

BarChip Technical Note



The Role of Creep in the Behaviour of Selected FRC Structures

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Introduction

The effects of creep on the behaviour of Fibre Reinforced Concrete (FRC) structures are complex and difficult to fully account for. This is particularly true for the types of structurally redundant applications that FRC is commonly used in, such as tunnel linings and slabs-on-ground. Nevertheless, some generalisations can be made regarding the effect of creep on structural behaviour in these applications.

Creep has the effect of reducing the structural rigidity of a member with the passage of time, especially if that member is highly stressed. This will usually cause a re-distribution of stress, but the magnitude of the re-distribution will depend on the degree of redundancy existent in the structure and the relative stiffness of alternative load paths (Gilbert and Ranzi, 2011). Since the alternative load paths are also likely to be affected by creep in some way, accounting for creep in one part of a structure must necessarily be accompanied by an assessment of creep in adjoining parts (Ghali and Favre, 1994; Bazant, 2000). Tensile creep at a crack will also lead to shedding of load on to adjoining parts of a structure and this will usually reduce the level of stress acting in tension and thereby progressively reduce the driver of crack width increase. For this reason, the extent of creep deformation observed in simply supported beam tests, which are non-redundant, represents the upper bound to the extent of deformations likely to be observed in real structures, since simply supported beams comprised solely of FRC are seldom encountered in structural design practice.

The creep properties of concrete in compression are not affected by the presence of fibres for commercially viable dosages rates of up to about 1.0% V/V. Similarly, there is no evidence that the creep properties of uncracked concrete loaded in tension are affected by the presence of fibres for commercially viable dosage rates. Post-crack tensile creep may occur when a crack arises in a FRC structure, but for deformations of engineering significance to occur tensile stress must usually be imposed for a significant period of time. The consequences of post-crack tensile creep may include:

- Possible increase in crack width with time, which may affect serviceability, sensitivity to corrosion, or water-tightness.
- Possible increase in structural deformation with time, which may affect serviceability or structural stability,
- Change in distribution of stress between concrete and steel rebar if FRC is used together with conventional reinforcement. Creep of FRC in tension and creep of concrete in compression will commonly lead to a

progressive increase in stress in reinforcing bars within a cracked RC/FRC section. This can lead to serviceability problems if the stress increase in the tension bars is significant, as this will increase crack widths, especially if the redistribution of stress results in yielding of the steel (Gilbert and Ranzi, 2011).

- Possible structural collapse if creep rupture occurs. In this context, 'rupture' is defined as the formation of a structural discontinuity in a material or member. This can occur as a result of either snapping of individual fibres at a crack or pull-out stemming from slip between individual fibres and the enveloping concrete at a crack.

Macro-synthetic FRC generally exhibits larger tensile creep strains in response to a short-term or sustained tensile stress than steel FRC, at least across narrow cracks in mature concrete. For macro-synthetic FRC, post-crack creep in tension may involve a combination of fibre pull-out and elongation of the fibres themselves. Most steel FRC will also exhibit a degree of tensile creep, primarily as a result of time-dependent pull-out of fibres. Given that concerns over corrosion mandate that maximum permissible crack widths are much smaller for steel FRC than macro-synthetic FRC, the smaller tensile creep that steel FRC typically exhibits must still be considered in terms of its long-term effect on crack widths. For macro-synthetic FRC, corrosion-based crack width limits are usually not relevant unless steel reinforcing bars are also included in a structure.

The following describes the role of tensile creep in the behaviour of FRC in three common structural applications: slabs-on-grade, shotcrete for ground control, and precast tunnel segments.



"...the final width of cracks and joints in the slab will be reduced by the presence of fibres..."

