Estimating service life of prestressed concrete systems exposed to chlorides

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Abstract. In general, pretensioned concrete (PTC) structures are being designed with a target service life of about 100 years. However, cases of premature/catastrophic corrosion-induced strand failures have been reported. This necessitates a re-examination of the current practices for service life-based design (SLD) as well as corrosion assessment of new and existing PTC structures respectively, especially the choice of limit states and the parameters considered. The work presented in this paper is a component of the research carried out to develop tools to assist SLD and assessment of PTC structures, and focusses on the estimation of time required for Passive-to-Active (P-to-A) transition, which is the first step of chloride-induced corrosion of prestressed steel strands. For this, ordinary Portland cement-based reinforced mortar specimens (both unstressed and stressed categories) were prepared using prestressing (PS) steel king wires extracted from 7-wire strands. Totally, 10 specimens (5+5) were cast, cured for 28 days and then subjected to dry-wet (5-day drying followed by 2-day wetting) cycles in simulated concrete pore solution containing sodium chloride. The P-to-A transition was detected by continuous monitoring of the open circuit potential and impedance measurements at the end of every wet exposure period. The specimens were then autopsied and the concentration of chlorides in the mortar at the level of steel was determined and defined as Cl_{th}. It was found that the Cl_{th} of PS steel can reduce by half in OPC system when prestress is applied. A case study was performed to understand the implications of using overestimated values of Cl_{th} on the service life. An overestimation in service life of about 40% was observed when the Cl_{th} of unstressed PS steel was used - emphasizing the importance of determining the Cl_{th} of stressed steel and using it for service life estimation.

Keywords: prestressed concrete; corrosion; service life-based design; corrosion assessment

1 Introduction

A significant proportion of the world's bridges consist of pretensioned concrete (PTC) members. Usually, these important (and expensive) PTC bridges are expected to be serviceable for a 'deemed-to-satisfy' life of more than 100 years. However, many of them have started showing signs of corrosion-related distress in even less than 40 years [1]. Corrosion induced failures in PTC bridges are catastrophic in nature [2]. Though the number of reported failures is low at present, it is still a point of concern as most of the existing PTC structures are relatively young (couple of decades old) and may not have sufficient build-up of chlorides yet. But if they start corroding, structural performance can be affected adversely and more drastically due to corrosion of prestressing (PS) steel at a given rate, as opposed to that of conventional reinforcement since the PS strands are under a tensile stress. Engineers will also find it difficult to cope up with the repair and rehabilitation work that this would necessitate. Ensuring an improved durability of these structures will also indirectly contribute to sustainability, as usage of large quantities of materials for restoring or replacing the corroded members will be avoided. In addition to adversely affecting the economy and sustainability, corrosion of PTC structures can result in safety issues. If a single wire of a strand breaks due to corrosion, the carried load is redistributed to the remaining wires, increasing the probability of failure of the entire strand [3]. A PTC element with corroded reinforcement may thus fail in a brittle manner, as demonstrated in the cases of failed PTC bridge in North Carolina [4] and failed girder in Pennsylvania [5] and in many other bridges. This possibility of brittle failure should be considered in the service life design (SLD) and corrosion assessment of PTC structures; and was the focus of a doctoral research work at IIT Madras. This paper intends to give an overarching view on the key findings from the doctoral research work reported in [6]–[8].

The initiation of corrosion (phenomenon of Passive-to-Active (P-to-A) transition) is the first step of degradation of steel due to chloride-induced corrosion. Assuming that the transport of Cl^- is primarily by diffusion mechanism, the time to corrosion initiation (t_i) can be estimated based on Fick's second law if the concentration of chloride at the concrete surface (Cl_s), the chloride diffusion coefficient (D_{Cl}) and the chloride threshold (Cl_{th}), which is the minimum concentration of Cl^- necessary to initiate corrosion, are known. Very limited information on the Cl_{th} of unstressed PS steel is available with inadequate evaluation of the effect of stress [9]. It is reported that the application of tensile stress, even well below yield limit, can degrade the passivity of carbon steel. Presence of tensile stress is reported to cause retardation in passive film formation, and result in a film structure with more defects and low resistance to breakdown [10]. However, in field structures, the complete formation of passive film occurs in cementitious environment prior to chloride buildup at the level of steel. This must be adequately simulated in the laboratory studies. The in-service stress level may vary across countries, but is almost close to 75% of the ultimate tensile strength (f_{pu}) of the PS strand- which is very high. In this paper, an attempt was made to understand the implications of using the Cl_{th} of unstressed PS steel for estimation of t_i of PTC members of bridges such as girders.

