



Chloride-induced corrosion and service life of reinforced concrete structures with Fusion Bonded Epoxy (FBE) coated steel rebars

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ABSTRACT

Numerous reinforced concrete (RC) structures have been constructed along the coastal region with significant chloride exposure and with a target service life of 100+ years. In anticipation of achieving such long target service lives, the steel reinforcing bars ('rebars,' herein) in many of these structures are coated with Fusion-Bonded-Epoxy (FBE). However, the FBE coated steel rebars are scratch damaged and exposed to sunlight/UV during transportation, storage, bending, and other construction activities. These inadequate practices can adversely affect the corrosion of steel reinforcement; hence, chloride threshold and the service life of such steel-coating-concrete systems. The practitioners tend to use existing test methods that are meant for uncoated steel rebars to test corrosion performance of coated rebars. However, the results from such tests may lead to erroneous conclusions on the corrosion performance of coated rebars – highlighting a need for a suitable test method for FBE coated rebars in concrete. In addition, the single-step chloride diffusion models used to estimate the service lives of RC systems with uncoated rebars may not be valid for coated rebar systems. The degradation of coating and its characteristics must be accounted for service life estimations. In short, this paper presents develops test methods, generate database on chloride threshold (Cl_{th}), and develop suitable service life estimation models for RC systems with FBE coated rebars, and with field practices in mind.

Keywords: Concrete, fusion-bonded-epoxy, coating, corrosion, service life

1 Introduction

A lot of reinforced concrete (RC) structures, such as highway/railway bridges, high-rise buildings, and power plants, have been constructed along the coastal region with significant chloride exposure and with a target service life of more than 100 years. To achieve this target service life, the steel-cementitious (SC) systems in these structures must have good corrosion resistance, especially when exposed to chlorides. In anticipation of enhanced corrosion resistance, the steel reinforcing bars ('rebars,' herein) in many of these structures are coated with organic materials. Usually, these coatings are made of either a polymer or a polymer-modified material and work by (i) providing a shield/physical barrier between the underlying steel and the deleterious elements, such as moisture, oxygen, chlorides, and (ii) restricting the ionic flow between anodic and cathodic areas [1]–[3]. One of the widely used coated rebar in construction industry is fusion-bonded-epoxy (FBE) coated steel rebars. FBE coating is obtained by placing the clean and hot (at about 200 °C) steel rebars in a mist of powdered epoxy, which is allowed to fuse and bond to the steel surface [4]. This fusion-bonding and subsequent quenching help to form a uniform, continuous, and well-adhered epoxy coating on the steel surface [5]. A good quality FBE coating is expected to insulate and protect the steel surface from the

corrosive/chloride environment and delay the initiation of corrosion. However, Figure 1 (a) shows that the FBE coated rebars are inadequately handled during transportation, storage, bending/cutting of rebars and during the placement/vibration of concrete at construction sites.



Mechanical damage

Rebars during storage and construction of a bridge

Figure 1 Examples of inadequate practices/quality associated with the use of FBE coated steel rebars at construction sites

The poor practices can lead to scratching, cracking, and/or degradation of the epoxy coating, which in turn reduces its corrosion resistance and premature initiation of corrosion [6]. Considering the

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current quality control measures, it is challenging to avoid damage and degradation at construction sites. Many field studies on coated steel rebars report the premature initiation of corrosion, disbondment of coating, or permanent corrosion-induced failure of structures [6]–[10] (see Table 2). On the other hand, many laboratory studies report good performance of coated steel rebars [3],[11]–[15](see Table 3). This difference in opinion from lab and field studies can be due to difference in (i) quality of coated steel rebars used at sites and at laboratories, (ii) the techniques used for assessing corrosion. Due to the unavailability of standard test methods, the practitioners tend to use existing test methods that are meant for uncoated steel rebars. A few literatures report the assessment or comparison of coated steel rebars embedded in cementitious systems using Electrochemical Impedance Spectroscopy (EIS) [16]–[25]. The authors developed and reported a test method named ‘cs-ACT’ to detect the “initiation” of corrosion of FBE coated rebars embedded in concrete [26], which is briefly presented in this paper.