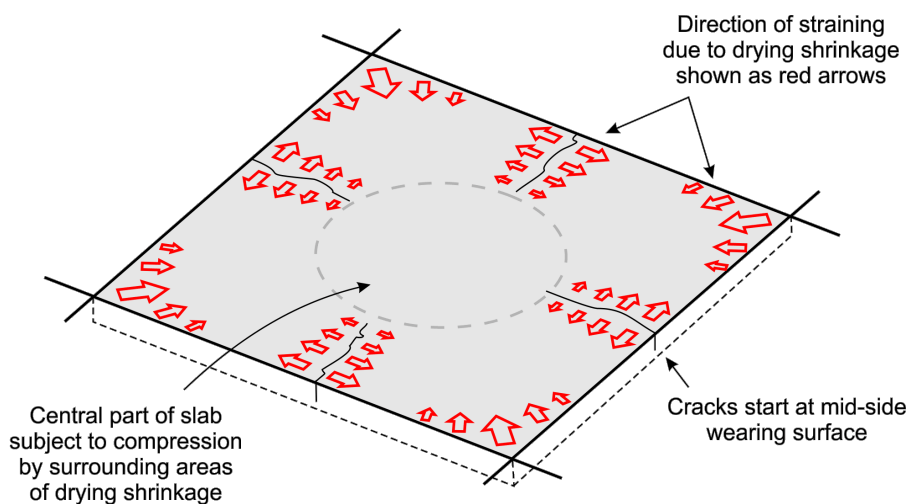


Figure 1. Drying shrinkage strains in a slab-on-grade leads to mid-side cracking from wearing surface. Central part of slab will be in compression if reinforcement is included in slab.

In slabs-on-grade, cracks most commonly arise as a result of tensile stresses induced by drying shrinkage, thermal shrinkage, and/or curling. Cracks seldom arise as a direct result of external mechanical loading. The distribution of tensile stress associated with drying shrinkage or curling is not uniform but tends to be higher near the exposed mid-side wearing surface of a slab (Figure 1). The magnitude of this stress can be significant, evidenced by the fact that it may cause the concrete to crack in tension, but the magnitude will change with time depending on the degree of drying shrinkage and thermal gradients that occur in the concrete.

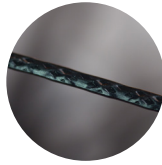
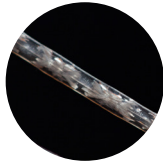
While thermal shrinkage-induced stresses are partially reversible, tensile stresses induced by drying shrinkage tend to be sustained in nature and will vary in absolute magnitude with time.

Fibre reinforcement does not prevent cracks occurring (at least, not at the dosage rates typically used in slabs-on-grade) but can act to delay the onset of visible cracks or limit visible crack widths once a crack arises. Fibres are therefore potentially useful in reducing the width of cracks to the point where they are 'client tolerant' compared to the width of cracks that will arise in a plain concrete slab (Figure 2). In a properly designed slab-on-grade, the

cracks will occur in a pattern defined by the saw-cuts that form joints and will therefore not be visible to the user. The exception to this are floors specifically designed to be jointless in which shrinkage strains are accounted for within the design.

The presence of fibres at a crack (or joint) will allow the crack to sustain a tensile stress and thereby induce tensile creep in the adjoining uncracked concrete as it shrinks leading to a reduction in the total restrained shrinkage strain occurring in the concrete. This means that the final (long term) width of cracks and joints in the slab will be reduced by the presence of the fibres compared to an unreinforced alternative. The more fibres that are present, and the more resistance they provide to widening of the crack, the more effective they will be in limiting total crack and joint widths in the long term. It is generally desirable that crack widths be limited so that shear transfer by aggregate interlock is maintained. This is made more difficult as the span between joints is increased and as the inherent drying shrinkage tendency of the concrete increases (caused by, for example, use of a high cement content, a high water/binder ratio, or poor aggregates).

It should be noted that steel reinforcing bars, and especially cold-rolled steel mesh, are not effective for preventing crack development and propagation in slabs (at least for crack widths < 0.3 mm) at the levels of reinforcement typically used in most slabs-on-grade. This is due to the fixed elastic modulus of steel and the requirement to induce a considerable strain in bars before substantial resistance to crack width increase occurs. The stress transfer length between bars and concrete is typically about 50 mm on either side of a crack (depending on the size of bar and other factors) so a considerable increase in bar length will occur before



resistance to crack width increase is engaged (Amin and Gilbert, 2018). In contrast, fibres have a shorter stress transfer length, especially fibres with embossments and other geometric irregularities along their length, generally resulting in better crack width control due to improved bond to the surrounding concrete matrix.

