Durability of Shotcrete Tunnel Linings due to Steel Fibre Corrosion in Cracks

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ABSTRACT Steel fibre reinforcement in homogenous, intact, wet-mix shotcrete show an excellent durability against corrosion. The alkaline concrete environment gives good protection but the relatively thin shotcrete layers may crack due to shrinkage and other deformations. Durability requirements today often demands service-life of more than 100 years, which is not realistic with a maintained load-bearing capacity. Special measures must therefore be taken in the design of shotcrete rock support, such as addition of extra amount of fibres if the shotcrete is cracked or increased structural thickness, which is here demonstrated with examples. Due to the complex situation with requirements on service-life, climate impact and cost-efficiency, the design of future shotcrete supports will be optimized based on life cycle and life cycle cost analyses.

KEYWORDS: Tunnelling, Shotcrete, Fibres, Corrosion, Service-life

1. INTRODUCTION

Using steel fibre reinforcement in wet-mix shotcrete (sprayed concrete) has been common practice since the late 1980s. Steel fibres show an excellent durability against corrosion in homogenous concrete, due to their small size that gives good protection in the alkaline concrete environment. However, the relatively thin layers applied in shotcrete structures give rise to the potential for cracks resulting from deformation or shrinkage and this has raised questions regarding shotcrete structures overall resistance to corrosion. The risk for shrinkage cracking depends on the geometry of the tunnel rock walls, the shotcrete thickness and the even or unevenly distributed restraints that occur between the rock and shotcrete through the bonding interface. Other important factors are e.g. the hardening conditions, such as if water spraying have been undertaken during hardening of the shotcrete. Further comments on this topic are e.g. given by Bryne et al. (2014) and Sjölander and Ansell (2018).

1.1 Service life requirements

Public and private clients are beginning to set complex optimization requirements, taking into consideration environmental and cost-efficiency parameters over the lifetime of an underground construction or structure. For example in Sweden, where as a result of a government guidance (Swedish Government, 2017) the Swedish Transport Administration has established a procurement system with climate efficiency requirements on the contractors (STA, 2019). A climate reduction goal for all infrastructure projects to become fossil-free by the year 2045 has been set. For infrastructure investments, this means a reduced climate impact of 15% by 2020 compared to 2015, in each infrastructural project. For comparison, it can be noted that concrete and shotcrete support in present tunnel projects may account for up to 30% of the overall climate impact from one project (Strömberg et al., 2019).

For comparison, it should be noted that the Swedish authorities (STA, 2016) prescribes a technical service life of 120 years for the main supporting systems of tunnels, including the linings. Also the Norwegian Public Roads Administration specify long design lifetimes, at the present 100 years for rock support (Hagelia, 2018; NPRA, 2015). A minimum requirement of a 100 mm minimum thickness for aggressive subsea environments is also prescribed, due to potential durability problems (Kompen, 2008).

The results of an ongoing project (Strömberg et al., 2020) show that the optimization of environmental impact from use of construction materials cannot be disconnected from national technical design methods and procurement requirements. However, it is not realistic to expect a 120 year long service-life with a remained load-bearing capacity in chloride-exposed environments and, at the same time, fulfilling the climate impact reduction requirements. There is a dilemma in complying with existing standards to achieve technical requirements while optimizing a concrete structure in order to reduce the climate impact. Special measures must therefore be taken in the design of shotcrete rock support with service-life predictions based on an acceptable reduction of load bearing capacity, which is here demonstrated with examples. Measures taken at the design stage to ensure the capacity can be addition of extra amount of fibres, increased structural thickness or a change to a more corrosion resistant material.