2 Research significance

The realistic quantification of t_i has two-fold importance in the civil engineering field. Firstly, the quantified t_i for various steel-cementitious systems can be compared with the target service life and the most suitable steel-cementitious system can be chosen for a particular project. Secondly, the correct quantification of residual service life (RSL, number of years left until corrosion initiation) for a PTC structural element (using D_{Cl} and Cl_s obtained from concrete core samples) can help in assessing the corrosion state of the PTC element. This is dependent on the accuracy of the Cl_{th} input. The methodology presented in this paper can help in a more realistic estimation of Cl_{th}.

3 Methodology

Fig. 1 (a-b) shows the schematic of the test setups used to estimate the Cl_{th} of unstressed and stressed PS steel wire embedded in mortar. Central (king) wires of 5.28 mm diameter, extracted from 7 wire PS strands of nominal diameter 15.2 mm, were used. The mortar was made with ordinary Portland cement, and a water: binder: fine aggregate ratio of 0.5:1: 2.75 was adopted. The fine aggregate consisted of a 50:50 mix of standard sand [11] of particle sizes 1 to 0.5 mm and 0.5 to 0.09 mm, to ensure adequate packing. Distilled water was used to prepare the corrosion test specimens and test solutions. The chemical composition of the PS steel and cement used in the study are presented in Table 1 and Table 2. Self-reacting frames to stress the king wires to the desired prestress level were fabricated and the prestress used in Indian practice [12], i.e. 0.76 f_{pu} was selected for the study. Unstressed PS steel samples were also prepared for comparison.

Table 1. Elemental composition of PS steel (in weight%)

C	Si	Mn	S	Cr	Ni	Cu	Al	Pb	Nb	Ti	W	N	Re
0.89	0.19	0.72	0.01	0.56	0.09	0.03	0.03	0.09	0.05	0.06	0.11	0.01	96.6

***Re-Remaining including Fe and other trace elements**

Table 2. Chemical composition of ordinary Portland cement (in weight%)

CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	Na_2O	K_2O	TiO_2	SO_3	LOI
64.59	19.01	4.17	0.88	3.89	0.16	0.59	0.23	1.70	1.40

LOI – Loss on ignition

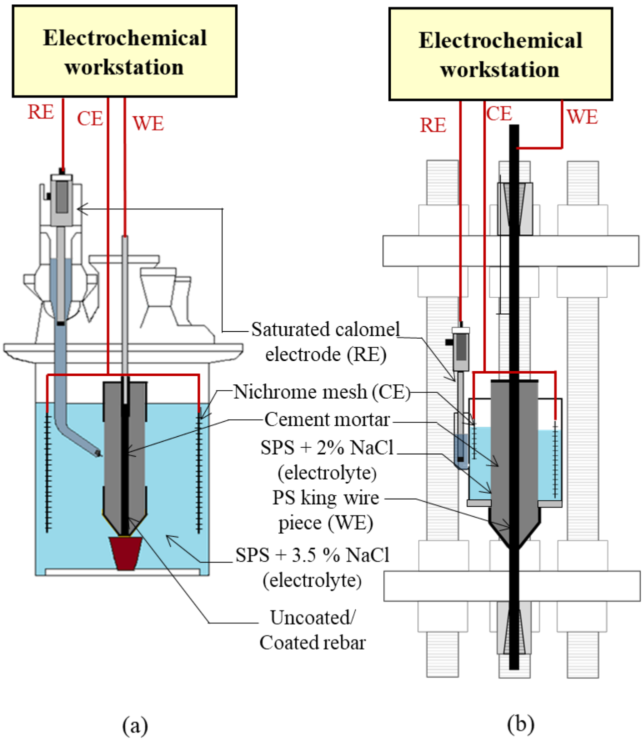


Fig. 1. Experimental setup for testing chloride threshold of prestressing steel embedded in cement mortar: (a) Unstressed wire and (b) Stressed wire

