EFFECT OF DAMAGED AREA ON SERVICE LIFE OF EPOXY-COATED REINFORCEMENT

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ABSTRACT:

This report presents a literature review of the effect of coating damage on the corrosion resistance and service life of epoxy-coated reinforcement (ECR). Epoxy coatings obtain damage during fabrication, handling, and placement of reinforcement, as well as during casting of concrete. The body of literature was searched for the impact of the extent of this damage on the chloride threshold of ECR, as well as the corrosion rate after initiation of corrosion and the time from corrosion initiation to repair of the structure. An example service life calculation for reinforced concrete bridge decks subject to deicing chemicals is presented.

Numerous studies show that an increase in damaged area adversely impacts the corrosion resistance of ECR, both in terms of corrosion initiation and corrosion rate after initiation. Conversely, proper handling and inspection to patch regions of damage can greatly increase the service life of ECR. The theoretical service life calculation indicates a 100-year design life is possible even in the presence of minor damage.

KEYWORDS: Corrosion, epoxy-coated reinforcement, service life

Introduction:

Epoxy-coated reinforcement is a widely used corrosion-protection system in reinforced concrete infrastructure. Inspections of structures with epoxy coatings dating back to the 1970s have shown overall good performance of the coated reinforcement (Lawler and Kraus 2011). Corrosion on epoxy-coated reinforcement typically occurs at defects in the coating (Weyers et al. 2008); these defects form either during the production process or after handling in the field. Research by Samples (1998) conducted on ASTM A775 epoxy-coated reinforcement found that the majority of damage to ECR occurred during placement of concrete, particularly when concrete was placed via pump. This damage exposes the underlying steel and allows localized corrosion to occur (Manning 1996, Ramniceanu 2008). Even in the presence of damage, ECR is capable of very good corrosion performance, but reducing the amount of damage has great potential to extend the service life of ECR.

The service life of a reinforced concrete structure can be broken into two phases-the time to corrosion initiation and the time from initiation to required repair (Tutti 1982). The length of these phases depends both on concrete properties (such as cover, permeability, and the presence of cracks) and reinforcement properties. The benefits of reducing damage on each of these phases of corrosion are outlined below.

Corrosion Initiation

Chloride-induced corrosion initiates when the concentration of chlorides in the concrete surrounding the reinforcement reaches a certain value, termed the critical chloride threshold. Although the underlying steel composition is identical between uncoated reinforcement and epoxy-coated reinforcement of the same type, ECR still increases the critical chloride threshold of reinforcement. Chlorides do not progress into concrete evenly; rather, its ingress is impeded by aggregates and accelerated by low-permeability regions, cracks, and voids. For concrete containing uncoated reinforcement, corrosion will occur when the critical chloride threshold is reached at any location along the bar. Epoxy coatings form a barrier that greatly impedes the progress of chlorides; therefore, corrosion will only initiate on ECR when chlorides reach the critical chloride threshold at one of the damage sites as opposed to anywhere on the surface of an uncoated bar. Due to the uneven nature of chloride ingress into concrete, the critical chloride threshold of damaged ECR is several times that of uncoated conventional reinforcement (Darwin et al. 2014, Lawler et al. 2021)

The nature of corrosion initiation in ECR suggests that reducing the damaged area will increase the chloride threshold, though limited research is available in this area. Darwin et al. (2011) evaluated the chloride threshold and corrosion rate for eight different epoxy coatings with damaged areas of 0.5% and 0.2% and found that reducing the damaged area resulted in an average increase in critical chloride threshold of 45%. A large degree of scatter was seen in the data, with some coatings exhibiting a decrease in critical chloride threshold as damaged area decreased.

The impact of chloride threshold on service life depends largely on the properties of the concrete, not the reinforcement. A study by Lindquist et al. (2006) examined chloride contents in bridge decks exposed to deicing chemicals both at crack locations and away from crack locations at depths to 3 in. (76.2 mm). Lindquist et al. found that the rate of chloride ingress in uncracked concrete (Figure 1) was significantly lower than that in cracked concrete (Figure 2). Using a critical chloride threshold of 1.52 kg/m^3 for ECR (Darwin et al. 2020) and the formulas in Figures 1 and 2, ECR with 0.5% damage and 3 in. of concrete cover will reach its chloride threshold in 53 years in uncracked concrete, but only 5.5 years in cracked concrete. If the damage is reduced to 0.2% and the 45% increase in chloride threshold observed by Darwin et al. (2011) is achieved, the time to initiation in uncracked concrete increases from 53 years to 76 years, whereas the time to initiation in cracked concrete increases from 5.3 years to 10.7 years. Harsher chloride exposure conditions or lower covers will lower these numbers (Jaegermann 1990, ACI 222.3R).