1.2 LCA and LCC analyses

A common measure when estimating the total cost of a product, a building, or an underground construction, is the Life Cycle Cost (LCC). The entire technical life span of the structure should be considered and for a tunnel, the calculation will include building costs, use of materials and labour, maintenance, repairs and possibly also costs associated with the future closing of the tunnel. Previous studies (Eriksson and Edelman, 2014) have shown that costs due to maintenance and disturbance on traffic may be equally large or larger than the investment cost. Optimizing the structural design of a tunnel with the aim of few and short future repairs are thus important measures to reduce the total cost by minimizing traffic interference on personal and gods transports. Including all factors that affect the need for repairs and upgrading work, e.g. due to steel fibre corrosion which is the focus of the current paper, is a complex procedure due to the need for accurate data. However, when successful, the measure is and will be an important optimization tool in the design for sustainable underground and tunnel structures.

The European directive 2014/24/EU on public procurement in the Member States (EU, 2014) proposes a supplement to the traditional tender evaluation model in which competitive bidding proposals are no longer evaluated on the basis of price. For example in Sweden, the directive was adopted as a new Public Procurement Act (Swedish Parliament, 2016), which proposes that alternative tenders are evaluated on the basis of the total LCC. It is known that long service life, less maintenance, less amount of used construction materials and lower energy consumption during a tunnels entire life cycle have a decisive impact. However, one of the major obstacles in reaching the climate impact reduction goals is that the current calculation procedures used creates several problems concerning the implementation of Life Cycle Analyses (LCA) and LCC analyses, which leads to that builders still order the reliable, traditional design solutions (Strömberg, 2017). The reason for this is also that lack of reliable service life data on different tunnel supports and structural elements results in that the LCA and LCC alculations must be made on basis of generic approximated data. This leads to difficulties in presenting information to enable the infrastructure project stakeholders to understand the inter-relationship between costs (LCC), environmental impact and design alternatives. Because of the low experience in multidisciplinary optimization design based on LCA and LCC most tunnels through hard rock, in e.g. Sweden (Strömberg et al, 2019), are over-designed with too thick shotcrete layers and too large amounts of steel fibres used.

2. CORROSION IN STEEL FIBER SHOTCRETE

Ductility of fibre reinforced concrete and shotcrete, i.e. the capability to deform in bending, is given from the interaction between fibre and concrete matrix via bond-strength, friction and fibre deformation. Corroded fibres with reduced diameters can still contribute to the ductility as long as the fibre strength is larger than the pull-out resistance. Thus, the load-bearing capacity is unaffected as long as this prerequisite is fulfilled (Nordström, 2005). Severely corroded fibres across a shotcrete crack will rupture instead of being pulled out and this will with increased time occur successively on fibres deeper in the crack. However, there is a need to study this mechanism more in detail and one possible method can be to extract cored samples over shotcrete cracks in situ for investigation using tomography X-ray techniques, see e.g. Ansell et al. (2018). Traditional service-life criteria are not valid for steel fibre corrosion in cracks and instead the service-life prediction should be based on an acceptable reduction of load-bearing capacity. Measures taken in the design stage to assure the load-bearing capacity can be addition of extra amount of fibres, increased thickness of the structure or change of fibre material to more corrosion resistant materials. However, to replace steel with synthetic fibres can give other practical problems (see e.g. Myhren et al., 2018) and the focus of this paper is therefore set on steel fibres.

2.1 In situ tests

It has been observed that steel fibre corrosion due to chloride penetration in thin layers of shotcrete can have a severe effect on the durability. However, for shotcrete layers thicker than about 100 mm this problem will not be as severe, see e.g. Bernard (2004) and Hagelia (2018). For cracked shotcrete exposed to de-icing salts there will still be significant problems, depending not on the shotcrete thickness but on the crack depth. A project for long-term in situ exposure of cracked steel fibre reinforced shotcrete samples up to 17 years of age clearly demonstrate degradation of the load-bearing capacity with time (Nordström, 2017). Shotcrete panels were exposed in three different environments considered as typical for steel fibre reinforced shotcrete; a road tunnel, a motorway and a fresh-water river. For the tunnel environment, a heavily trafficked road tunnel, the Eugenia tunnel in Stockholm, Sweden, was chosen. Pre-cracked shotcrete panels were mounted close to the road surface, as shown in Figure 1. The environment in the tunnel exposes the panels to humidity, chlorides from de-icing salts, exhausts from vehicles and frost.