After 28 days of curing, the unstressed specimens (OPC_0 f_{pu}) were exposed to dry-wet cycles (5 and 2 days, respectively) in simulated pore solution, SPS, (with 0.3 g $Ca(OH)_2$ + 10.4 g NaOH + 23.2 KOH and 967 g H_2O per litre of solution) containing 3.5 % NaCl. Because of a previous experience with very early initiation in stressed specimens resulting in less data points for analysis, the concentration of chloride used in the exposure solution was reduced to 2% for the stressed specimens (OPC_0.76 f_{pu}). Circumferentially placed nichrome mesh was used as the counter electrode (CE), saturated calomel electrode was the reference electrode (RE), and the king wire was the working electrode (WE). Open circuit potential (E_{corr}) and electrochemical impedance spectroscopy (EIS) techniques were used to detect corrosion initiation. For the EIS test, an AC signal of 10 mV amplitude was applied over a frequency range of 0.01 to 10^5 Hz. Upon corrosion initiation, the specimens were split at the level of steel and the mortar adjacent to the steel was powdered and collected. The chloride content (% bwob - percent by weight of binder) was determined as per the guidelines available in SHRP S 330 [13] and defined as the Cl_{th} of PS steel in OPC mortar.

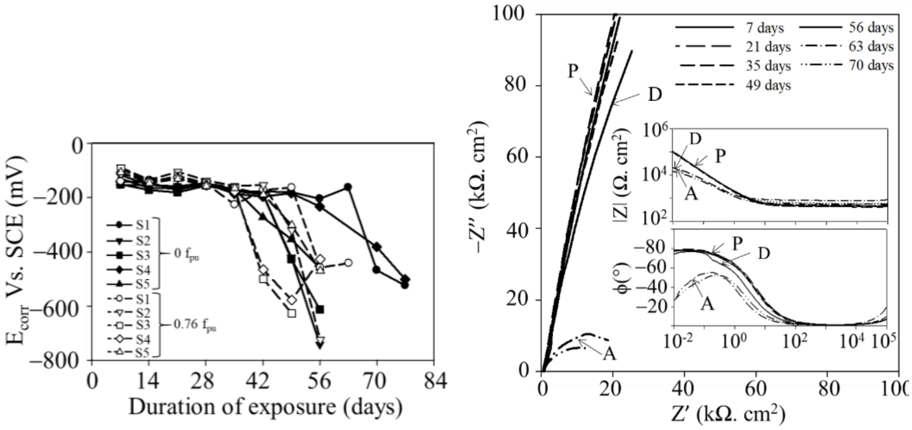
A case study was then performed to understand the implications of using the Cl_{th} of unstressed PS steel to determine the t_i of a typical PTC bridge girder. For this, an in-house developed Matlab® program for service life estimation (SL-Chlor [14]) was used. The probabilistic estimation of T_i was done by means of 1000 random realizations of the cover depth, D_{Cl} and Cl_{th}. During this, the concentration of chloride across the depth was calculated for each year and compared with the Cl_{th}. The probability of corrosion initiation was calculated based on the number of instances of the chloride concentration at the level of steel exceeding Cl_{th}, and a cumulative distribution function (CDF) was generated. Refer Joseline (2021)[8] for more details.

4 Results and discussions

4.1 Effect of stress on the chloride threshold

The E_{corr} measured during the test period is shown in Fig. 2(a). It can be observed that the potentials transitioned from around −100 mV Vs, SCE to very negative values as the duration of exposure to chlorides increased. The time required for this transition was found to be less in the case of stressed specimens although the exposure solution was less aggressive (2% NaCl instead of 3.5% NaCl; reason is presented in Section 3). This indicates that a lesser amount of chlorides can lead to active corrosion of PS steel under in-service stress conditions.