Traditionally and conservatively, the service life of RC structures is defined as the time to the initiation of corrosion of rebars (t_i) [27]–[29]. The estimation of t_i necessitates the estimation of the chloride threshold of embedded steel systems. However, literature do not provide sufficient quantitative and probabilistic data on the chloride threshold of coated steel systems. This makes it difficult to estimate the service life of such systems. Therefore, authors investigated and reported the first set of chloride thresholds for FBE coated steel rebars with various damaged and degraded coating conditions [26],[30]–[32], which is summarized in this paper. Also, the existing service life models made for uncoated steel rebars are not valid for systems with coated steel rebars because they do not consider the chloride ingress through the coating and the associated corrosion initiation. Therefore, there was a need to develop a framework to estimate the service life of RC structures with coated steel rebars. Authors reported a modified service life model for RC structures with FBE coated steel rebars in [26,32], which is summarized in this paper. Therefore, this paper presents effect of various damages and degradation of coating on the service life of RC structures with FBE coated steel rebars.

2 Research Significance

Worldwide, many countries/states have either banned or recommended not to use the FBE coated steel rebars (see Table 1). In India, still, a large number of infrastructures are being constructed using FBE coated steel rebars. Many of the structures are built with poor quality control measures. To take any action to regulate the use of coated steel rebars, approving authorities are asking the data showing the performance of coated steel rebars. However, there is a lack of data available on how the poor site conditions and practices affect the electrochemical characteristics, chloride threshold, and time to corrosion initiation. Also, many literatures focus on rate of corrosion, mass loss of coated steel rebars, etc. showing reported literatures show different opinion than the performance of FBE coated steel rebars at construction sites. This paper presents data on service life estimates in terms of corrosion initiation, which can be used to modify national and international standards on specifications for FBE coated steel rebars to help achieve durable structures with FBE coated steels.

Table 1 Field studies and their opinion on the performance of FBE coated steel rebars

Location	Age (years)	Conditions/Observations	References
Florida, USA	20	Outdoor storage; severe corrosion in five out of 300 structures.	[7]
Minnesota, USA	< 35	Minor cracks and disbondment of coating	
New York, USA	NA	17,000 structures performed good (age not mentioned)	
South Dakota, USA	33	1,300 structures performing good based on visual inspection	
Various states in Canada	5 to 16	Disbondment of coating; under film corrosion	[33]
Virginia, USA	5	Disbondment of coating	[10]
Various states (MI, WI, NY, PA, OH, VA, and IA) in USA	< 20	Underfilm corrosion, cracking, blistering, and disbondment of coating	[8],[34],[35]
Various bridges in USA	<30	Early corrosion in Florida bridges was the result of a combination of the highly aggressive environment (such as heat cooling cycle, ultraviolet exposure), highly permeable concrete, and flaws & damage to FBE coating	[36]

3 Chloride induced corrosion of FBE coated steels

3.1 Test method to detect initiation of corrosion in systems with FBE coated steels

To assess the feasibility of MCC and HCP to detect initiation of corrosion in FBE coated steel rebars, ten macrocell specimens (see Figure 2) of each with following rebars were cast, (i) uncoated steel, (ii) FBE coated steel with no damage (FBEC-ND), and (iii) FBE coated steel with scratched damage (FBEC-SD).

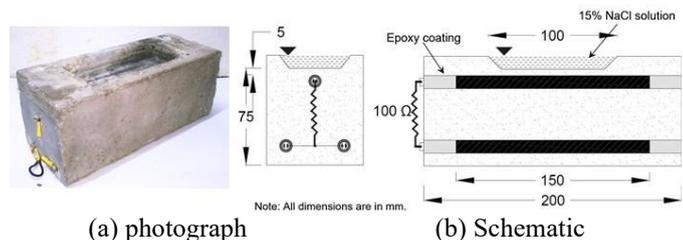


Figure 2 Macrocell corrosion (MCC) test specimen with FBE coated rebars [44]

Table 2 Laboratory studies and their opinion on the performance of FBE coated steels [32]

Test method/technique	Observations	Opinion	References/ Country
Salt spray, bendability, long-term exposure of prism specimens to artificial and natural exposure conditions	Good adhesion, toughness, good resistance to saltwater spray and alkaline solution	Good	[13]/India
Half-Cell-Potential (HCP), Macrocell corrosion current (MCC)	FBE coated steel performs well with a damage to coating < 1% of the defect size.	Good	[11],[13],[14],[37] USA, India
HCP, MCC	Performs good when all the condition as per ASTM A775 are satisfied	Conditional	[3],[12]Germany
Linear polarization resistance (LPR)/weight loss	The corrosion rate of undamaged FBE was found significantly low. However, the corrosion rate increased with an increase in the damaged area.	Good	[38]Saudi Arabia
Visual observation (VOB), HCP, MCC	FBE coated rebars were intact even after exposure to chloride solution for about 8.5 years	Good	[15]/USA
Electrochemical Impedance Spectroscopy (EIS), VOB	No evidence of corrosion even with cracked concrete; the resistance of the high-frequency loop was low with the damaged coating	Good	[17]/USA
HCP, EIS	Measurement of HCP can be misleading, delamination of the coating after 1-year long exposure to 3.5% NaCl solution. However, the corrosion rate was low.	Good	[39]/UK
VOB, HCP, MCC, EIS	Review paper	Mixed	[40]/USA
Coating adhesion, HCP, MCC	No correlation between the rate of corrosion and measured corrosion potential.	Mixed	[2]/USA
LPR, EIS	Underfilm corrosion	Poor	[41]/Saudi Arabia