Prior to being mounted in situ, the 500×125×75 mm test panels were pre-cracked using four-point loading until cracks with widths of 0.1, 0.5 and 1.0 mm appeared. Evaluation of the corrosion was done by measuring the remaining fibre diameters crossing the cracks. To achieve this, some panels were sliced, saturated with water and exposed to repeated freeze-thaw cycles until the concrete matrix was pulverized and the fibres could be collected. The amount of corrosion is expressed as loss of cross sectional area in comparison with the original area. After various times of in situ exposure some panels were also re-loaded in the laboratory to determine the remaining residual (material) strength, as exemplified in Figure 2. Two different approaches were used, first a direct comparison between the ultimate load levels before and after in situ exposure. A statistical comparison was also made, between the load level at 2 mm deformation after exposure with the statistically expected load at the same deformation, but before exposure.

The results show that all cracked panels suffered from steel fibre corrosion after 17 years of exposure. The attacks are most severe in the motorway environment, with a combination of high level of humidity and high exposure to de-icing salts. The chloride contents in the samples from the tunnel environment were also high which also in this case had accelerated the initiated corrosion. Here, de-icing salts from the outside roads follow the vehicles into the tunnel where it is accumulated due to not being washed away by rain. Crack width rules the time for initiation but only show a limited influence on the corrosion rate. Longer fibres corrode faster due to the larger cathode area. Conclusions from the long-term project (Nordström, 2005, 2016, 2017) are that it can be stated that steel fibre corrosion in cracked concrete exposed to an environment with chlorides from de-icing salts must be expected to occur for the most commonly used steel fibre types. It is therefore not realistic to expect a service-life of 100 years with remained load-bearing capacity in chloride exposed environments.

Figure 1 Shotcrete test panels in the Eugenia tunnel, Stockholm. From Nordström (2016).

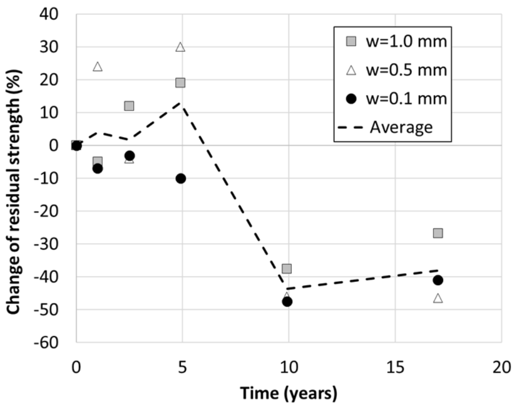

Figure 2 Loss of residual strength – example data from the Eugenia tunnel. According to Nordström (2016).

2.2 Analytical model

In the design of rock supports with shotcrete in combination with bolts, the flexural capacity is an important factor. A design model that incorporate the influence from corrosion on fibres in the crack region on the residual strength of shotcrete is put forth by Nordström (2005). The simplistic, analytical model for estimation of the influence on the load-bearing capacity with increasing loss of fibre diameter with time is schematically illustrated in Figure 3. Assuming a moment equilibrium where the corrosion front is taken into consideration and with forces and distances according to that in the figure will give a moment capacity $M(z)$ that depend on the propagation of the front for fibre rupture as:

