project and design approach using steel fibre reinforcement for the precast segment and slip formed inner lining

Precast segment manufacture for London's deepest ever tunnel, Thames Water's 6.8km long, 7.8m diameter, Lee Tunnel sewer project, is under construction. The Lee Tunnel will be the largest diameter tunnel in the UK to use steel fibre only reinforcement to date, but this is nothing new for the companies involved with the project and at the precast plant. The precast plant at Ridham Dock have been working with fibres for over 10 years, since the factory was first set up to produce segments for the London Heathrow Terminal 5 tunnel extensions to the Heathrow Express and the London Underground Piccadilly Line. The benefits of using steel fibres are significant, resulting in reduced manufacturing costs, improved durability and crack resistance and less damage during handling.

Also a new challenge was to introduce SFRC for the shaft slip formed inner lining. The Beckton Overflow Shaft's internal lining is probably the largest structure ever slip-formed using only steel fibre reinforcement. This is a radical structural rethink of the shaft lining design and has eliminated more than 500 tonnes of reinforcing steel from the Beckton Overflow Shaft. The adoption of this design approach and construction methodology at the Beckton Overflow Shaft has led to the decision to adopt the same approach for the Connection Shaft and Abbey Mills Shaft.

Introduction

The 7.2m ID, 6.9km long Lee Tunnel is under construction in East London between the Beckton Sewage Treatment Works and the Abbey Mills Pumping Station complex. With depths ranging from 65m and 80m, it is London's deepest tunnel. When completed in 2015, it will reduce by 40% the foul water discharges to the River Thames system in London.

In January 2010 Thames Water commissioned contractor MVB Consortium (comprising Morgan Sindall, Vinci Construction Grands Projets and Bachy Soletanche) to design and build the Lee Tunnel under the NEC 3 Option C form of contract. Four shafts, the largest ever constructed in London, have been completed. The main tunnel is being constructed through the Chalk using a Herrenknecht slurry shield TBM. Groundwater pressures of up to 8 bar are expected.

This paper will focus on the use of SFRC for this big project and specific testing program realized and will include a basic introduction of the new model code edited by fib in 2010 and officially approved in 2012. A description of the innovative design concerning the precast segmental and inner slip formed inner lining. Some innovative aspects of the main tunnel drive will be described, as well as other interesting facets of this huge and exciting project.

Basic Project description

For the last 150 years, London's wastewater has been disposed of through an elaborate network of interceptor sewers built by Victorian engineer, Sir Joseph Bazelgette. This system was a single combined storm water and sewer network, which incorporated over 50 (No.) Combined Sewer Overflows (CSOs) to the River Thames and the River Lee. These overflows were designed to operate only during occurrences of exceptionally heavy rainfall, but now significant discharges happen, on average, at least once a week, and can be triggered by as little as 2mm ofrainfall. The discharges exceed the requirements of the Urban Wastewater Treatment Directive (UWWTD) as enacted in the Urban Wastewater Treatment Regulations 1994. To comply with the UWWTD, Thames Water have proposed a program of work to upgrade London's five principal sewage treatment works (at Mogden, Crossness, Beckton, Long Reach and Riverside), as well as undertaking two major tunneling projects, which will collect and transfer both foul sewage and storm water run-off to the upgraded and enhanced treatment works. This article details the first of the two Thames Tideway Tunnels, the £635m Lee Tunnel.

