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Post-cracking ductility of fibre reinforced concrete linings in combined bending and compression

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A B S T R A C T

It is often assumed that the post-crack ductility of Fibre Reinforced Concrete (FRC) and Shotcrete (FRS) is wholly defined by the result obtained in a standard flexural performance test such as ASTM C1609/C1609M or EN14651. However, the results revealed by these tests are only valid for the case of pure bending and do not incorporate the effects induced by the possible presence of an axial force within a member. A compressive axial force will substantially change the distribution of stress across a section subject to bending, and this will delay cracking, control the propagation of cracks when they occur and increase deformability, and hence ductility. The current investigation examines how an axial compressive stress changes the ductility of FRC and FRS tunnel linings, giving rise to post-crack strain hardening flexural behaviour in linings that otherwise exhibit strain-softening behaviour in standard flexural tests. The outcome has significant implications with respect to design, because enhanced ductility can thereby be exploited for moment re-distribution at ultimate load even for relatively economical levels of fibre reinforcement in concrete tunnel linings.

1. Background

The use of fibre reinforced concrete and shotcrete is now well established as a means of constructing underground infrastructure. Fibre Reinforced Shotcrete (FRS) is widely used both in underground civil and mining construction, and tunnel segments commonly include conventional reinforcement, fibre reinforcement, or a combination of the two. Shotcrete for ground support is most commonly reinforced with fibres and is effective for support in both hard rock and soft ground conditions. In hard rock, it is generally applied as a slender lining between rock bolts, in which case the primary modes of load resistance are flexure and shear (Barrett and McCreath, 1995). In soft ground conditions, shotcrete will often comprise a thick shell-like structure for ground support, in which case it is commonly subject to a combination of flexural and compressive stresses (BTS, 2004).

Fibre Reinforced Concrete segments are subject to a wide range of forces during production, handling, storage, transport, installation, and in service. Most loads imposed on young segments are transitory, and bending moments can usually be kept small relative to bending capacity during production and handling. However, under certain in-service conditions, significant bending moments may possibly be imposed on some segments in conjunction with substantial axial (hoop thrust) loads. Tunnel linings are highly redundant structurally, thus the post-crack ductility of segments in response to a combination of axial load and bending moment is potentially useful for re-distribution of moments so that a higher ultimate load capacity can be sustained.

Numerous methods of design are available for both FRS linings and FRC tunnel segments. One can either use engineering first principles, or one of a number of guidelines that purport to represent a consistent set of engineering principles for segments made from fibre reinforced concrete (FRC) or fibre reinforced concrete combined with conventional steel reinforcement (RC/FRC). One such set of principles is embodied in CNR DT 204 (2006) which includes fibre reinforcement in combination with conventional reinforcing bars. Other methods include the DBV guideline for steel fibre reinforced concrete (SFRC) (2001), or the Model Code 2010 (2012). In the majority of design approaches, the lining is modelled as an elastic structure and the post-crack performance of the FRC is not exploited. In some of these guidelines, the tensile capacity of the fibres is modelled as a distributed tensile stress across cracked regions of a section. However, the addition of fibres at normal dosage rates provides only a small increase in the ultimate bending moment capacity compared to a plain or reinforced concrete cross-section subject to pure bending. To fully exploit the advantage of FRC it is necessary to account for the enhanced section ductility and hinge rotation capacity that fibres provide in situations where bending is combined with a compressive axial load. Highly ductile hinges allow

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greater moment redistribution which generally results in a higher peak load resistance. However, estimating the ductility of a FRC section under a substantial axial stress is challenging, and confirming the changes in behaviour by experimental means is difficult.

Given that the internal actions imposed on cross-sections of shotcrete linings and tunnel segments are similar in nature to the axial and flexural loads normally applied to prestressed concrete sections, existing methods of section analysis for prestressed concrete can readily be extended to FRC tunnel linings (Gilbert et al., 2017). This paper describes a method of analysis incorporating the principles described in MC2010 (2012) to determine the effects of combined flexural and axial loads on the post-crack behaviour of macro-synthetic fibre reinforced concrete cross-sections. The analytical model can also be used for concrete with other types of fibres. The predictions of this numerical model are confirmed experimentally using two macro-synthetic fibre reinforced concrete mix designs tested in combined bending and axial compression.

2. Objectives of investigation

The primary objective of the present investigation is to determine the effect of axial compression on the post-crack flexural ductility of a cracked Fibre Reinforced Concrete or shotcrete section. The purpose is to identify the degree of improvement in ductility for moment redistribution that a FRC tunnel lining can sustain under the action of an axial compressive load in combination with bending. A simple analytical model has been developed and validated using the results of a number of laboratory experiments.