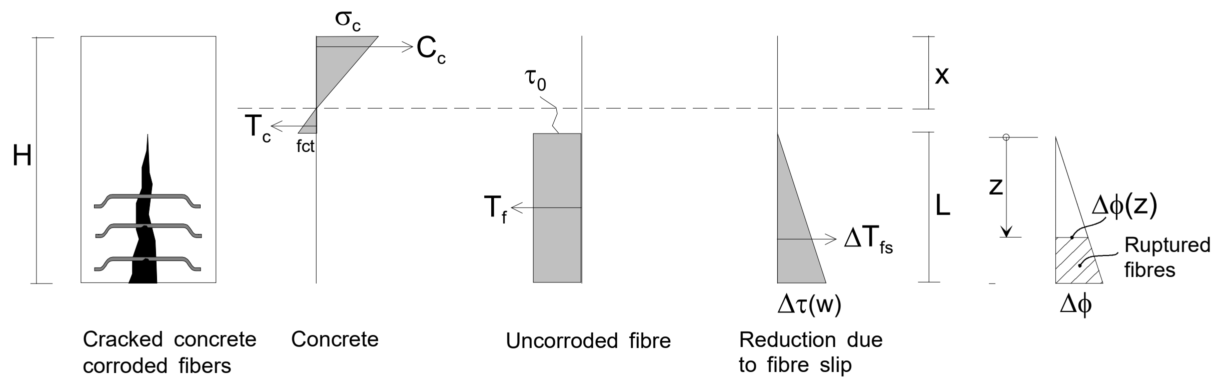

Figure 3 Analytical model for flexural load-bearing capacity on a cracked fibre reinforced shotcrete specimen and loss of fibre diameter due to corrosion in a crack. From Nordström (2005).

$$M(z) = T_c \cdot \frac{2}{3} \cdot (H - L) + T_f \cdot \left(H - L - \frac{x}{3} + \frac{z}{2} \right) - \Delta T_{fs} \cdot \left(H - L - \frac{x}{3} + \frac{2z}{3} \right) \quad (1)$$

where H is beam height, L crack length, x height of compressive zone and z distance from crack bottom to front for fibre rupture. The beam width is B, included in the expression for the tensile force capacity in the shotcrete, which also depends on the tensile strength f_{ct}, as:

$$T_c = f_{ct} \cdot \frac{B}{2} \cdot (H - x - L) \quad (2)$$

The expression for the tensile force capacity of un-corroded fibres

$$T_f = \beta \cdot B \cdot L \cdot \frac{l}{2} \cdot \tau_0 \cdot \pi \cdot \phi \quad (3)$$

contain parameters for fibre density at a crack surface β, fibre length l, initial frictional stress τ_0 and fibre diameter ϕ. The reduction of pullout resistance due to fibre slip is:

$$\Delta T_{fs} = \beta \cdot B \cdot L \cdot \frac{l}{2} \cdot \frac{\Delta \tau(w) \cdot \pi \cdot \phi}{2} \quad (4)$$

where also the reduction of frictional stress due to fibre slip $\Delta\tau(w)$ is included.

2.3 Service-life modelling

The above analytical model can be implemented and used for service-life modelling, aiming at describing how the functionality or load-bearing capacity is reduced with increasing steel fibre corrosion. The initiation of corrosion can be more or less instantaneous for cracked steel fibre reinforced shotcrete. The service life, i.e. the time until the limit state is reached, should therefore be a function of the corrosion rate and the current strength achieved from fibres with no or only corrosion below the limit of rupture. Taking the propagation period into consideration a suitable limit state can be to define an acceptable reduction in load-bearing capacity. As no unexpected, brittle failures can be accepted, the criteria for when the fibres cannot be used in a load-bearing calculation should be when the fibre diameter is too small to create a ductile pull-out of a fibre. The change of load-bearing capacity, expressed as bending moment capacity, can be calculated using Eqs. (1-4). In the model, the fibre slip (s) at the crack mouth is assumed to be the same as the crack width (s=w). An important input for the analytical model is the corrosion rate, which for ordinary steel fibres usually varies with exposure time, see the example given in Table 1 that are representative for samples placed outdoors and very close to a road surface. Further background data and a thorough discussion on the influence from different parts of the equations is given by Nordström (2005).