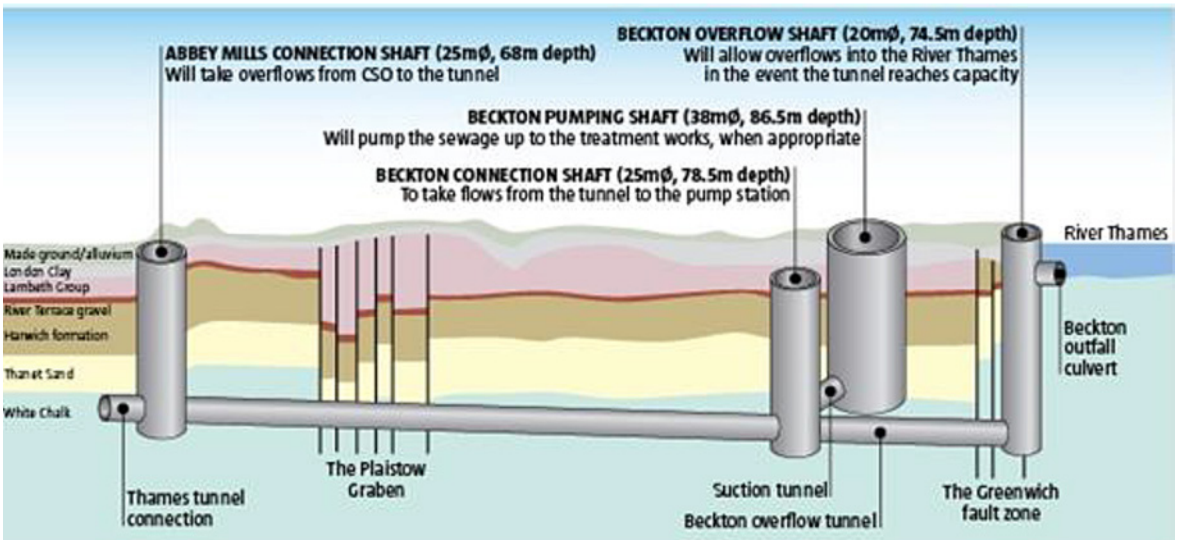


Figure 1. Project description

Fibre Reinforced Concrete:
MODEL CODE 2010 new performance class proposal

After more than 40 years of research on FRC guidelines for structural design of FRC elements are now available within the new fib Model Code 2010 (fib, 2010) that represents an update of the previous CEB-FIP Model Code 90 (1993); the latter can be considered as the reference document for many international building codes and, in particular, for Eurocode 2 (2005). Construction materials require Standards for measuring their mechanical properties and for quality control. Mechanical properties of FRC are traditionally determined from beam tests that are usual EN 14 651 “Test method for metallic fibered concrete - Measuring the flexural tensile strength (limit of proportionality (LOP), residual)”.

This European Standard EN 14 651 specifies a method of measuring the flexural tensile strength of metallic fibered concrete on moulded test specimen. The method provides for the determination of the limit of proportionality (LOP) and of a set of residual flexural tensile strength values. This testing method is intended for metallic fibres no longer than 60 mm. The method can also be used for a combination of metallic fibres and, a combination of metallic fibres with other fibres, generally micro polypropylene.

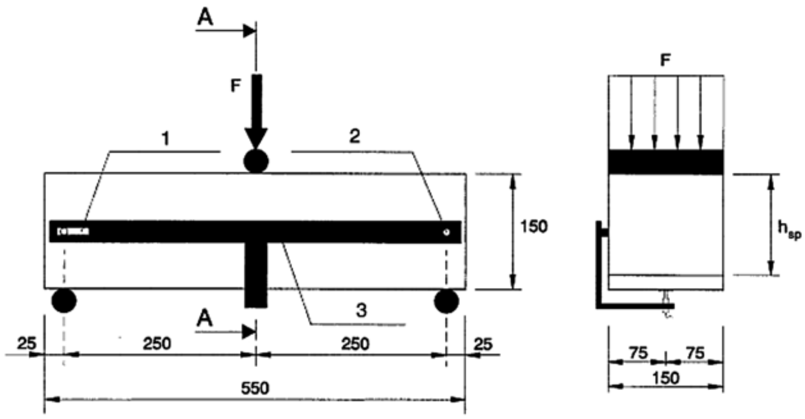


Figure 2: Three point bending test with notch according to EN 14 651

The residual flexural tensile strength fR,j is given by the expression:

$$f_{R,j} = \frac{3F_j l}{2bh_{sp}^2}$$

Where:

$f_{R,j}$ is the residual flexural tensile strength corresponding with *CMOD* = $CMOD_j$ (*j* = 1,2,3,4), in Newton per square millimeter.