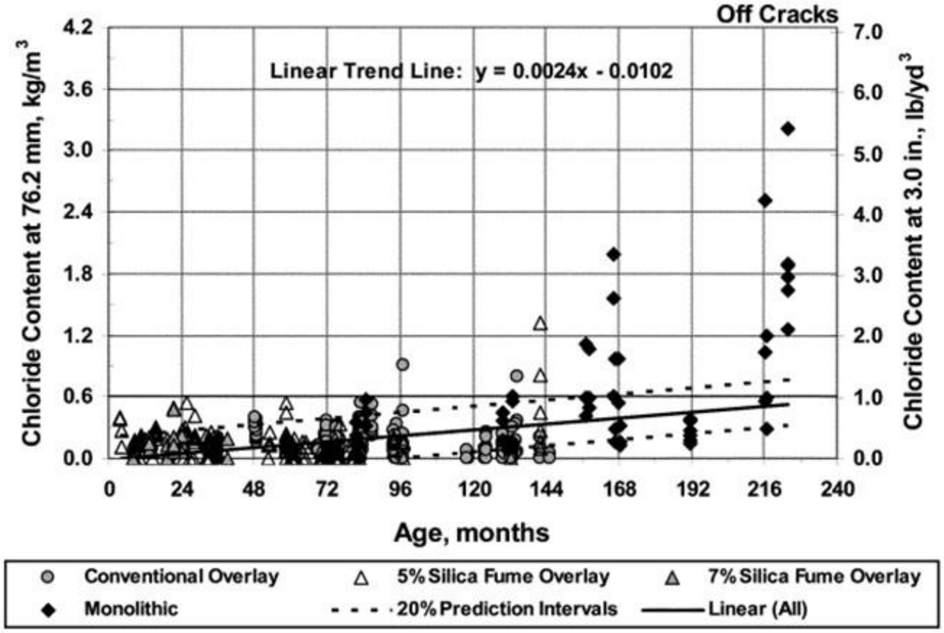

Figure 1: Chloride content vs. age in uncracked concrete on bridge decks (Lindquist et al. 2006)

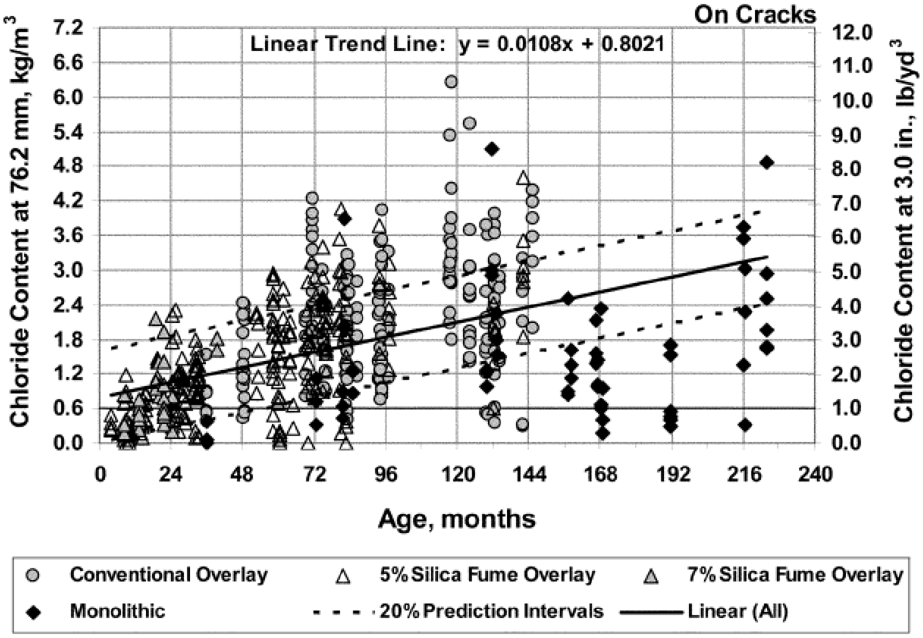

Figure 2: Chloride content vs. age in cracked concrete on bridge decks (Lindquist et al. 2006)