Table 1 Corrosion rates (for fibres in the crack mouth) for Dramix 30/0.5 fibres in exposed shotcrete samples with a crack width of w=0.5 mm. Example from Nordström (2005).

Time, shotcrete age	Corrosion rates
0–1 year	0.030 mm/year
1–2.5 years	0.041 mm/year
2.5–5 years	0.008 mm/year
> 5 years	0.008 mm/year

3. EXAMPLES

The following examples, based on earlier examples from Nordström (2005), are chosen to demonstrate the effect of different strategies to reach a long technical life for a fibre reinforced shotcrete lining in a tunnel. A case with an initially high load-bearing capacity is compared to cases where different types of repairs are carried out within the time span in question. The evaluation of the alternatives will focus on the total use of material. In a LCC or LCA analysis, also the labour cost must however be included. An area of 2×400 = 800 m^2 of a tunnel wall reinforced with steel fibre shotcrete is studied. The shotcreted area is situated relatively close to the tunnel entrance where a high concentration of de-icing salts leads to an aggressive environment with respect to the risk for steel corrosion damage. The corrosion rates must be chosen with respect to the local environment and chloride exposure. Here, the examples are assumed to follow the relatively high values given in Table 1 and it should be noted that further into the tunnel lower values will be more representative. The required technical service life for the tunnel is set to 120 years and during this time the bending moment capacity of the shotcrete lining is not allowed to decrease below 85% of the initial design value.

3.1 Material data

The steel fibres used is of type Dramix 30/0.5, i.e. 30 mm long including end-hooks, with a diameter of 0.5 mm and made from low carbon steel. The shotcrete corresponds to a concrete in strength class C35/45, with a maximum aggregate size of 8 mm and a water to cement ratio of 0.42. The basic shotcrete mix is given in Table 2, but it should be noted that 55-70 kg/m^3 steel fibres are added depending on the case studied. The design value for the bending moment capacity is 4050 kNm/m, which can be obtained for various combinations of steel fibre content and shotcrete thickness (see the following section). The limiting value at 85% of this capacity is thus 3440 kNm/m. For these example cases it is assumed that the length of shotcrete bending cracks (*L* in Figure 3) extends 60 mm into the lining. Further details on the material data is given by Nordström (2005).

Table 2 Basic mix for the shotcrete in the examples, with 55-70 kg/ m^3 steel fibres added. From Nordström (2005).

Water	214 kg/m^3
Cement	510 kg/m^3
Aggregates (0-8 mm)	1200 kg/ m^3
Sand (0-1 mm)	300 kg/ m^3
Set-accelerator and plasticizer	

3.2 Studied cases

Four different basic cases with initial bending moment capacities that exceed the design value of 4050 kNm/m is studied. These are:

Case 1 - With 75 mm shotcrete and 55 kg/m^3 (0.7 vol-%) steel fibres

Case 2 - With 75 mm shotcrete and 70 kg/m^3 (0.9 vol-%) steel fibres

Case 3 - With 125 mm shotcrete and 70 kg/m^3 (0.9 vol-%) steel fibres

Case 4 - With 125 mm shotcrete and 70 kg/m^3 (0.9 vol-%) steel fibres with doubled diameter.

As seen in the following results section (Figures 4-7), the first case is closest to the design capacity but case 4 is the only of the four that exceed the limit value during the entire life span of 120 years. It should be noted that case 4 is based on an unspecified, assumed type of steel fibres with a diameter of 1.0 mm but with other properties identical to that of Dramix 30/0.5. The above four cases corresponds to shotcrete with initially maintained capacity that after about 30-40 years starts to decrease due to steel fibre corrosion. This behaviour is here compared to that of a further four cases, where repair is undertaken to restore the bending moment capacity, by strengthening and/or stopping further corrosion by sealing shotcrete cracks. These cases are:

Case 5 - With shotcrete as in case 2. Repairs are carried out after 46 and 92 years. The cracked outer 60 mm of shotcrete is removed and re-sprayed.