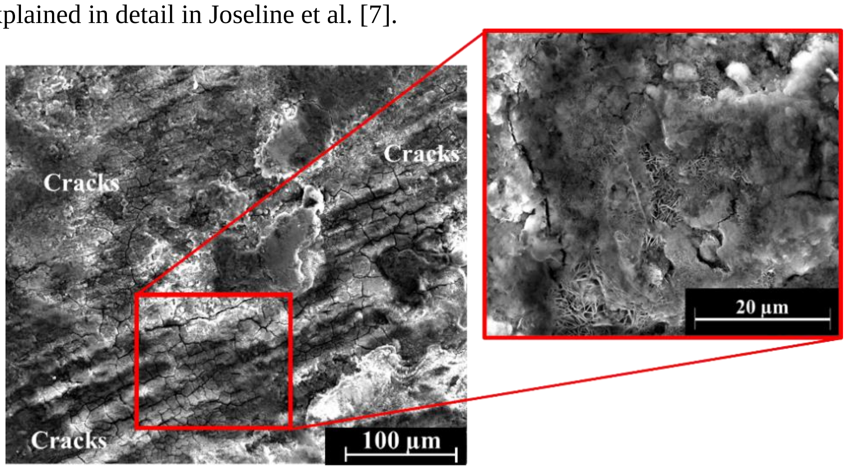
The interpretation from the impedance spectra obtained during the test period was in agreement with that from the E_{corr} results. At the same cycle when a drastic drop in E_{corr} occurred, the low frequency impedance of the system reduced drastically (by about an order). A representative evolution of impedance spectra with exposure to chloride ions is presented in Fig. 2(b). The pattern was observed to be similar for the unstressed and stressed wires embedded in similar mortar, the only difference being in the test cycle at which the reduction was observed – indicating a difference in the Cl_{th}. Corrosion was initiated much earlier in the case of stressed (OPC_0.76 f_{pu}) specimens than unstressed (OPC_0 f_{pu}) specimens.



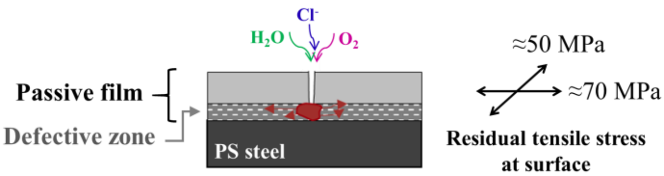
(a) E_{corr} (b) Typical evolution of EIS response

Fig. 2. Variation in electrochemical responses during the P-to-A transition

(P-Passive; D-Depassivated; A-Active) The occurrence of a drastic reduction in the E_{corr} and EIS responses during P-to-A transition is attributed to the passive film cracking indicated by scanning electron micrographs of the surface of PS steel after P-to-A transition Fig. 3(a)). This phenomenon is believed to have occurred either instead of or along with localized pits due to chloride attack. This is expected to be due to various metallurgical factors- the key factor being the presence of tensile stress (residual/applied in the unstressed and stressed case respectively) at the time of passivation. Because of this tensile stress, the inner passive film layers are expected to be defective, and the expansive stress of the corrosion products is believed to cause the cracking in both directions as illustrated in Fig. 3(b) and explained in detail in Joseline et al. [7].



(a) Micrographs showing cracks on the passive film after P-to-A transition



(b) Mechanism proposed for passive film cracking (adapted from [7])

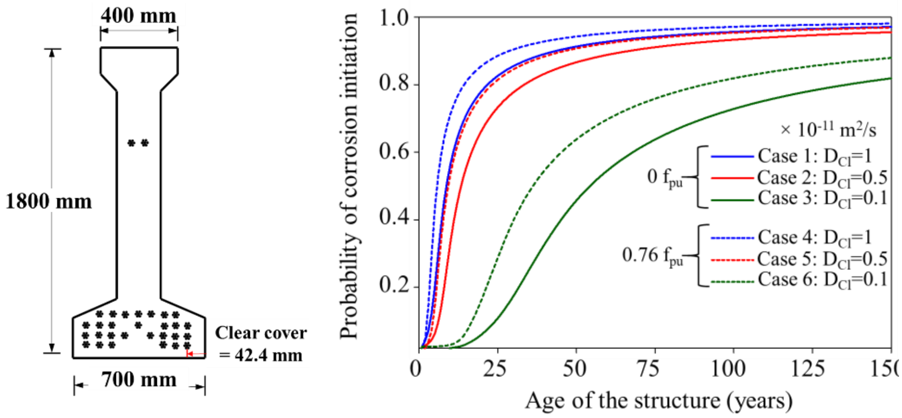
Fig. 3. Cracking of passive film – Micrographs and proposed mechanisms

