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O'FLAHERTY, Fin <<http://orcid.org/0000-0003-3121-0492>>, ELOMARI, Ibrahim and LAMBERT, Paul <<http://orcid.org/0000-0002-2815-1674>>

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Corrosion induced losses in pre-stressed tendons

Fin O'Flaherty, Ibrahim R. Elomari and Paul Lambert
Centre for Infrastructure Management, Materials and Engineering Research Institute,
Sheffield Hallam University

ABSTRACT

The diameter of single tendons in pre-stressed concrete is typically around 5mm, corrosion combined with high levels of pre-stress can lead to a catastrophic, sudden rupture if not discovered in time. However, even if corrosion is present but not severe enough to cause rupture, a loss in pre-stress may result which may influence the load carrying capacity of the member

This paper investigates the loss in pre-stress of tendons subjected to different levels of corrosion and different level of pre-stress. Twelve timber moulds were manufactured as a base for applying the pre-stressing technique. Ungalvanised tendons measuring 5.4mm diameter were pre-loaded to two extreme target levels of stress, namely 30% and 80% of ultimate tensile strength (UTS) and surrounded by mortar. Accelerated corrosion of 0% (control), 3% and 6% target loss of cross-sectional area were applied to replicate in-situ conditions. The strain in the tendons was continuously monitored throughout the corrosion process via vibrating wire strain gauges.

The results show that the lightly pre-stressed tendon (30% UTS) exhibited a negligible change in pre-stress for 0% and 3% corrosion which increased to 17MPa when the degree of corrosion was doubled to 6%. Similarly, a decline in the initial high target level of pre-stress of 80% UTS was recorded as 9 MPa for 3% corrosion but when the corrosion doubled to 6%, the loss in pre-stress increased by a factor of 7 to 63MPa reduction. This indicates that higher degrees corrosion coupled with higher levels of pre-stress leads to higher losses of pre-stress and this should be accounted for as an additional loss at the design stage.

1. Introduction

Corrosion of steel in concrete was first observed in marine structures and chemical manufacturing plants [1]. Corrosion of embedded reinforcement is the most common cause of deterioration of reinforced concrete (RC) structures and a major economic cost for maintenance of national infrastructures. This will affect the residual capacity of the RC structures and, therefore, is of concern to those who are in charge of ensuring safe operation of concrete structures [2]. Environmental processes may cause salts, oxygen, moisture or carbon dioxide to penetrate the concrete cover and eventually lead to corrosion of embedded steel reinforcement. As the steel corrodes, apart from the resulting loss in its cross-sectional area, the corrosion products expand in volume causing cracking rust staining and spalling of the concrete cover zone [3]

For many pre-stressed structures exposed to marine environment and de-icing salts, attack by chloride ion is the chief factor that causes corrosion of steel bars. Durability failures of pre-

stressed structures caused by chloride contamination are happening continuously all over the world [4]. Offshore structures, piers, dams, docks or harbours are also attacked by chlorides from seawater especially in the tidal, splash and spray water zones.

The most common types of corrosion that affect pre-stressing steels are uniform corrosion, localized or pitting corrosion and stress corrosion. Hydrogen embrittlement had for some time been considered as a separate type. However, now it is being considered as a variation of stress corrosion. Brittle fracture of pre-stressing steel by either stress corrosion or hydrogen embrittlement is especially dangerous and of grave concern to engineers and designers. Other types of corrosion are crevice corrosion and stray current corrosion [5].

2. Design, manufacture, pre-tensioning and mortar casting

Twelve pre-stressing timber moulds were manufactured with external dimensions (675x200x100mm). The timber mould was

fastened to a wisa-form base and was used to pre-load the tendon, providing formwork for the cast mortar and conducting accelerated corrosion. A hollow cylinder/pre-stressing jack, hand pump, wedges, washers and anchorage were used for pre-stressing the tendon to different level of pre-stress, Figure 1.