The static calculation of the Fiber Reinforced Concrete elements should be made by considering the prescription of the FIB Model Code 2010. This document, approved in October 2011 by the FIB represents the reference document for the future Eurocodes on concrete materials. The document is chosen because it is the most advanced one regarding the fiber reinforced concrete. The adoption of this document allows the designer to analyze not only the structural strength at ULS but also to verify the ductility of the elements and to perform a design at SLS, with crack opening limitations.

The behavior of the FRC in tension will be characterized by considering the three point bending tests defined in the EN 14651. In order to identify the constitutive law, residual flexural tensile strengths f_{Rj} are used.

Since the residual strength varies during the test, at least two deformation values should be considered: the first one should be significant for serviceability conditions (SLS) while the second one should be significant for Ultimate Limit States (ULS). European standard EN 14651 (2005) requires four different values of the residual strength (*fr1, fr2, fr3, fr4;* corresponding to different values of the Crack Mouth Opening Displacement (*CMOD* = 0.5, 1.5, 2.5 and 3.5mm, respectively) of the notched specimen. The two parameters significant for SLS and ULS can be chosen as the values *fr1* (corresponding to $CMOD_1$ = 0.5 mm) and *fr3* (corresponding to $CMOD_3$ = 2.5 mm), respectively.

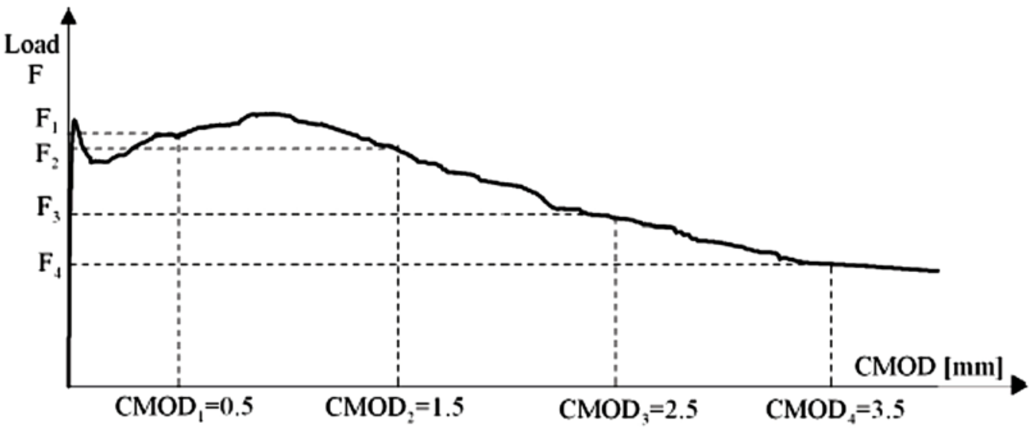


Figure 3: result of Results of the beam test – Load vs crack mouth opening displacement (CMOD)

With the previous assumptions, FRC toughness can be classified by using a couple of parameters: the first one is a number representing the fR1 class while the second one is a letter representing the ratio *fR3/fR1:*
The strength interval for *fR1k* is defined by two subsequent numbers in the series:
1.0; 1.5; 2.0; 2.5; 3.0; 4.0; 5.0; 6.0; 7.0; 8.0 [MPa]
The *fR3k/fR1k* ratio can be represented with letters a, b, c, d, e, corresponding to the ranges:
"a" if 0.5 ≤ *fr3/fr1* ≤ 0.7; "b" if 0.7 ≤ *frk/fr1* ≤ 0.9; "c" if 0.9 ≤ *fr3/fr1* ≤ 1.1
"d" if 1.1 ≤ *fr3/fr1* ≤ 1.3; "e" if 1.3 ≤ *fr3/fr1*
Example *FRC* 40/50 - 5.0c means recommended for precast segment:

- Residual flexural strength at CMOD = 0.5 mm   *fr1k* = 5 N/mm^2
- Residual flexural strength at CMOD = 2.5 mm   *fr3k* = 5 N/mm^2

The use of SFRC in Lee Tunnel project

Precast segment

Designed by MVB's design engineer, Morgan Sindall Underground Professional Services (UnPS), the 1.7m wide, 350mm thick, seven segment + key universal tapered ring is currently under production at Morgan Sindall's permanent precast factory, at Ridham Dock, in Kent. A number of emerging technologies – such as steel fibre reinforcement, cast-in EPDM gaskets, 3D laser checking of cast segments.