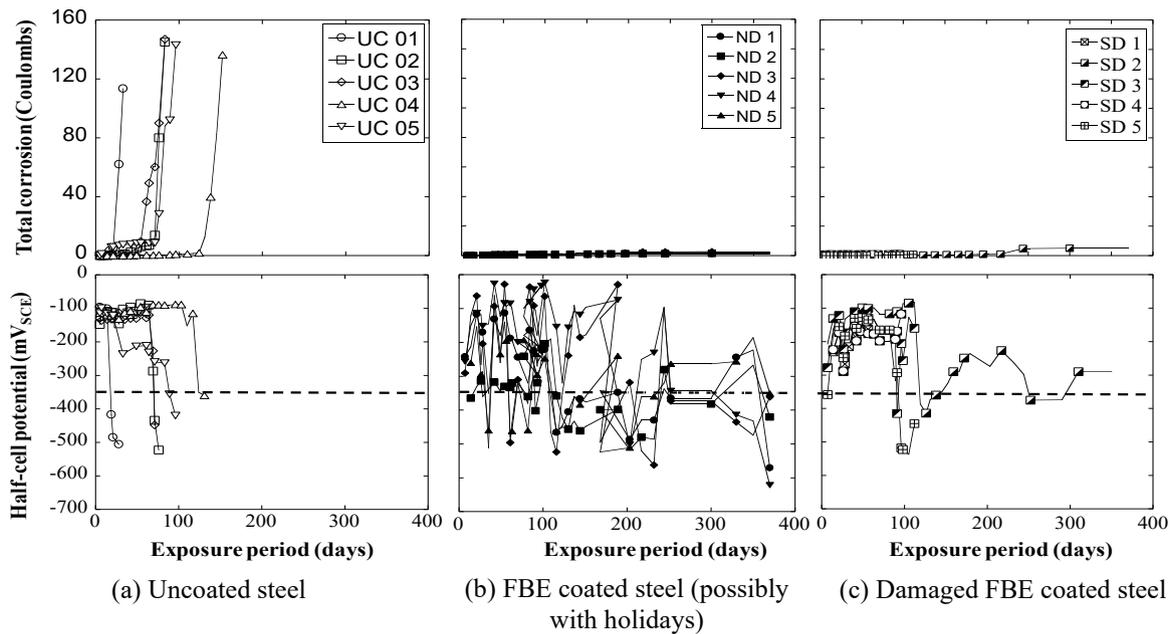
**Figure 3 Total corrosion and half-cell potential (HCP) of uncoated and damaged FBE coated steels in mortar [26],[32]**

Table 3 Details on the ban of FBE coated steel [32]

Country; Reference	Recommendation on the use of FBE coated steel rebars
Florida, USA; [9]	In 1979, banned to be used in bridges and large infrastructure.
Florida, USA	In 1988, banned from all the construction projects.
Oregon, USA; [42]	In 1989, (recommended to stop using FBE coated steel rebars.
Quebec, Canada; [33]	In 2000, the further use of FBE coated steel rebar was not recommended.
Ontario, Canada; [43]	In 2000, the use of FBE coated steel rebar was not recommended based on technical reasons and life-cycle cost analysis.
Virginia, USA; [10]	In 2000, recommended stopping to use FBE coated steel rebar.

The spikes and drops in Figure 3 (a) show that the MCC and HCP test methods, respectively, could detect the initiation of corrosion of uncoated steels. However, the very low corrosion and lack of a detectable pattern in Figure 3 (b) and (c) [for ND (no damage) and (SD) scratched damage cases] and a comparison with the visual observations of autopsied rebars showed that these methods failed to detect the initiation of corrosion in FBE coated steel rebars. The reason for this is discussed next.