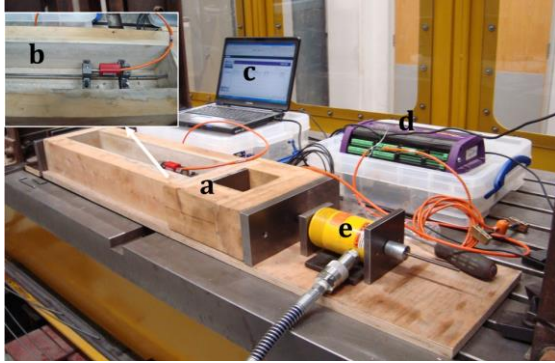


Figure 1. Pre-stressing System (a) mould; (b) strain gauge; (c) laptop; (d) data logger; (e) hydraulic jack connected to hand pump

The ungalvanised tendon used was from a 15.7mm, seven strand stay cable where the king wire measured 5.4mm diameter and length 1.4m was selected. The ultimate strength is approximately 1850MPa.

A number of trials were conducted beforehand to determine the magnitude of losses once the loading apparatus was removed. In these trials, losses exceeded 20%, primarily due to slippage which had a huge influence on the pre-stress in the relatively short tendon. The target stress was, therefore, exceeded by approximately 20% to allow for all losses including relaxation of the tendon and contraction of the wooden pre-stressing mould. However, in some of the tests, the predicted losses did not materialise when the loading system was removed due to better control of slippage leading to a higher pre-stress than originally planned. The strain in the tendons was obtained throughout the test using vibrating wire strain gauges (VWSG) firmly attached to the tendons. Two different types were used, one had a gauge length of 89mm and the other 150mm. The change in microstrain ($\Delta\mu\epsilon$) was obtained by subtracting the initial strain from subsequent strains as shown in Eq. 1:

$$\Delta\mu\epsilon = \left[\left(\frac{F_2^2}{1000} \right) - \left(\frac{F_1^2}{1000} \right) \right] (\text{Gauge} \times \text{Batch}) \quad (1)$$

where:

$\Delta\mu\epsilon$ = the strain in microstrain

F_1 = datum frequency of the VWSG (Hz).

F_2 = subsequent frequency of the VWSG (Hz).

Gauge and Batch are constants provided by the supplier (if applicable).

The tendons were tensioned to different levels of pre-stress (30%, 80% UTS - the higher stress/strength ratio is above in-service pre-stress levels but was selected for maximum impact). After a one day period for relaxation to the tendons, mortar (cement, sand and water) was cast around the pre-stressed tendons (Grade 35 N/mm² with a cement content of 340 kg/m³). This mix was used to replicate pneumatic mortar used on site in pre-load applications.

3. Accelerated corrosion process

Corrosion of steel in concrete usually takes several years to be initiated, which is too long for laboratory studies. Thus, laboratory accelerated corrosion is necessary. In order for the corrosion process to take place, there must be differences in potential; anodic and cathodic surface zones of the steel must be connected electrically. A flow of electrons and ions between them must be possible. The electrolytic connection is represented by the mortar which was continually moistened to enhance conductivity.

Impressed anodic current has been used widely to accelerate the corrosion of steel in concrete. This method has been selected for this study on the basis of being relatively fast and the amount of corrosion generated can be calculated from the current passed using Faraday's Law as shown in Eq. 2.

$$\Delta\omega = \frac{A \times I \times t}{Z \times F} \quad (2)$$

where:

$\Delta\omega$ = weight loss due to corrosion in (g)

A = atomic weight of iron (56g)

I = electrical current in (A)

t = time in (sec.)

Z = valence of iron which is 2

F = Faraday's constant (96 500 coulombs)

A direct current (DC) power supply system has been used to provide current and initiate corrosion on the tendon. The tendon, therefore, is the anode and the cathode is provided by means of a mixed metal oxide (MMO) coated titanium cast into the top surface of the mortar. The positive terminal is connected to the tendon (anode) and negative to the MMO (cathode).