Corrosion Rate After Initiation

Unlike uncoated conventional reinforcement, where corrosion occurs over a large portion of the surface of the bar, corrosion on ECR takes the form of localized corrosion at areas where the coating is damaged; corrosion can also spread underneath the coating from damage sites (underfilm corrosion), which can lead to blistering and loss of coating adhesion to the steel, causing disbondment (Manning 1996, Weyers et al. 1998, Ramniceanu 2008, Draper et al. 2009).

Given the importance of damage sites on corrosion propagation, reducing the damaged area on ECR has great potential to reduce corrosion rate after initiation. In addition to reducing the total number of potential corrosion sites, reducing the damaged area of ECR will also limit oxygen and moisture access to the underlying steel, limiting the cathodic reaction. Al-Amoudi et al. (2004) examined the corrosion rate of ECR bars in chloride-contaminated in both the undamaged state and with three damage levels-0.5%, 1.0%, and 1.5%; bars with intentional holidays were also evaluated. Even after over seven years of exposure in heavily chloride-contaminated concrete (2% by weight of concrete), undamaged ECR showed negligible corrosion activity. Increasing the damaged area from 0.5% to 1.5% increased corrosion activity, but not proportionally–tripling the damaged area resulted in doubling the corrosion rate. The presence of holidays-defects not visible to the unaided eye-in otherwise undamaged ECR resulted in a slight increase in corrosion activity relative to undamaged ECR, but measured corrosion rates were still an order of magnitude lower than ECR with any amount of visible damage.

Lee (2018) evaluated ECR along with numerous other corrosion resistant bars in concrete blocks exposed to chlorides over a 10-year period. Bars were tested with damage levels of 0%, 0.15%, 0.5%, and 1%, with damage consisting of both holidays and intentional defects. Lee found that ECR exhibited the lowest corrosion rates of any bar in the study, regardless of damage level, and that bars with lower damage levels exhibited less disbondment of the coating at the end of testing.

Darwin et al. (2011) evaluated corrosion rate for eight different epoxy coatings with damaged areas of 0.5% and 0.2% and found that increasing the damaged area resulted in an average increase in corrosion rate of 172%; similar to Al-Almoudi et al., the increase in rate was less than the 250% increase in damaged area. Sturgeon et al. (2010) evaluated ECR in the rapid macrocell test (Annex of ASTM A955) in the damaged (0.83% damaged area) and undamaged conditions, as well as after putting four holidays in an otherwise undamaged bar (0.04% damage). Much as Al-Amoudi et al. found, the presence of holidays did not result in significant increases in corrosion rate relative to undamaged bar. This suggests that damage during handling and placement, not holidays introduced during production, are key to controlling corrosion performance of ECR, but also that reductions in corrosion rate will be less than the reduction in damaged area. The reason for the latter behavior is likely that all damaged areas on ECR are unlikely to corrode simultaneously, so removing a damage site will not necessarily result in a proportional decrease in rate. Regardless, the benefit of reducing damage on corrosion rate is clear.

Corrosion Loss to Cause Cracking

In most cases, corrosion-induced damage to reinforced concrete is not a result of section loss of the reinforcing steel, but of cracking and spalling of the concrete cover due to the expansive nature of steel corrosion products. Most studies examining the corrosion loss required to crack concrete examined general corrosion, such as occurs on uncoated conventional reinforcement, but some research of localized corrosion and cracking does exist.

Torres-Acosta and Sagues (2004) studied the effects of localized steel corrosion on the corrosion loss required to crack concrete and derived an expression relating bar cover, bar diameter, and localized corrosion length with the corrosion loss required for crack initiation.

$$x_{crit} = 11.0\frac{c}{\phi}\left(\frac{c}{l}+1\right)^2$$

Where:

x_{crit} = corrosion loss at crack initiation, μm

c = cover, mm

Φ = bar diameter, mm

l = length of exposed steel, mm

It should be noted that the smallest exposed length tested was 8 mm (0.3 in.), much larger than the size of a typical defect or holiday on epoxy-coated reinforcement. Torres-Acosta and Sagues also used a ring-shaped damage pattern around the entire circumference of the bar, significantly different from damage patterns that occur naturally.