Figure 4 (a) and (b) show the difference in the macrocell corrosion circuits in the case of uncoated and coated steels. The resistance offered by FBE coating is significantly high and hence, the corrosion cell forms across various points in the top rebar itself – without the participation of other rebars. Such corrosion may not be reflected in the macrocell corrosion current measurements made across the resistor (see Figure 4 (a) and (b)) in the ASTM G109 type MCC tests. Likewise, because of the high ohmic drop across the FBE coating, the HCP measurements made using ASTM C876 did not reflect the true corrosion activities at the steel surface. Figure 4 (c) shows visible corrosion of steel on the scratches at the center of the rebar - proving the inadequacy of MCC and HCP measurements in detecting the ongoing corrosion in coated rebars. This also shows that only one rebar is required for assessment of FBE coated steel rebars. Therefore, steel-embedded mortar (lollipop) specimens were cast to evaluate the feasibility of LPR and EIS [Figure 5 (a)].

Ten lollipop specimens each with (i) uncoated steel and (ii) FBE coated steel (with no damage; FBEC-ND) rebars were cast. Figure 5(b) shows the photograph and schematic of lollipop specimen and schematic of corrosion cell used for EIS and LPR tests. Figure 6(a) shows an ideal EIS response with three semicircles, (i) response from the cement mortar, (ii) response from the coating (R_c), and (iii) response from steel surface/ steel-coating interface (herein, $R_{p,s-c}$).

Monitoring of R_c revealed the slow degradation of coating, and the monitoring of $R_{p,s-c}$ could detect the initiation of corrosion in FBE coated steel rebars. Figure 7(a) shows that the LPR measurements failed (no rise in $1/R_p$) to detect the initiation of corrosion in FBE coated rebars, whereas EIS could detect the corrosion (sudden increase in $1/R_{p,s-c}$). Note that the EIS measurements could detect the initiation of corrosion at early stages, even before significant rust spots were formed. For example, Figure 7(b) shows the photograph and micrograph of steel cross-section at the time when initiation of corrosion was detected using EIS - deposits of corrosion products between the steel and coating are visible. Hence,

a systematic methodology based on EIS technique was developed to detect the initiation of corrosion and determine chloride threshold of FBE coated steel rebars embedded in cementitious systems. Note that initiation of corrosion was observed where the thickness of coating was found less than 175 μm (see Figure 8). Also, the bond of systems with coating thickness more than 370 μm is a concern.

3.2 Degradation of FBE coating

A total of 45 as-received FBE coated steel rebars without damage or degradation (denoted as FBEC-ND; each with 8 mm diameter and 50 mm length) were kept in UV chamber for 60 days. Three specimens each were removed after regular interval of exposure. Then, micrographs of these samples were obtained. The chemical composition and atomic bond characteristics of three coating samples (with 0 and 10 days of UV exposure) were obtained using EDAX, Fourier Transform - Infra Red (FT-IR) spectra. SE micrographs indicated that the exposure to UV rays for about one month can crack the FBE coating. Further exposure to FBE coating can result in crack widening and formation of new cracks. EDAX study on these samples revealed that the cracking occurred preferentially at the locations where photo-stabilizers were not adequately available. In addition, FT-IR analysis of these samples revealed that the FBE coating cracks because of shrinkage-induced due to the formation of carbonyl bonds. Then, ten lollipop specimens, each with following steel reinforcement were cast with uncoated, FBEC-ND, and FBEC-UV rebars, to understand the degradation mechanism of FBEC-ND and FBEC-UV specimens. Also, these specimens were used to estimate the effect of UV exposure on chloride threshold of FBE coated steel rebars using the test methodology developed [30]. The lollipop specimens were subjected to cyclic wet-dry exposure. The R_c of coating was found to change as a function of exposure. A 4-stage and a 2-stage degradation processes are proposed for FBEC-ND and FBEC-UV rebars, respectively (see Figure 8 and [26]).

3.3 Mechanism of corrosion in systems with FBE coated steel rebars

For FBEC-ND specimens (see Figure 8 (a)), the Stage 1, when the resistance (R_c) of ND coating specimens (i.e., without UV exposure) was constant during the first few weeks of exposure to chloride solution – indicating that the FBE coating could resist the entry of moisture for about three to four weeks. Later, in Stage 2, R_c decreased to about half of the R_c after 1st wet period. During this time, the moisture and chlorides might have penetrated through the epoxy coating – resulting in the decrease in the R_c of ND coating. Then, when sufficient moisture and oxygen are available at the steel surface, corrosion may initiate and propagate. In Stage 3, R_c was found to be increasing. This can be attributed to the additional resistance offered by pores in the coating that are filled with the insoluble corrosion products [46], which was confirmed by SE micrograph and XRD analysis of filled products in the pores (see Figure 8 (a)). These corrosion products can obstruct the further entry of deleterious elements and delay the corrosion process. However, in Stage 4, the expansive stresses from the corrosion products continues to build and crack the coating, which in turn enhances the interconnectivity of pores/pinholes/cracks. This allows the entry of more moisture into the cracked coating filled with corrosion products. The coating with interconnected pores/pinholes/cracks filled with moist corrosion products can exhibit a low coating resistance in Stage 4.