Any factor that increases the shrinkage deformation experienced at a crack will tend to increase the stress induced in the fibres bridging the crack, possibly leading either to pull-out of the fibres or increased straining as a result of tensile creep. However, creep rupture is unlikely since the total widening of cracks in a slab-on-grade is unlikely to exceed the strain limit of most fibres used in slabs. Only if the anchorage strength of the fibre within the concrete exceeds the tensile strength of the fibre is creep rupture possible in a slab-on-grade. For steel fibres, creep rupture is more likely if corrosion occurs concurrently with sustained tensile stresses. Relaxation of fibres at a crack (by elongation or progressive slippage) can possibly lead to a reduction in the tensile stress acting across the crack thereby reducing the amount of tensile creep occurring in the adjoining uncracked concrete. This can lead to increased crack widths in the long term. For this reason, it is important to select a fibre that is resistant to elongation and progressive slippage relative to the cement paste. Embossed macro-synthetic fibres have been found to be more resistant to elongation and slippage than tape-based macro-synthetics, and experience similar levels of relaxation to hooked-end steel fibres in concrete of moderate strength



Figure 2. Drying shrinkage cracks in a slab-on-grade originating from the mid-sides and meeting at the centre.

(Garcia-Taengua et al, 2017; Bernard, 2021; Bernard and Amin, 2023).

The period of time over which drying shrinkage may act to induce tension in fibres bridging a crack in a slab is typically 3 to 18 months (this will vary with ambient conditions at site). Thermal cycling may also induce additional tensile stresses in fibres at cracks at any point in the life of a slab-on-grade should ambient temperatures vary substantially. This most commonly occurs as a result of diurnal or seasonal change. Given the long time periods over which these stresses act, there is usually sufficient time for tensile creep to dissipate the majority of stress existent in the slab resulting in diminished crack frequency and width but this will only occur if adequate tensile reinforcement is present.

"Only if the anchorage strength of the fibre within the concrete exceeds the tensile strength of the fibre is creep rupture possible in a slab-on-grade."

Shotcrete

The vast majority of Fibre Reinforced Shotcrete (FRS) is used for ground support (Figure 3). The amount of Fibre Reinforced Shotcrete used in other applications such as pools and buildings is minimal. This section will therefore focus on the role of post-crack creep in the behaviour of FRS for ground stabilization.

The behaviour of fibres within FRS depends primarily on three factors: the age of the shotcrete, the thickness of the lining relative to the span, and the type and degree of ground movement. Shotcrete linings used in hard rock excavations are usually quite thin (50-150 mm) and slender (ratios of span between bolts to thickness of 100-150 are common) and are often irregular in geometry due to the rough ground surface generated during drill-and-blast excavations. Shotcrete linings in hard ground provide resistance to local ground movement primarily through flexure and shear action. Moreover, loads imposed on a thin-walled lining from hard rock are difficult to quantify and can, at best, only be approximated. For this reason, lining design for hard rock excavations is usually based on post-crack energy absorption in panels measured over a large range of deformations (for example, using the Q-method). Global deformation and convergence control is achieved through the use of appropriate excavation geometry and bolting and is not controlled by the shotcrete lining. In these circumstances, it is difficult to quantify the magnitude of tensile stress that may arise in a lining and even more difficult to quantify the degree of tensile creep that might occur in the longer term. Generalizations regarding the performance of different types of fibre must therefore suffice.

In soft ground, shotcrete linings are typically much thicker (in excess of 200 mm) and the geometry is deliberately controlled to achieve

load transfer around the excavation through compressive arching action in the shotcrete lining. The behaviour of FRS in compression is therefore of much greater significance to overall lining behaviour in soft ground than is apparent in hard rock excavations. Soft ground is usually less able to support in situ stresses than hard rock and thus the lining is usually required to carry substantial loads. Fortunately, the pattern and magnitude of stress applied to a lining in soft ground are usually more amenable to estimation using deterministic engineering models. In these circumstances it is more likely that long-term straining due to creep can be quantified in a meaningful manner. Creep will contribute to a steady reduction in crack widths for a section subject to sustained high net compressive load (and minor bending), thus the tensile creep behaviour of fibres usually diminishes in importance with time for thick FRS shells in soft ground. Creep of the concrete in compression is therefore much more significant to the long-term behaviour of the lining than tensile creep of fibres.