Following a two week curing period of the grout, the tendon in each specimen was subjected to general corrosion by applying an anodic impressed current provided by a DC power supply. The relationship between corrosion current density and the weight of metal lost due to corrosion was determined by applying Faraday's Law. A constant current density, i , of 1 mA/cm^2 was adopted in this investigation and three different percentages of corrosion were selected following trials: $m=0\%$ (control), 3% and 6%. Eq. 3 was used to determine the time taken to achieve 3% and 6% corrosion [6]:

$$\frac{2 \times R \times T}{D} = \frac{m}{100} \rightarrow$$

$$R = \frac{m \times D}{2(100)T} = \frac{m \times D}{200 \times T} = 1165i \rightarrow \quad (3)$$

$$T = \frac{m \times D}{200(1165 \times i)}$$

where

R = material loss per year due to corrosion
 T = Time in years
 D = diameter of the tendon.

Substituting, $m=3\%$, $i=1 \text{ mA/cm}^2$ and $D=0.54 \text{ cm}$ into Eq. 3 gives:

$$T = \frac{3 \times 0.54}{200(1.165)} = 0.00695 \text{ yrs} = 60.8 \text{ hrs} \quad (4)$$

The length of tendon, L , surrounded by the mortar is 32cm. The total surface area, a , of the tendon is shown in Eq.5.

$$a = \pi \times D \times L = 17.28\pi \text{ cm}^2 \quad (5)$$

The current required for 3% degree of corrosion per tendon is obtained from Eq. 6:

$$I = i \times a = 1 \times 17.28\pi = 54.28 \text{ mA/tendon} \quad (6)$$

Applying the same procedure above for 6% degree of corrosion, the time required is double that for 3% i.e. 121.8 hours. The current remained constant at 54.28mA.

3. Results and discussion

Figure 2 shows the performance of the tendons with the target pre-stress of 30% UTS. It compares the gross variation in pre-stress of the tendons with the different degrees of corrosion 0%, 3% and 6% over time. The corrosion period, that being when the impressed anodic current is applied, is between Days 32-37 (Cathodic Protection is employed

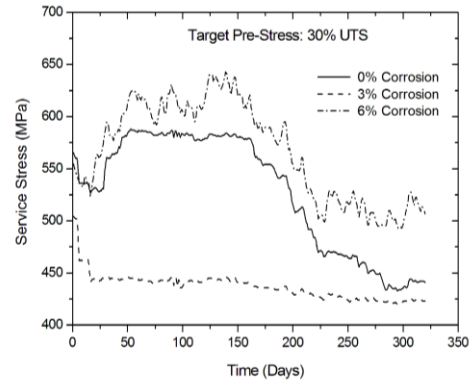


Figure 2. Gross loss in service stress with time (30% UTS)

from Day 43 but its influence is not considered here). Similar stress versus time profiles are given in Figure 3 for the higher stressed tendons (80% UTS). Since the corrosion period (Days 32-37) in Figure 2 and Figure 3 is difficult to examine due to scaling, this time period is shown rescaled in Figure 4 (30% UTS) and Figure 5 (80% UTS).

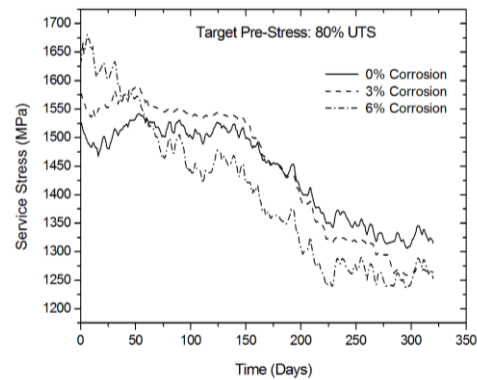


Figure 3. Gross loss in service stress with time (80% UTS)

Referring to Figure 4 and Figure 5, it is evident that there are smaller variations to the strain profiles for the 30% UTS pre-stressed tendons compared to the 80% UTS. This is particularly noticeable as the degree of corrosion increases from 0% (control) to 3% and 6%.