Case 6 - With shotcrete as in case 3. Repairs are carried out after half time, i.e. 60 years. The cracked outer 60 mm of shotcrete is removed and re-sprayed.

Case 7 - With shotcrete as in case 3. Repairs are carried out after 90 years. The cracked outer 60 mm of shotcrete is removed and re-sprayed.

Case 8 - With shotcrete as in case 2. After 46 years is a further layer of 50 mm shotcrete sprayed on top of the old. The old cracks will then be sealed as they are now on the compressive side of the flexural loaded shotcrete layer. The moment capacity is thus up-graded to correspond to that of case 3.

3.3 Results

The material consumption for the 800 m^2 area of shotcrete, performed as in the eight studied cases, are given in Table 3. The volumes of water, accelerator and plasticiser have been excluded. Note that the values for case 4 are based on steel fibres with a doubled diameter. The decrease in bending moment capacity for the basic cases 1-4 is shown in Figure 4. Here it is evident that only case 4 remains outside the dashed limit lines representing 3440 kNm/m and 120 years of technical life. The remaining four cases with repair and strengthening actions are shown in Figures 5-7, also with case 4 for comparison.

For the cases where repair is undertaken, (5)-(7), the amount of total material will be doubled. It should be noted that the total material volumes for case (5) is the highest due to that two repairs are undertaken. Still, this case has a relatively low maximum moment capacity, at least when compared to cases (3) and (4). Case (8), where no shotcrete is replaced but instead a second layer added, show the same total material consumption as for case (4), but without use of the more expensive large diameter fibres. A comparison between Figures 5-7 shows that cases (5) and (8) have significantly lower initial moment capacity compared to the other cases that fulfils the requirements.

Table 3 Total material consumption for each case 1-8.

Case	Thickness (mm)	Shotcrete (m^3)	Cement (1000×kg)	Aggregate (1000×kg)	Sand (1000×kg)	Steel fibre (1000×kg)
1	75	60	31	72	18	3.3
2	75	60	31	72	18	4.2
3	125	100	51	120	30	7.0
4	125	100	51	120	30	7.0*
5	125 (+60+60)	196	80	187	47	11.0
6 & 7	125 (+60)	148	75	178	44	9.6
8	75 + 50	100	51	120	30	7.0

* Steel fibres with doubled diameter.