Figure 3. Spraying a fibre reinforced shotcrete tunnel lining onto hard rock to provide local support.

Apart from low strength, young shotcrete is noted for its low elastic modulus and very high capacity for creep strain. The matrix can therefore deform substantially at early ages without exhibiting macro-cracks. These properties are a result of the structure of the cementitious matrix and have nothing to do with the presence of fibres. These properties also explain why young shotcrete exhibits such high resilience in response to early-age ground movement and dynamic stresses induced by, for example, blasting or rock burst.

As the shotcrete matrix hardens, the compressive strength and elastic modulus increase. The strain capacity also declines making it more likely that ground deformation will lead to cracking (especially if loaded in flexure or shear). Fortunately, both steel and synthetic macro-fibres become more effective as the matrix hardens leading to the development of post-cracking tensile load capacity. Embossed macro-synthetic fibres have been found to perform very well in young shotcrete of 1-7 days age (Larive et al, 2016),

thereby aiding the development of flexural resistance in young linings. Embossed macro-synthetic fibres have also been found to enhance early-age bond strength between concrete and conventional reinforcing bars (Watts et al, 2021), so the presence of this type of fibre can reduce the spacing and width of drying shrinkage cracks in hybrid RC/FRC or FRS linings. However, the post-crack shear capacity of FRS remains low regardless of the development of substantial shear capacity in the cementitious matrix, so post-crack strain-softening in response to shear action generally increases with time (Bernard, 2008).

The movement of the ground around hard rock excavations is largely controlled by the geometry of the excavation and the type and pattern of bolting used. The FRS comprising the lining does not ‘hold the ground up’, nor does it limit deformations. Instead, it must be able to accommodate deformation while continuing to restrain the rock surface so that it does not unravel and the lining itself does not collapse. Should cracking of a mature shotcrete matrix occur, the post-cracking capacity provided by the fibres may be engaged. The contribution of the fibres to structural support will then depend on the type of stress acting and the characteristics of the ground surrounding the excavation. In most hard rock excavations, the ground itself and rock bolts carry the majority of the stress around an excavation; a FRS lining primarily provides shallow support to the ground surface between the rock bolts helping to prevent the surface from unravelling and maintaining the integrity of the ground around the bolts. This will require a degree of post-cracking performance so that the lining continues to restrain the rock face if cracks arise in the lining.

The preferred approach to lining

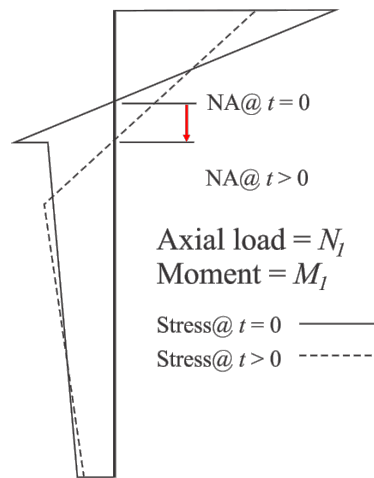


Figure 4. Fibre reinforced concrete cross-section subject to sustained axial load N_l and moment M_l , showing a progressive migration of the neutral axis (NA) toward the tensile surface and reduction in magnitude of tensile stress.