Darwin et al. (2011) examined corrosion loss to cause cracking in epoxy-coated reinforcement with circular damage, more similar to that occurring naturally. Darwin et al. found the corrosion loss in μm required to cause cracks in concrete is:

$$x_{crit} = 45\left(\frac{\left[{C}/{25.4}\right]^{2-A_f}}{D^{0.38}{L_f}^{0.1}{A_f}^{0.6}} + 0.2\right)\times 3^{A_f-1}$$

where

x_{crit} = corrosion loss at crack initiation, μm

C = cover, mm

D = bar diameter, mm

L_f = fractional length of bar corroding, $L_{\text{corroding}}/L_{\text{bar}}$

A_f = fractional area of bar corroding, $A_{\text{corroding}}/A_{\text{bar}}$

Figure 3 compares the corrosion loss to crack concrete versus damaged area of bar predicted by the Torres-Acosta and Sagues work as well as the work by Darwin et al., assuming a bridge deck with 3 in. (76 mm) cover and No. 5 (16 mm) reinforcing steel. As seen in the figure, although the two models do not predict similar losses at low damaged areas both clearly show that the required corrosion loss to crack concrete increases significantly as damaged area decreases. The exponential increase in both curves as damaged area decreases suggests that halving the damaged area will more than double the corrosion loss required to crack concrete.

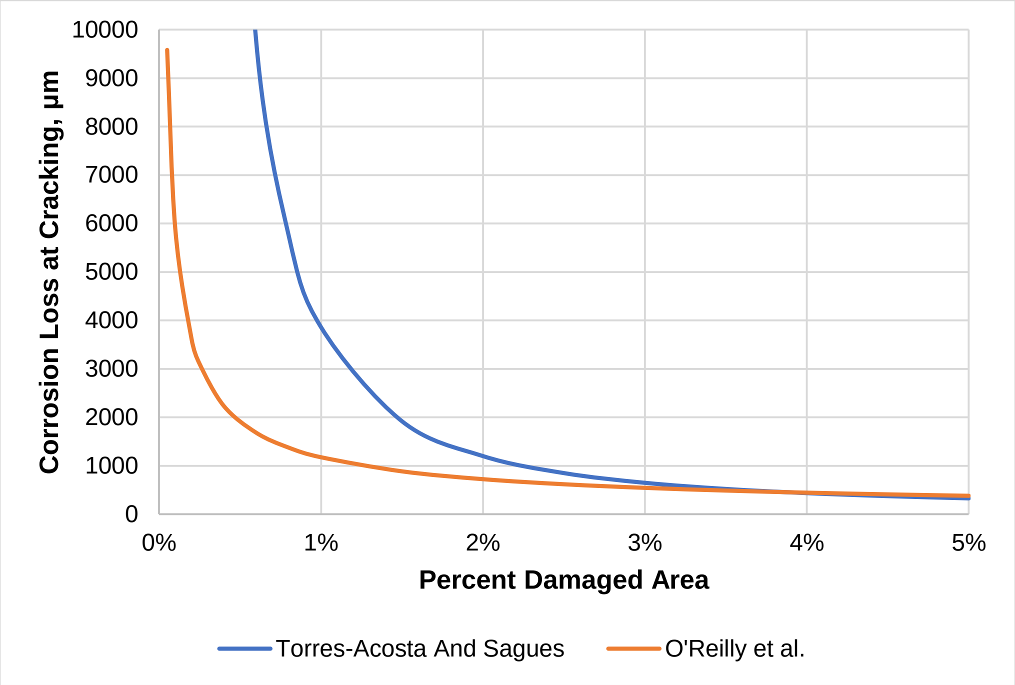

Figure 3: Predicted corrosion loss to cause cracking vs. percent damaged area

Predicted Service Life:

Darwin et al. (2011, 2013, 2020) developed a method for estimating the service life of various corrosion protection systems, including ECR, in reinforced concrete bridge decks. The method estimated the time to corrosion initiation using the research by Lindquist et al. (2006) described previously, converted measured laboratory corrosion rates to equivalent field corrosion rates based on work by O'Reilly et al. (2011), and determined the corrosion loss to crack concrete using the equation from Darwin et al. (2011) provided above. Repair was assumed to occur 10 years after the onset of the first corrosion-induced crack. For bridge decks with a 3-in. cover and No. 5 reinforcing bars, Darwin et al. (2011, 2013, 2020) estimated the service life of bridge decks with ECR with 0.25% damaged area to be between 53 and 67 years.