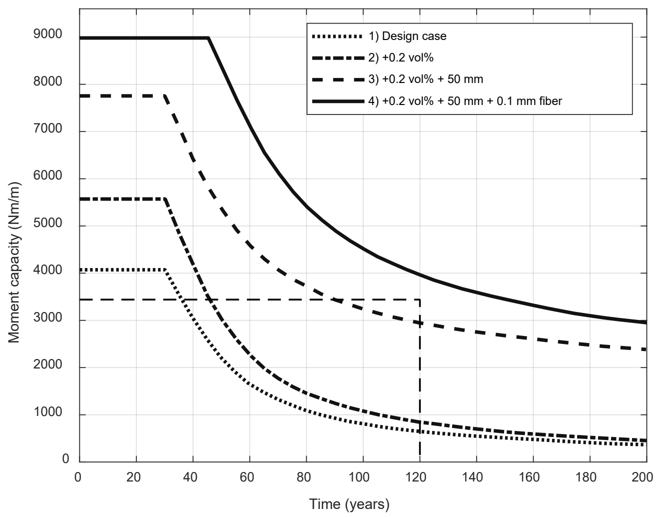

Figure 4 Bending moment capacity vs. shotcrete age, cases 1-4

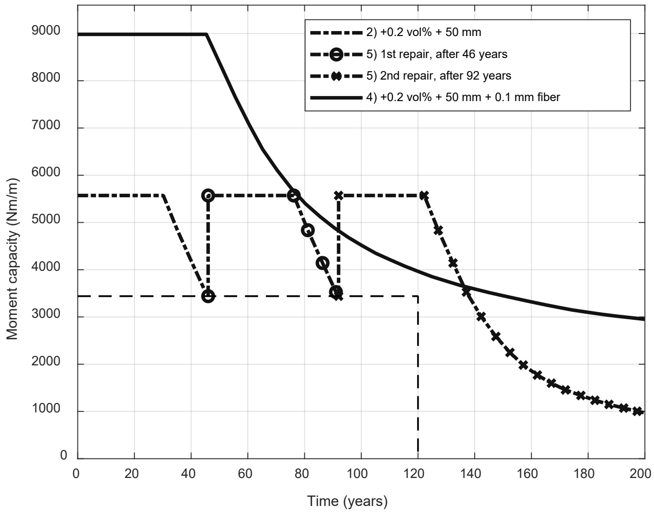

Figure 5 Bending moment capacity vs. shotcrete age, cases 4 and 5

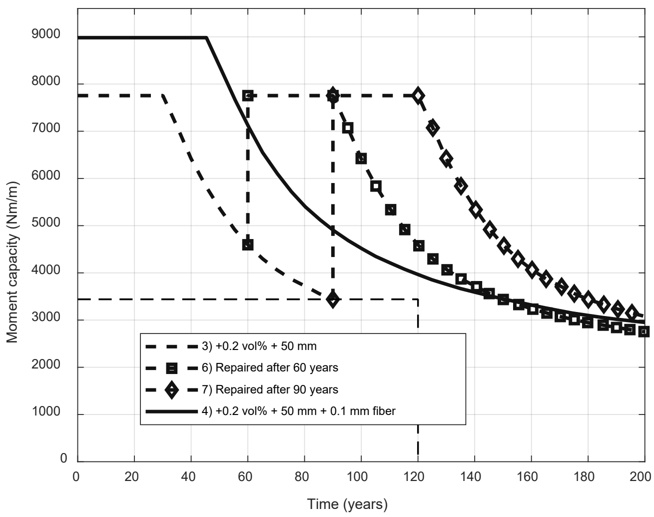

Figure 6 Bending moment capacity vs. shotcrete age, cases 4,6 and 7

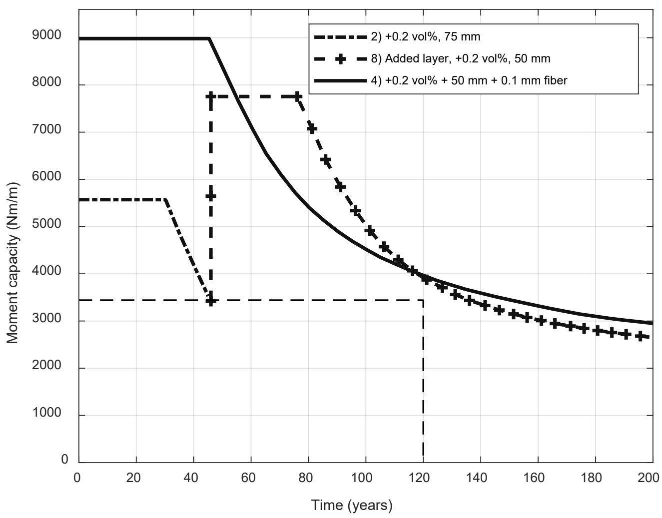

Figure 7 Bending moment capacity vs. shotcrete age, cases 4 and 8

4. SUMMARY AND CONCLUSIONS

The increasing demands set on infrastructure projects, with a focus on climate and sustainability, affects large tunnels where concrete and shotcrete structures represent a substantial part of the overall climate impact. Authorities have started to set climate impact reduction goals and at the same time are public and private clients beginning to set requirements for taking into consideration environmental and cost-efficiency parameters over a structures entire lifetime. In e.g. Sweden and Norway are often a service lifetime of 100-120 years set for a tunnel and its structural support systems. But for steel fibre reinforced shotcrete in chloride-exposed tunnel environments such long service lengths with a remained load-bearing capacity cannot be guaranteed and special measures must therefore be planned. The examples presented here demonstrate how an initial investment in a much higher load-bearing capacity than specified relate to the alternative with a strategy for repair and strengthening during the service life.