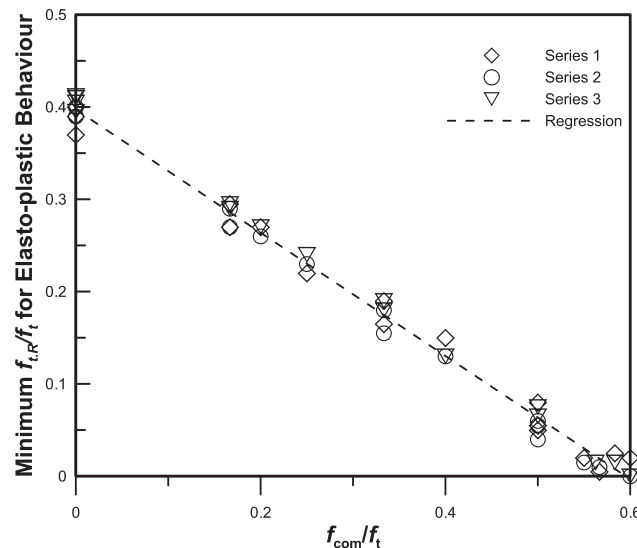


Figure 5. Minimum ratio $f_{t,R}/f_t$ required to achieve elastic-perfectly plastic behaviour for increasing ratios of axial compressive stress over direct tensile strength of the concrete matrix f_{com}/f_t (Bernard, 2018).

design is to preclude the occurrence of tensile stresses through appropriate geometric design. If tensile stresses cannot be avoided, the consequences of sustained tensile creep in a shotcrete lining may include time-dependent deformation of the lining and/or a change in crack width over time. In order to calculate the effect of creep on either deformations or crack widths it is necessary to consider both tensile and compressive creep. If a cracked cross-section is comprised entirely of FRS (Figure 4) and is subject to

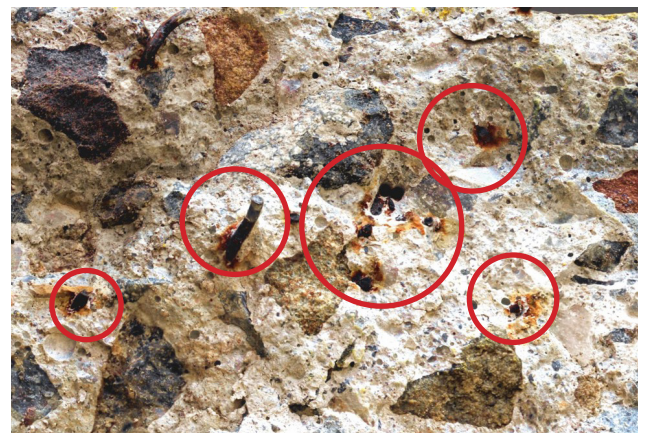
both an axial compressive load and a moment, the usual consequence of creep of the concrete and fibres on the stress distribution through the lining is a migration of the neutral axis toward the tensile surface. This will increase the curvature, reduce the effective flexural rigidity, and either increase or decrease crack widths with time. If an axial load is absent, the neutral axis will move toward the compressive face and the curvature will increase. This will very likely lead to an increase in crack width with the passage of time.

Calculation of crack widths in strain-softening materials is difficult because the spacing between cracks cannot be assessed by normal means. However, the spacing between cracks is more predictable if a FRS section exhibits deflection-hardening behaviour in bending. This can be achieved even with a strain-softening material if a sufficient axial stress is applied concurrent with the moment (Gilbert and Bernard, 2018). Bernard (2018) showed that as the average axial compressive stress f_{com} is increased relative to the direct tensile strength of the concrete f_t , the minimum post-crack direct residual tensile strength of FRC over f_t ($f_{t,R}/f_t$) required to achieve elastic-plastic behaviour in bending also falls (Figure 5). This means that crack spacing can be estimated for strain-softening sections when subject to axial stress typically present in a tunnel lining (2-3 MPa). The spacing between cracks, L , in such sections has been found to be close to the flexural thickness of the section, D (Gilbert and Bernard, 2018).