The research outlined in this report can be used in conjunction with the service life estimation model to predict the effect of damaged area on the service life of ECR. To do so, the following assumptions are made:

- Doubling the damaged area will decrease the critical chloride threshold by approximately 25% (interpolating from Darwin et al. (2011), where a 2.5x increase in damaged area decreased the critical chloride threshold by 30%).
- Doubling the damaged area will increase the corrosion rate after initiation by 33% (interpolating from Al-Amoudi et al. (2004), where tripling the damaged area doubled the corrosion rate)
- Doubling the damaged area will decrease the corrosion loss required to crack concrete by ~38% (found from plugging values into the equation from O'Reilly et al. (2011))

The results of these assumptions are plotted as the predicted service live versus damaged area in Figure 4, for concrete with 2 in. and 3 in. cover. The figure should be taken as an approximation at best; a field study over a range of damaged areas would be needed to establish a more reliable correlation. The trend, however, is clear; reducing damaged area on ECR is critical to increasing service life, and eliminating damage entirely is not necessary to achieve a 100-year design life.

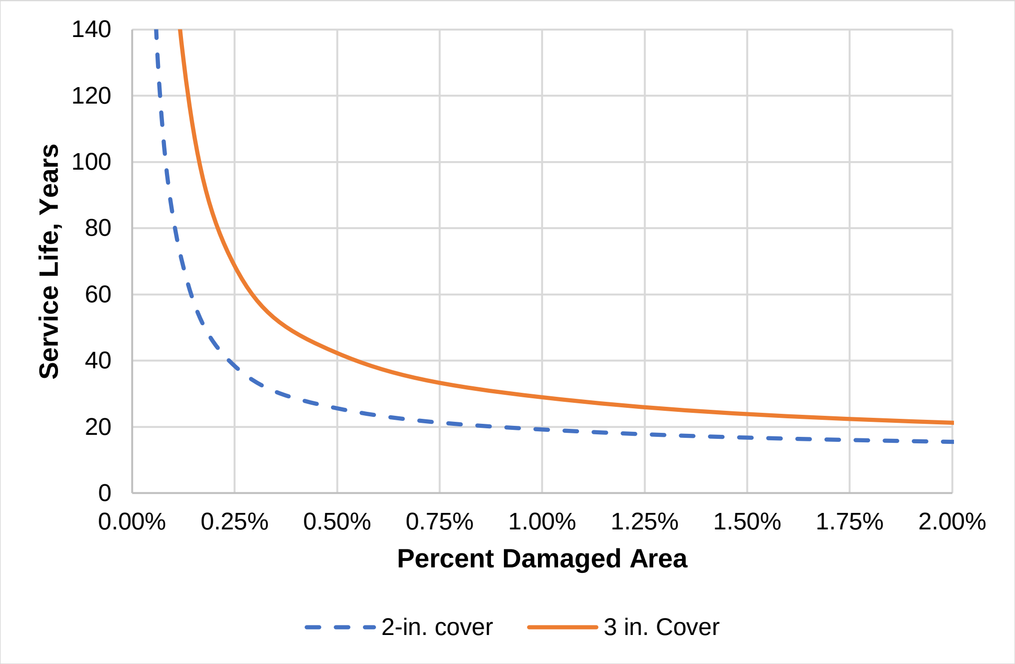

Figure 4: Predicted service life vs. percent damaged area

Discussion and Conclusions:

Decreasing the amount of damage ECR undergoes requires proper procedures to be followed during handling, installation, and inspection. ECR should not be dragged (or have equipment dragged over it, supports and form ties should be non-conductive or coated, and any visible damage should be patched before placement (CRSI 2008). The development of damage-tolerant coatings will also greatly assist in reducing damage to ECR in the field. Taken together, these factors are critical to reducing damage to ECR and extending service life in practice–as seen in the service life prediction above, a 100-year design life is possible even in the presence of minor damage.

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