The load-bearing capacity of rock support structures in hard rock tunnels often depend on the ductility and capability of fibre reinforced shotcrete to deform in bending. Steel fibres are mixed in to provide additional tensile strength to the shotcrete where the alkaline environment give a good protection against steel corrosion, as long as the shotcrete remains un-cracked due to shrinkage and other stress concentrations. The knowledge on long-term effects on shotcrete support from steel fibre corrosion is limited, partly due to that the use of fibre reinforcement have been the practise only for about 25-30 years, and to that very few long-term investigations have been carried out during this time. An exception is a Swedish investigation that have been ongoing for almost two decades. These results clearly show a degradation of the shotcrete load-bearing capacity with time and the main conclusion is that steel fibre corrosion in cracked shotcrete exposed to chlorides from de-icing salts must be expected to occur in traffic tunnels. Therefore should service-life predictions for shotcrete in the risk of being cracked and exposed to chlorides from de-icing salts be based on an acceptable reduction of load-bearing capacity. The analytical model here used in the examples describe how the functionality or load-bearing capacity is reduced with increasing steel fibre corrosion. The model show that the shotcrete initially maintain the capacity but that after 30-40 years this starts to decrease.

For the presented examples the criteria is that the bending moment capacity for the shotcrete lining during a technical lifetime of 120 years should not be allowed to decrease below 85% of the initial design value. For the four basic cases with varying thickness and fibre content, only one fulfilled this criteria without any repair actions during this life span. In this case, the original fibres had to be substituted by fibres with a doubled diameter, probably increasing the cost for fibres 3-4 times. The basic cases are compared with cases where repair is undertaken. Replacement, or as in one case spraying of an additional layer of shotcrete, restores the bending moment capacity and delays further fibre corrosion. For several of these cases the total amount of used material increases, without any increase in bending moment capacity. When shotcrete are repaired by replacing its outer layer, waste material is created which is not effective from a climate impact point of view. However, the case with spraying of an additional layer gives no waste but one practical drawback may be that the total shotcrete thickness will increase. A technical solution designed to be operational during a long time will also be vulnerable to damage, here e.g. from traffic accidents and collisions or rock failure. If such a damage occur, un-planned repairs must be undertaken, and thereby possibly erase the advantages with the technical solution. For cases with planned repairs, this risk will be greatly reduced. This is demonstrated by examples (cases 6 and 7) that show how a planned repair can be carried out in advance and thereby still manage to withhold the bending moment capacity throughout the prescribed technical life-time.

It has today become common that alternative tenders are evaluated on the basis of a LCA or LCC analysis. An optimal design for a long service life with less maintenance and less consumption of construction materials will be the goal. The future development of LCC and LCA analyses must be focused on the total use of materials and also include the labour cost associated with repair and maintenance work, and the disturbance of traffic and transports during the extent of the repairs. Considering all these parameters and requirements in the design process means that complex optimization problems must be solved. For these to become accurate, reliable data on the long-term performance of construction materials and structural systems is required. The examples presented here show that one strategy can be to design shotcrete systems in tunnels with a significant over-capacity, while another is to plan for future repairs and strengthening work. For all such possible solutions that satisfy the technical serviceability criteria must also cost for future material use and labour time be included in the overall comparison, as well as the long-term environmental impact. The future research must thus be made in at least three directions; collecting observations and knowledge from in situ long-term shotcrete performance, describing efficient maintenance and repair strategies, and the set-up of tools for optimized design based on LCC and LCA, with realistic and reliable data as input.

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