For the well-established Ridham Precast factory which has been has been turning out high quality tunnel lining segments since it opened 10-years ago – one of the most unique innovations about the Lee segment design is the adoption of cast-in gaskets that has been successfully employed and are working very well.

However Lee will be the largest diameter tunnel in the UK to use steel fibre only reinforcement to date, but this is nothing new for Ridham Precast. They have been working with fibres for over 10 years, since the factory was first set up to produce segments for Heathrow's Terminal 5 tunnels. The benefits of using steel fibres are significant, resulting in reduced manufacturing costs, improved durability and crack resistance, and less damage during handling. Fibres also represent a significant reduction in the overall amount of steel used on the project. Traditional rebar reinforced segments will typically incorporate anywhere between 80kg to 120kg of steel rebar, whereas an equivalent steel fibre segment is likely to contain 30kg to 35kg of steel. There are also labor considerations, there is no steel fixing of cages or placement in mould's, no storage or cage handling, these operations are eliminated. With using steel fibres you just fill the hopper and you're done for the day. The Lee Tunnel's segments were designed utilizing UnPS's extensive experience in steel fibre reinforced concrete linings (reaching back to the Heathrow Baggage Tunnel in 1994), the design was validated by full scale physical modeling at the Building Research Establishment, at Garston near Watford. EN 14651 Beam test were realized in order to get the detail material properties to enable detailed design to progress.

The program of tests included the following

Radial joint crushing tests

Compressions tests (15 in total) were conducted on specimen assembled from a pair of tunnel linings, including a joint at their centre. The tests were conducted to determine the load capacity, the corresponding mode of failure and associated load-deformation behavior of the joint between the tunnel lining segments. The 1000mm high, 850mm long and 350mm wide lining segments had both flatend circular interfaces at the joint. Two angular configurations at the joint interface were tested, somewhere aligned with no rotation at the interface (i.e. vertically) while the others were arranged with a rotation of approximately 0.60 (as specified by the client). All test configurations are summarized in figure 4 below. The tests were carried out in BRE's 10,000kN compression testing machine. The details of the test set-up, instrumentation and results obtained are described in the BRE report.

Test		1, 2, 3	4, 5, 6	7, 8, 9	10, 11, 12	13, 14, 15
Segment joint interface	Upper	C1	C2	C2	C1	F
	Lower	C1	F	F	C1	F
Segment configuration		Rotated	Rotated	Vertical	Vertical	Rotated
Joint rotation (deg)		0.6	0.6	0.0	0.0	0.6

Key:
C1 – Circular interface, 3500mm radius
C2 – Circular interface, 2500mm radius
F – Flat interface

Figure 4: Summary of the radial joint crushing tests conducted

Ram shoe bearing tests

A concrete fibre-reinforced block, 750mm high x 1000mm long x 350mm wide, was tested to determine its ability to withstand the bearing pressure exerted by the hydraulic rams used in practice to placing the tunnel linings during construction. The block was loaded eccentrically via a 40mm thick 300mm square neoprene pad, at three different locations along its longitudinal centre line, using BRE's 5,000kN testing machine. More details on the test set-up and results are reported in Section 4 of this report.

Flexural tensile strength test

A material testing program of 12 notched fibre-reinforced concrete prisms (EN 14651 beams), with a nominal cross-section of 150 x 150mm and a simply supported span of 500mm, were tested in flexure by applying a central load in accordance with BS EN 14651:2007. The tests were to determine the flexural tensile characteristics of the concrete material

Compressive/Tensile strength tests

A summary of the compressive strength tests (BS EN 12390-3:2009) and tensile splitting strength tests (BS EN 12390-6:2009) were conducted on fibre-reinforced concrete cubes (150mm) and cylinders (150mm diameter x 300mm high).