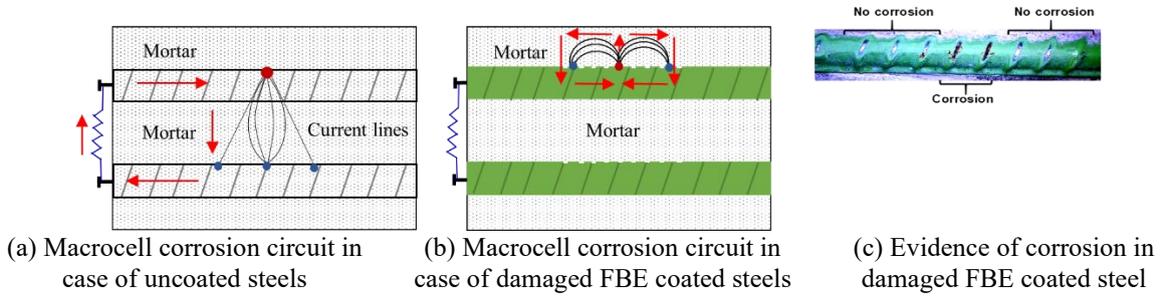


Figure 4 Difference in the macrocell corrosion circuits (see arrows) in cases of uncoated and damaged FBE coated steels embedded in mortar/concrete [26],[32]

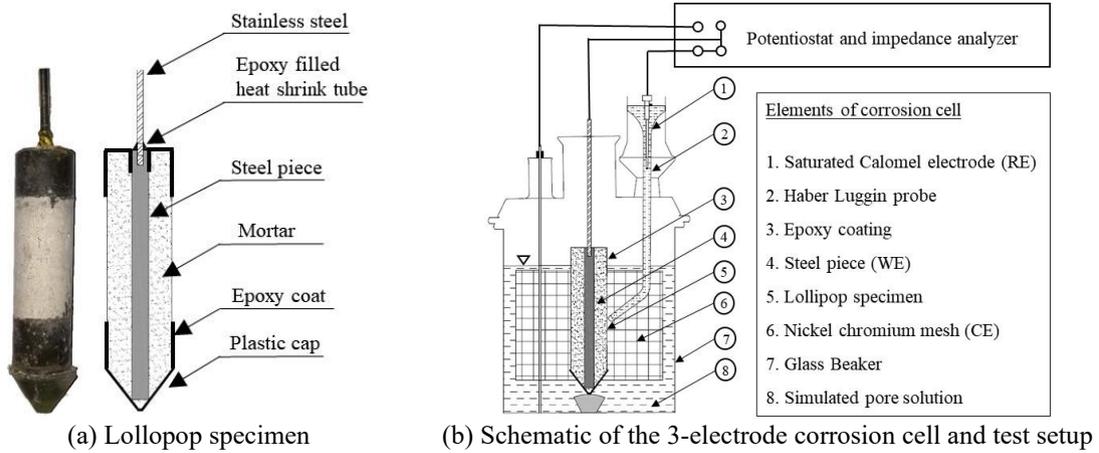


Figure 5 Corrosion test specimen and test setup used for the LPR and EIS tests [32]

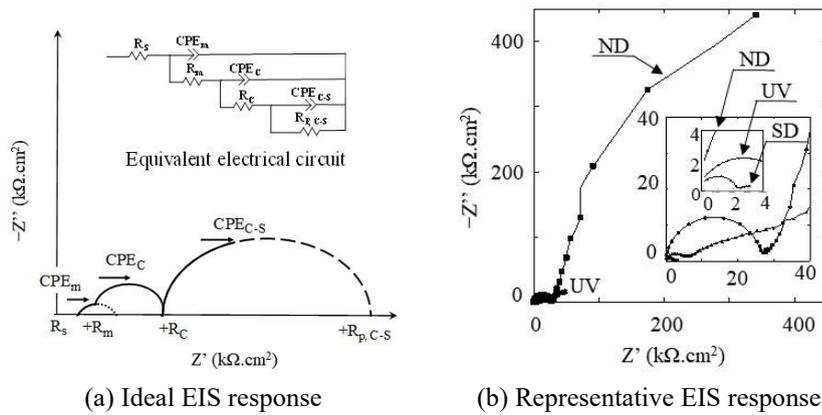


Figure 6 Ideal and representative EIS responses from coated steel rebar in mortar [26],[31],[32]