3. Numerical model

3.1. Cross-sectional discretisation

A spreadsheet-based section analysis was developed to model the short-term post-crack flexural resistance of a FRC cross-section subjected to an axial compressive force and a bending moment. Any concrete cross-section reinforced with fibres can be analysed, with the concrete cross-section divided into 50 layers. In Fig. 1a, a discretised rectangular cross-section is shown, with the reference axis taken as the centroidal axis of the uncracked cross-section. Division of the cross-section into 50 layers allows the development of cracking through the thickness of the cross-section to be accurately modelled and has been found to be a suitable compromise between accuracy and tractability. A greater number of layers results in insignificant differences in the stress and strain distributions. Also shown in Fig. 1b is the strain distribution caused by the applied axial force and bending moment. The two unknowns that define the strain diagram are the strain at the reference axis ε_r and the slope of the strain diagram κ (which is the curvature of the cross-section). Further details of the structural model underlying the analysis are described below.

3.2. Assumed constitutive relationships

For the strain diagram of Fig. 1b, the strain at any height y above the reference axis is given by:

$$\varepsilon = \varepsilon_r + y\kappa \tag{1}$$

where y is measured positive upwards from the reference axis, i.e. the z-axis. In this study, tensile stresses and strains are taken to be positive (and hence compression is negative) and bending moments that induce tension at the bottom fibres of the cross-section are taken to be positive.

The value of strain is determined at the centroid of each concrete layer. The stress in each fibre-reinforced concrete layer is determined based on the appropriate constitutive relationship as outlined in the following.

3.2.1. Fibre reinforced concrete in compression

A typical stress-strain curve for FRC in compression is curvilinear as shown in Fig. 2a. The piece-wise linear approximation shown in Fig. 2b has been adopted in the present study. When the applied stress is less than about 60% of the compressive strength, the curve of Fig. 2a is essentially linear and the instantaneous strain may be considered to be elastic (fully recoverable). In this low-stress range, the secant modulus $E_{c.c}$ does not vary significantly with stress and is only slightly smaller than the initial tangent modulus. At higher stress levels, the stress-strain curve is decidedly non-linear and is modelled as shown in Fig. 2b, where a significant proportion of the instantaneous strain is irrecoverable upon unloading. The value of the initial elastic modulus in compression $E_{c.c}$ is largely independent of the fibre content and may be determined by tests or by well-established formulas for plain concrete, such as in AS3600, Eurocode 2 or ACI318. After the peak stress is reached, the fibres provide confinement to the concrete and the slope of the unloading curve depends on the fibre dosage. In Fig. 2b, this is accommodated by noting that the strain limit $\varepsilon_{c.4}$ is dependent on the fibre content and also on the compressive strength. For a given fibre dosage, higher strength concrete has a steeper unloading curve and a smaller value of $\varepsilon_{c.4}$. With the idealization shown in Fig. 2b, just five parameters are required to define the stress-strain curve in compression for any FRC mix, ε_{c1}, ε_{c2}, ε_{c3}, ε_{c4}, and σ_{cu}, all of which can be obtained from a standard compressive strength test.

For the quantity of Barchip BC48 macro-synthetic fibres used in the experimental study (i.e. $\gamma_f = 7\ \text{kg/m}^3$), the strain values that define the idealised stress-strain curve of Fig. 2b are:

$$\varepsilon_{c.1} = 0.6\ \sigma_{cu}/E_{c.c} \tag{2a}$$

$$\varepsilon_{c.2} = 2.5\ \varepsilon_{c.1} \tag{2b}$$

$$\varepsilon_{c.3} = -(0.0385\sigma_{cu} + 5.88) \times 10^{-3}\ \text{but} -0.0035 \geqslant e_{c.3} \geqslant -0.005 \tag{2c}$$

$$\varepsilon_{c.4} = -(\gamma_f/7)(0.673\sigma_{cu} + 47) \times 10^{-3}\ \text{but} -0.004 \geqslant e_{c.4} \geqslant -0.025 \tag{2d}$$

where σ_{cu} is the mean compressive strength of the concrete and is taken

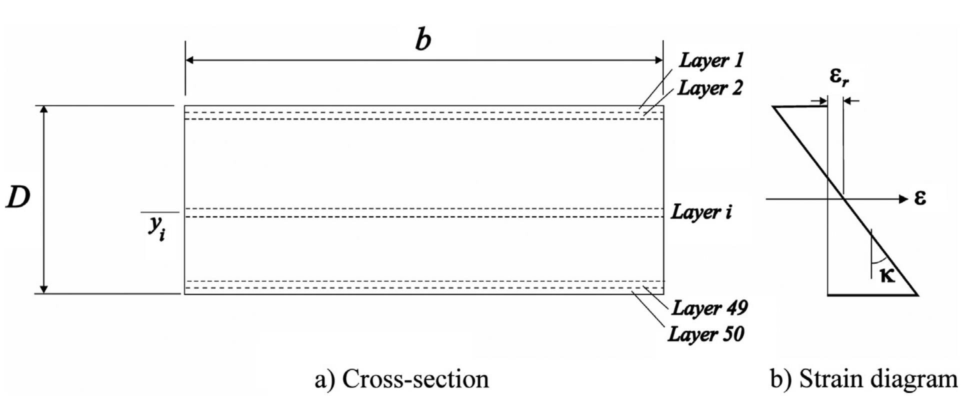

Fig. 1. (a) Typical layered cross-section, and (b) strain diagram under axial compression and bending.