The changes in pre-stress due to increasing corrosion from Figure 4 and Figure 5 is summarised in Table 1. Referring to Table 1, the results show that the tendon with lower pre-stress (30% UTS) exhibited a negligible change in pre-stress for 0% and 3% corrosion and 17MPa for 6% corrosion. Similarly, a decline in the initial high target level of pre-stress of 80% UTS was recorded as 9MPa for 3% corrosion but when the corrosion doubled to 6%, the loss in pre-stress increased by a factor of 7 to

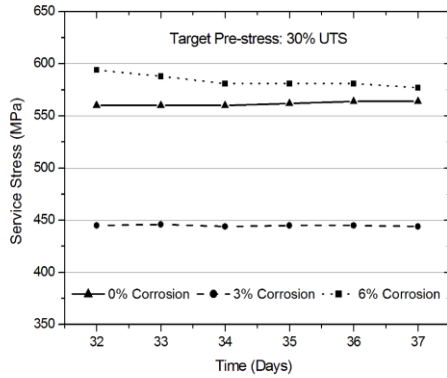


Figure 4. Loss in tendon pre-stress over corrosion time (30% UTS).

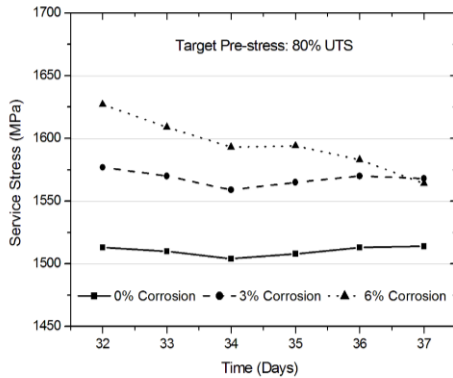


Figure 5. Loss in tendon pre-stress over corrosion time (80% UTS).

Table 1 Residual service stress due to corrosion

| | Deg. of Corr. (%) | Residual Stress (MPa) | | |
|--------------|-------------------|-------------------------------|-------------------------------|--|
| | | Target Service Stress 400 MPa | Target Service Stress 1200MPa | |
| Before corr. | 0 | 560 | 1513 | |
| (day 32) | 3 | 445 | 1577 | |
| | 6 | 594 | 1627 | |
| After corr. | 0 | 564 | 1514 | |
| (day 37) | 3 | 444 | 1568 | |
| | 6 | 577 | 1564 | |

63MPa reduction. This indicates that higher degrees corrosion coupled with higher levels of pre-stress leads to higher losses of pre-stress. However, it is clear to see from Figure 1 and 2 that further losses in pre-stressing levels are evident, perhaps as a combination of the effects of both corrosion and cathodic protection (hydrogen generation) and further analysis is required to isolate the effects of both.

The results shown in Table 1 were plotted in Figure 6. Referring to Figure 6, it is clear that as the degree of corrosion increases from 3% through to 6%, there is a rapid increase in loss of pre-stress for the highly stressed tendon (80% UTS) compared to the tendon exhibiting a pre-stress of 30% UTS. This indicates that tendons subjected to higher degrees of

corrosion coupled with higher levels of pre-stress will suffer higher losses which should be accounted for at the design stage as an additional loss. Further research is required to establish losses due to corrosion at other in-service pre-stresses as would commonly be found in structures e.g. 40-70% UTS (750-1300 N/mm²). Although this could be estimated via interpolation in Figure 6, it will enable a more accurate design equation to be developed linking losses in pre-stress to degree of corrosion for all levels of pre-stress.

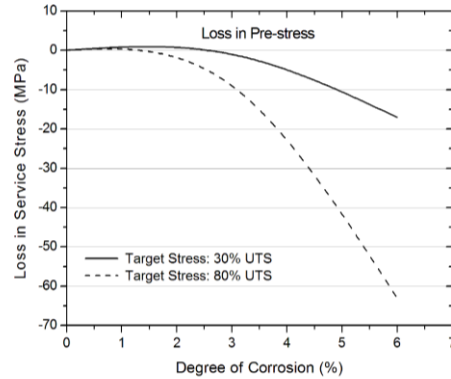


Figure 6. Relationship between degree of corrosion and different levels of pre-stress.

4. Conclusions

A higher degree of corrosion leads to a higher loss in pre-stress in highly pre-stressed tendons which is an additional loss to be accounted for at the design stage.

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