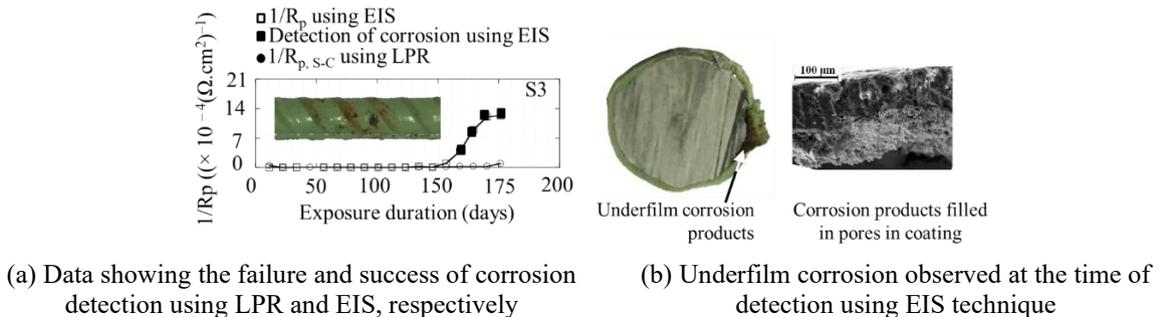


Figure 7 Detection of corrosion initiation of FBE coated steels in cement mortar [32]

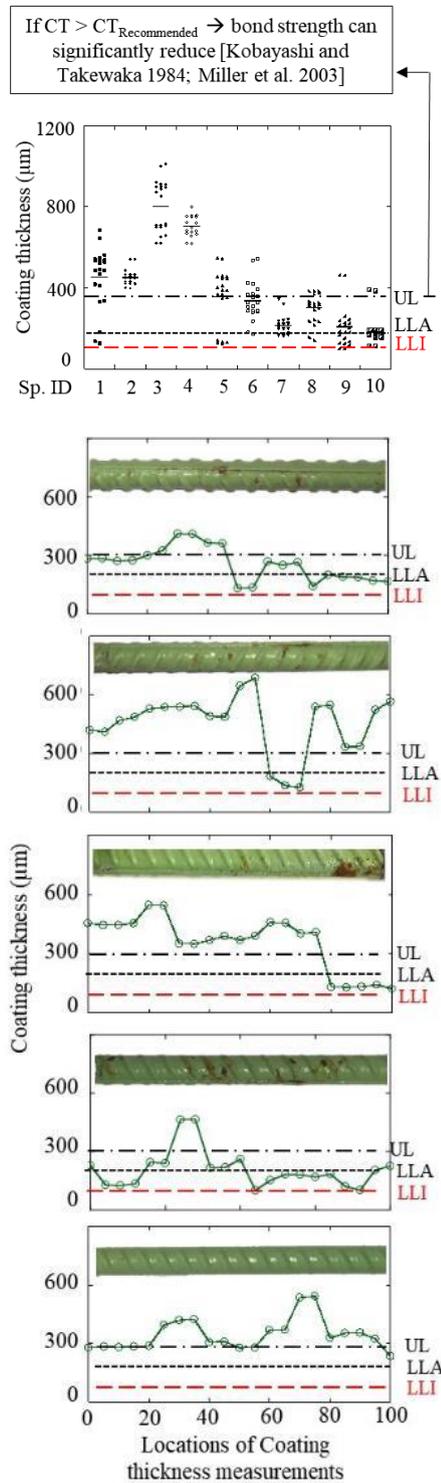


Figure 8 Variation of coating thickness in commercially available FBE coated steel rebars and associated corrosion [45]

Figure 8 (b) shows the 2-stage degradation of UV exposed FBE coating and then embedded in mortar. Stage 1 is when R_c offered by FBEC-UV coating was significantly high. Within four cycles of exposure to moisture (with chlorides), R_c decreased significantly. Unlike FBEC-ND, no increase in R_c was observed on FBEC-UV specimens. The corrosion products can diffuse or permeate out through the cracks in coating. With further exposure, R_c continued

to decrease in Stage 2, which can be attributed to the presence of moisture and chlorides in the damaged epoxy coating.