In practice it is difficult to differentiate post-crack ductility from creep deformation, but in unstable ground a capacity for post-crack creep strain has generally been found to be useful in allowing a FRS lining to maintain ground surface integrity while deformation occurs. In general, the more unstable the ground, the greater the deformation that will occur before stability is achieved (Hoek et al, 2000). Under some circumstances this may entail generation of tensile or flexural cracks many millimetres in width. Experience in highly unstable ground both in civil and mining environments has indicated that a capacity to accommodate substantial post-cracking tensile strain (whether accompanied by creep or not) is a necessary property of FRS in these circumstances. For this reason, embrittlement (through the use of overly strong shotcrete) can lead to the loss of structural effectiveness across widening cracks in unstable ground (Bernard, 2020). Tensile creep of steel fibres is largely manifested as pull-out by progressive slip at the fibre-cement paste boundary. If embrittlement occurs, this slip is precluded so tensile creep of steel FRS is negligible. This is one reason why embrittlement should be avoided by using a compressive grade of shotcrete that is appropriate to the tensile strength of the fibre. If the ground is relatively stable, deformations and stresses in the lining are low so crack widths remain small, if they occur at all. Tensile creep of FRS across a crack in relatively stable hard ground is therefore likely to be minor.

In soft ground conditions, FRS linings are normally designed so that resistance to convergence generates large axial loads in the lining while flexural loads are minimized. This ensures that the high compressive resistance of the lining is exploited rather than its relatively low flexural

resistance. However, ground stresses change with time, so flexural loads typically cannot be avoided entirely. For this reason, fibre reinforcement may be included to provide post-cracking flexural capacity should a flexural crack arise. The post-cracking flexural strength of FRS is not great so the contribution of fibres to total flexural capacity is usually small. About 3-4 MPa flexural stress is the most that can be sustained even in the short-term given the limitation on the amount of fibre that can be contained in a sprayable mix. Moreover, creep deformation occurs for all types of fibres in response to high tensile stresses, especially at early ages, so relaxation of post-crack resistance is likely to be rapid (Bernard and Amin, 2023). Conventional reinforcement, in the form of steel reinforcing bars, sets, or lattice girders, may therefore need to be included if very high sustained flexural stresses are expected. Given the relatively large magnitude of compressive stress that occurs in thick-walled linings in soft ground compared to flexural stresses, the creep behaviour of FRS in compression is likely to play a more significant role in overall lining performance than the tensile creep of FRS across cracks.



The effects of embrittlement on long term durability can be just as severe as corrosion

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Pre-cast concrete tunnel segments are used to line a tunnel after the passage of a boring machine. These arc-shaped segments are produced in a pre-casting plant and cured for a period of time before transport into a tunnel and installation. Due to the many steps involved in the process of production, handling, storage, transport, installation, and in situ service, the type and magnitude of loads imposed on segments can vary substantially.

Prior to installation, most loads imposed on a tunnel segment are short-term, so if cracking were to occur the duration of loading is likely to be insufficient for post-crack creep deformations to become significant. The exception to this is possible flexural loading during storage. Care must therefore be taken to avoid cracking prior to and during the stacking and storage phases of segment production. Handling and storage processes are usually designed to minimize bending stresses, usually by setting spacer locations to third points to minimize eccentricity, so that cracks do not occur as a result of overloading of the young concrete which can be exacerbated by creep during storage.

During installation, flexural stresses may arise as a result of handling, and high bursting (tensile) stresses are usually encountered briefly at and between the thrust points as the TBM is pushed forward. However, neither of these loading events normally last more than a few minutes so consideration of tensile creep is unnecessary. In the event of a TBM becoming stuck, loads may be imposed for a longer period but this is a rare occurrence. Once installed, the pattern and magnitude of stress actions imposed on a segment depends on many factors, including



Figure 6. Cracks in fibre reinforced concrete segments. These will be subject to hoop loading while in service and could either widen or become closed depending on the magnitude of axial loads and bending moments.

ground conditions, design decisions, mistakes made during planning, and errors during construction such as geometrical imperfections in ring build. Ideally, the segments should be free of cracks when the tunnel enters service. However, cracks may be induced by unforeseen stresses imposed during the installation process, such as improper grouting behind a completed ring, resulting in cracked in-place segments despite ostensibly low in-service stresses (Figure 6). In this circumstance, tensile creep of a cracked segment lining may require consideration. In-service tensile stresses are less likely to exist in the concrete if the bolts connecting segments are removed because moments at the junctions are then negligible resulting in smaller peak moments across the arc of each segment.