Although not a major risk, fires have been known to occur in tunnels under construction. Therefore, in addition to 30kg/m^3 of Dramixsteel fibres type RC80/60BN, Lee's segments also incorporate1kg/m^3 of Adfil polypropylene fibres to mitigate against spalling in case of fire.

Inner lining to the Shafts

Circular concrete structures work optimally in hoop compression. If the shaft lining could be kept permanently free of cracks and in compression, then by creating structural continuity between the lining, diaphragm wall and ground, the need for reinforcement could be removed altogether. Accordingly MVB chose to adopt a double sided slip form shutter to construct what was essentially the construction of a free standing chimney within the excavated shaft. This decision, together with innovative design features for the base slab and careful attention to the specification of the concrete used to fill the annulus between the diaphragm walls and the slip formed internal lining, represented a unique and radical approach which has proved to be successful.

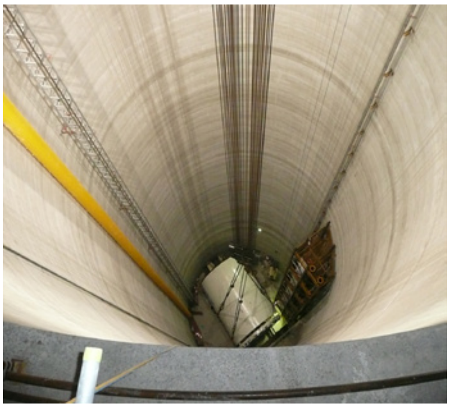
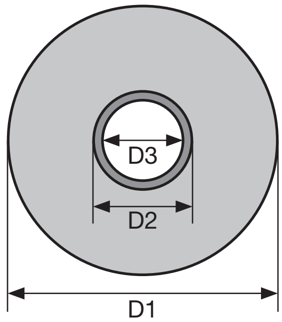


Figure 5: Shaft Bekton

To assist the slip form process progressed, the lining walls were designed as plain concrete with minimal reinforcement specified as required. Steel fibres were considered to increase the ductility of the unreinforced concrete, eliminate spalling damage, and to assist in controlling drying shrinkage cracking. Extensive shrinkage testing was carried out at Bekaert's laboratory in Belgium, followed up by trials on site to determine the optimum workability and dosages rates. The mix used incorporated 30 kg Dramix 3D65/35BG (35 mm length, 0,55mm diameter). The fibres were introduced in to the mix at the batching plant with dosing equipment (automatic system).

Description	Source	C50/60 DC3 36% GGBS (kg/m³)
CEM II/B-V+SR or CEM IIIA/+SR	Cemex Rugby	256
Cement replacement	–	144
0/4 mm	Angerstein Sand	853
4/10 mm	Raynes Limestone	288
10/20 mm	Raynes Limestone	674
Water	–	160
Admixtures (Superplasticiser)	CSP313	2.264
	TOTAL	**2377**

Table 1: Concrete mix



D1 = 525mm
D2 = 305mm
D3 = 235mm

Figure 6: Shrinkage testing program: ring test dimension

A radical structural rethink of the shaft lining design has eliminated more than 500 tonnes of reinforcing steel from the Beckton Overflow Shaft.
Believed to be a world-first, pressure from a concrete pour behind the shaft linings is being used to create and maintain hoop compression, counteracting hydrostatic pressure from within.
Not only have these design innovations yielded a significant commercial saving on steel, but by largely removing the need to handle and fix heavy steelwork, they have enabled faster, safer construction.
Over the lifetime of the Lee Tunnel, minimising the steel content significantly improves durability.

Conclusion

This extraordinary project confirms that once again a strong partnership between all the parties involved in this project brings an innovative, technical and economical relevant solution that will provide the client with a long life and durable project.

Steel Fibre Reinforced concrete solution taking in account at early stage of the design allows some innovation in the process and quality improvement. Durability is a key issue, Dramix Steel fibre remains the best option available.

For Lee Tunnel a solution with SFRC for the final lining is under study

The model code edited by fib will support the solution in the future as the lack of official standards or structural design was seldom a bottleneck.

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