3.4 Chloride threshold of FBE coated systems

The chloride threshold was determined using the lollipop specimens and the test method developed in [26],[32]. The difference in the determination of chloride threshold of uncoated and coated rebars is discussed next. The average chloride concentrations on the coating surface (at the coating-mortar interface) of FBEC-ND, SD, and UV specimens were found to be 0.75, 0.20, and 0.53 % by weight of the binder (%bwob) [26,30–32].

However, these chlorides in mortar of FBEC-ND and FBEC-UV specimens do not participate in the corrosion process. Therefore, chlorides below the FBE coating (at the steel-coating interface) were estimated by obtaining the chloride profiles through coating using the EDAX technique. Data from five coating specimens each showed that the average diffusion coefficient of FBEC-UV was about two orders of magnitude higher than that of FBEC-ND coating. Also, the average chloride concentration at the steel surface beneath the coating [defined as chloride threshold (Cl_{th})] for FBEC-ND and FBEC-UV steel rebars were found to be 0.12 and 0.08 % bwob, respectively; whereas, the Cl_{th} for uncoated and FBEC-SD steel rebars were found to be 0.40 and 0.20 %bwob, respectively [see Figure 10 (a)]. The low Cl_{th} of FBE coated steel rebars can be attributed to the low $pH \approx 6 \pm 1$ beneath the coating. In case of FBEC-SD, chloride profiles were not obtained because the steel at damage locations are in direct contact with mortar/cementitious systems. Therefore, chlorides do not need to travel through the coating to reach the steel surface and initiate corrosion. Figure 9(c) demonstrates the proposed corrosion initiation mechanism in FBEC-UV steel rebars. The steel below one of the deep cracks can act as an anode, and the remaining steel surface below other deep cracks with enough oxygen and moisture can act as cathode. These cracks can provide the low resistive path for ionic transfer, and lead to initiation of corrosion. Further, they can allow the entry of moisture, oxygen, and chlorides to the steel surface, and accelerate the corrosion.

3.4.1 Proposed framework and estimation of service life

The corrosion characteristics of coated steel rebars are affected by the quality of handling and storage of FBE coated steel rebars at the construction sites. It was found that the chloride concentration on the coating surface can mislead the estimation of time to initiation of corrosion (t_i). Therefore, Figure 10(b) shows the proposed two-stage chloride diffusion model, where transport of chlorides to steel surfaces takes through concrete and then coating. An existing service life estimation model (SL-Chlor) was modified, and a function for the chloride diffusion coefficient and thickness of coating was introduced in the program. Then, the t_i for a structural element was estimated as a case study. Figure 10(c) shows the schematic of a bridge element considered for this. Using the service life model proposed in Figure 10(b), it was found that the service life of RC systems with SD [coating thickness (CT) = 0 at damaged location] and UV (CT = 300 µm) was significantly less than SL of RC systems with uncoated and FBEC-ND (CT = 300 µm). Note that once corrosion was initiated, it was visually observed that the FBE coated steel rebars undergo a rapid under film corrosion process. Therefore, the propagation time for FBE coated steel rebars can be considered negligible.

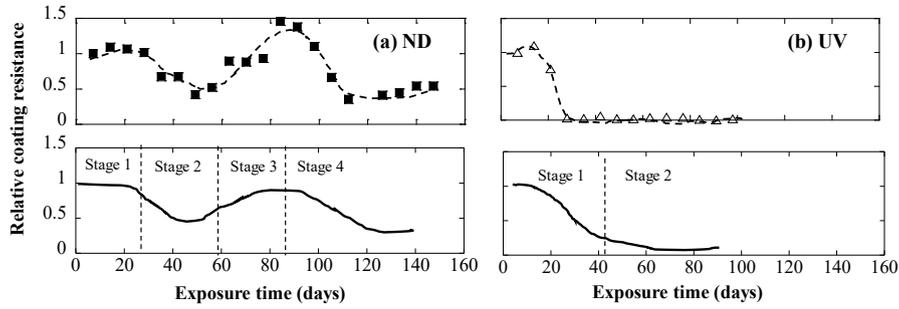


Figure 9 Variation in the relative resistance of FBE coating during the exposure time [26]