The majority of tunnels incorporating segmental linings tend to be driven through soft to medium-stiffness ground. The ground stresses present in the majority of environments tend to induce a large compressive hoop

stress in each segment ring together with a relatively small bending component that may steadily diminish over time as creep of the ground leads to re-distribution of stress around the excavation. The compressive hoop stress component present in a segmental lining is therefore normally substantial and sustained, while the bending component is often of relatively small magnitude and may diminish with time. For this reason, most segmental linings exist in a state of near permanent compressive stress across the entire cross-section. Under such conditions, compressive creep of the concrete is of much greater significance than tensile creep of fibres in the context of long-term behaviour.

For segments comprised entirely of FRC, the effect of creep on distribution of stress through a section in the long-term is similar to that for shotcrete linings (Figure 4). For the case of a cracked FRC cross-section that also includes steel bar reinforcement (Figure 7), the effect of creep of the concrete and fibres under a sustained

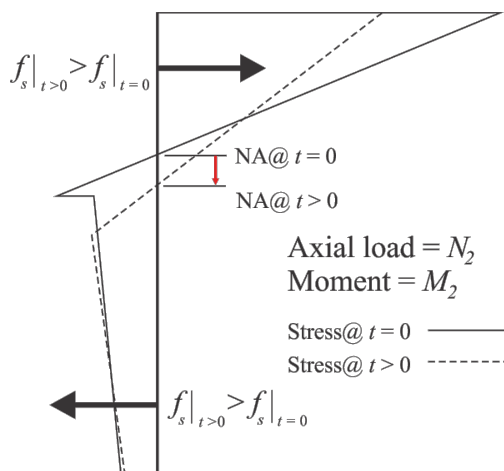


Figure 7. Fibre reinforced concrete cross-section with steel bar reinforcement subject to sustained axial load N_2 and moment M_2 , showing a progressive migration of the neutral axis (NA) toward the tensile surface, increase in stress in bars, and reduction in magnitude of tensile stress

axial load and moment is a shedding of stress away from the concrete and fibres toward the steel bars (since they experience negligible creep). This will also be accompanied by migration of the neutral axis toward the tensile surface, but to a lesser degree than for a pure FRC lining. The long-term curvature and flexural rigidity will also be greater than for the pure FRC lining. However, care must be taken to ensure that the load imparted into the steel bars does not cause yielding in the long-term (Gilbert and Bernard, 2015). In the absence of yielding, creep can cause flexural crack widths to either increase or decrease with time depending on the relative magnitude of applied moments and axial loads. Sections that include both fibres and steel bar reinforcement benefit from a reduction in average spacing between cracks (Model Code 2020, 2024; Watts et al, 2018). This generally has the effect of reducing maximum crack widths compared to sections reinforced with only fibres or only bars.

A factor that may help to minimise

long-term bending stresses in a segmental lining is the design of the segments themselves. Smaller segment arc lengths result in smaller peak bending moments because the moment supported at each junction between segments is of much smaller magnitude (approaching zero in some cases) than the moments supported across the arc of each segment. Smaller segment arcs also result in a more compliant ring resulting in less flexural demand. Moreover, compressive creep of the elastomeric gaskets, and the concrete itself, at each junction leads to a steady diminution in the magnitude of moments supported. The result is generally a time-dependent pattern of uneven (and steadily diminishing) moments around the circumference of a completed ring.

In response to a large permanent hoop stress, creep of concrete in compression has the effect of inducing a progressive increase in the net negative strain across the section that will either preclude the occurrence of cracks entirely, or possibly reduce crack widths in the

long term by progressively moving the neutral axis toward the tensile face of the section. Although flexural stresses may be sufficient to overcome the axial compressive strain in the short term, this can change with the passage of time leading to the elimination of tension in the long term. Creep of the ground around a lining often dissipates the differences in ground pressure around a tunnel that are responsible for the generation of moments (especially in soft saturated ground), so the bending moments that occur early in the life of a lining may diminish with time. For these reasons, consideration of tensile creep without simultaneous consideration of compressive creep of the concrete and creep of the ground is likely to result in over-estimation of long-term crack widths. Most analyses undertaken as part of tunnel design do not account for these non-linear time-dependent changes and thereby produce conservative estimates of long-term tensile stresses.

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