Upon chloride analysis, it was observed that the Cl_{th} of unstressed PS steel was around 0.4% bwob while that of stressed PS steel was around 0.2% bwob (a 50% reduction due to stress). Also, the variation in the values obtained for the stressed specimens was about 40% as opposed to 15% in case of unstressed PS steel - necessitating the testing of a larger number of specimens to arrive at a good estimate of Cl_{th} for a stressed PS steel. Considering the mean values, it can be said that the Cl_{th} reduced by about 50% when service level prestress was applied.

4.2 Implications of using overestimated Cl_{th} for estimation of T_i

A case study was performed to understand the consequence of using Cl_{th} of unstressed PS steel on the estimated T_i. A typical PTC bridge girder in a highway bridge was selected for the study. The geometric details of the girder are shown in Fig. 4(a).

SL-Chlor (a Matlab® program developed in-house) was used to estimate the t_i. The concrete was assumed to have a cement content of 350 kg/m^3. A maximum surface chloride concentration of 0.6% by weight of concrete was assumed and the time required to for its built up was assumed to be 15 years in all the cases. The value of the ageing factor, m, which captures the reduction in the chloride diffusion coefficient (D_{Cl}) as a function of time, was assumed to be 0.17 [15]. Typical magnitude of D_{Cl} of OPC concretes is in the order of 10^{-11} m^2/s [6]. However, OPC concretes can be designed to have lower values by adjusting the mix design. Hence, since the existing PTC bridges may be from different era of construction resulting in a possibility of D_{Cl} in the order of 10^{-11} to 10^{-12} m^2/s, three cases, namely (a) poor (b) moderate and (c) good quality cover concretes were considered with differences in the assumed D_{Cl}. The obtained CDFs for these 3 cases each of unstressed and stressed PS steels considered are presented in Fig. 4(b).



(a) Cross section of a typical PTC girder

(b) Probability of corrosion initiation

Fig. 4 Probability of corrosion initiation for various stress-D_{Cl} combinations

The effect of Cl_{th} on the estimated t_i can be understood from Fig. 4(b). Usage of Cl_{th} determined for OPC_0 f_{pu} for estimation of T_i resulted in about 40% overestimation.

Also, for the given inputs, the T_i was very less for the cases with high D_{Cl}. This means that the usage of correct Cl_{th} value is more critical for concretes which have poor resistance to chloride ingress. The concretes in the middle-aged and old bridge structures are also expected to fall in this category as the usage of supplementary cementitious materials and low water-binder ratios, which can produce concretes with compact microstructure and high chloride resistance, was not practiced at that time. This emphasizes the need for usage of Cl_{th} of stressed PS steel (instead of unstressed PS steel) for estimation of t_i of PTC systems. A test methodology (setup, test parameters, statistically valid estimates) was developed to address this need [8]; and is kept outside the scope of this paper.

5 Summary and conclusions

Literature provides limited information on the Cl_{th} of prestressing steel. Moreover, the reported values are predominantly for unstressed case. A methodology to determine the Cl_{th} of stressed steels (at in-service stress levels) is presented in the paper. For the OPC system considered in this study, it was observed that in-service prestress of 0.76 f_{pu} can reduce the Cl_{th} by about 50%. Although a higher scatter was observed in the Cl_{th} of stressed specimens (COV=40%) as opposed to unstressed PS steel (COV=15%), it can be concluded that the applied stress has a significant effect on the Cl_{th}. From a case study, it was inferred that a 50% overestimation of Cl_{th} (because of the usage of Cl_{th} of unstressed PS steel as input) can lead to a 40% overestimation of time for corrosion initiation, t_i (and hence the residual service life as well). The overestimation can be critical in the cases where the cover concrete had higher rate of chloride ingress. The findings presented in this paper emphasize the need of using Cl_{th} obtained from stressed steel as input for achieving a more realistic estimation of t_i of PTC systems.