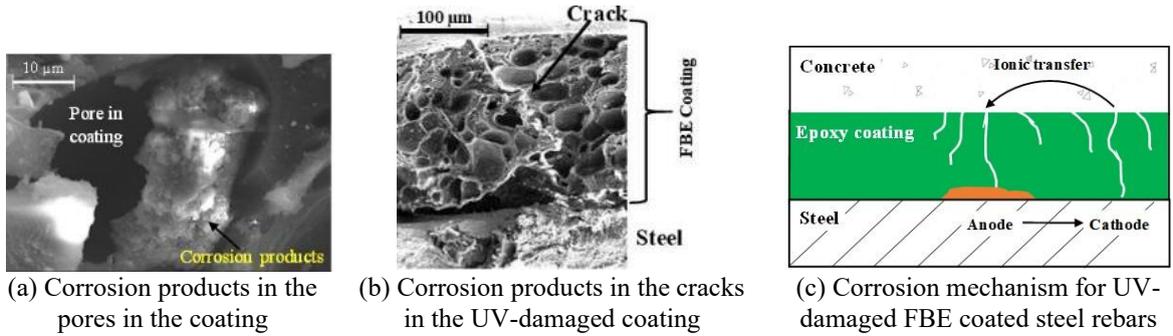
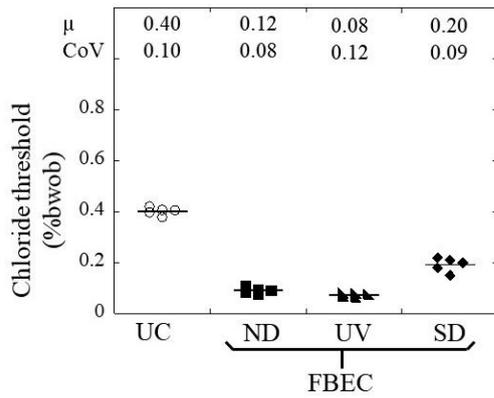
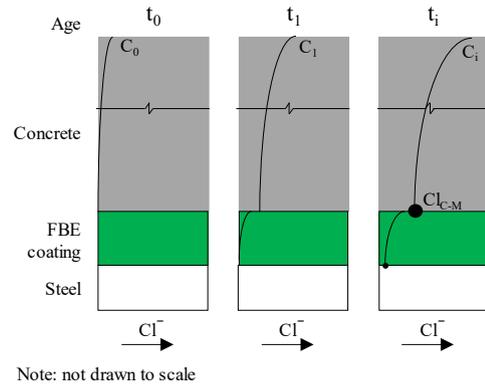


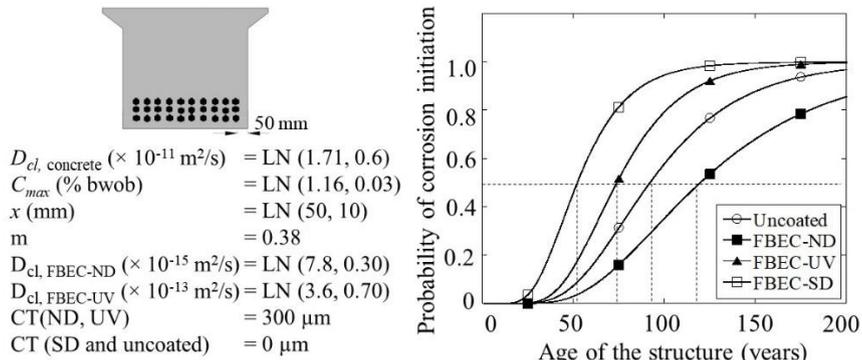
Figure 10 Coating degradation stages and the mechanism of initiation of corrosion [32]



(a) Chloride thresholds of FBE coated steel rebars



(b) Framework for estimating service life



(c) CDF for time to corrosion initiation

Figure 11 Chloride threshold, service life model (with chloride ingress through coating), and a case study on probabilistic service life of concrete with FBE coated steels [26]

4 Conclusions

ASTM G109 type MCC tests, ASTM C876, and test methods based on LPR failed to detect the initiation of corrosion in FBE coated steel. A test methodology is proposed to detect the initiation of corrosion in FBE coated steel rebars in cementitious systems using EIS technique. Corrosion mechanisms for FBE coated steel rebars are proposed. About one month of exposure to UV radiations can result in shrinkage-induced cracking of the FBE coatings due to the formation of carbonyl groups and irregular distribution of photo stabilizers. 4-stage and 2-stage coating degradation mechanism was proposed for FBE coating before and after exposure to UV radiation, respectively. Exposure to UV radiation can significantly reduce corrosion resistance. Also, result in premature initiation of corrosion. Damage to coating can result in premature and localized corrosion. A service life model based on chloride transport through the coating is proposed for FBE coated steel rebars. SL-chlor, a MATLAB® program, was modified to include the diffusion of chloride through the coating. Then, this program was used for the estimation of service life of RC systems with FBE coated steel rebars. The probabilistic service life of structural elements with damaged/degraded coating due to UV exposure exhibited initiation of corrosion even before the initiation of corrosion in uncoated steel rebars.

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