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7 References

1. R. A. Rogers, M. Al-Ani, and J. M. Ingham (2013), "Assessing pre-tensioned reinforcement corrosion within the New Zealand concrete bridge stock", New Zealand Transport Agency Research report 502.

2. K. Lau and I. Lasa (2016), “Corrosion of prestress and post-tension reinforced-concrete bridges” in Corrosion of steel in concrete structures, vol. 2, pp. 37-57, Elsevier Ltd.
3. M. S. Darmawan and M. G. Stewart (2007), “Spatial time-dependent reliability analysis of corroding pretensioned prestressed concrete bridge girders,” Struct. Saf., vol. 29, no. 1, pp. 16–31. doi: 10.1016/j.strusafe.2005.11.002.
4. C. Sly (2001), “An initial look at the Lowe’s motor speedway pedestrian bridge collapse,” J. Fail. Anal. Prev., vol. 1, no. 2, pp. 7–9. doi: 10.1361/152981501770352969.
5. C. Naito, R. Sause, I. Hodgson, S. Pessiki, and T. Macioce (2010) “Forensic Examination of a Noncomposite Adjacent Precast Prestressed Concrete Box Beam Bridge,” J. Bridg. Eng., vol. 15, no. 4, pp. 408–418. doi: 10.1061/(asce)be.1943-5592.0000110.
6. D. Joseline and R. G. Pillai (2020), “Enhancing service life of prestressed concrete structures by using fly ash and corrosion inhibitors,” Indian Concr. J., vol. 94, no. 11, pp. 54–67.
7. Joseline, D., Pillai, R. G., and Neelakantan, L. (2021). “Initiation of Stress Corrosion Cracking in Cold-Drawn Prestressing Steel in Hardened Cement Mortar Exposed to Chlorides.” Corrosion, 77(8), 906–922. doi: 10.5006/3730.
8. D. Joseline (2021), “Electrochemical and chloride-induced corrosion parameters for service life design and assessment of prestressed concrete”, Ph.D. Thesis, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai, India; URL: https://civil.iitm.ac.in/faculty/pillai/people.php
9. P. Y. Virmani and H. Ghasemi (2012), “Literature Review of Chloride Threshold Values for Grouted Post-Tensioned Tendons,” FHWA Publ. No. FHWA-HRT-12-067.
10. B. T. Lu, Y. Zeng, X. Pang, and J. L. Luo (2015), “Effects of hydrogen and tensile stress on passivity of carbon steel,” Corros. Eng. Sci. Technol., vol. 50, no. 3, pp. 186–190. doi: 10.1179/1743278215Y.0000000020.
11. IS 650 (1991), Specification for Standard Sand for Testing of Cement, Bureau of Indian Standards.
12. IS 1343 (2012), Prestressed Concrete-Code of Practice, Bureau of Indian Standards.
13. SHRP-S-330 (1993), “Standard Test Method for Chloride Content in Concrete Using the Specific Ion Probe.” Strategic Highway Research Program, National Research Council, Washington, DC, pp. 1–118.
14. S. Rengaraju (2019), “Electrochemical Response and Chloride Threshold of Steel in Highly Resistive Concrete Systems,” Ph.D. Thesis submitted to the Indian Institute of Technology Madras.
15. R. G. Pillai, R. Gettu, M. Santhanam, S. Rengaraju, Y. Dhandapani, S. Rathnarajan and A. S. Basavaraj (2019), “Service life and life cycle assessment of reinforced concrete systems with limestone calcined clay cement (LC3),” Cem. Concr. Res., vol. 118, no. February, pp. 111–119. doi: 10.1016/j.cemconres.2018.11.019.