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# CORROSION FORECASTING FOR 75-YEAR DURABILITY DESIGN OF REINFORCED CONCRETE

## PROBLEM STATEMENT

About two thirds of the 5,500 bridges in the Florida Department of Transportation (FDOT) inventory are exposed to salt water. The resulting corrosion of reinforcement has in the past created serious limitations to the durability of the substructure of those bridges, resulting in a continuing need for costly repairs or early replacement of the structures. Consequently, the nationwide mandate for 75-year durability construction represents an especially difficult challenge when designing new bridges for aggressive service marine applications.

Previous work has quantified chloride ion penetration into the concrete of the substructures of FDOT bridges by an effective diffusion coefficient “D” particular to structure location and type of concrete used. The value of D is obtained from the analysis of drilled cores. This value, combined with other chemical and structural information, can be used with computational models created for FDOT to produce a quantitative estimate of the length of the corrosion initiation stage, which is the length of time before active corrosion begins. Present design emphasizes extending the length of the initiation stage. Initial surveys have shown that concrete formulations, such as those intended for highest performance in Section 346 of the FDOT Standard Specifications for Road and Bridge Construction, yield extremely low values of D and consequent projections of long-lasting durability. Those concrete formulations include a high cement factor; a significant amount of pozzolanic cement replacement, usually by type F fly ash (FA) and occasionally by micro silica (MS); and a low water-to-cementitious content ratio (w/c). This initial information was limited to a few structures. The extent to which narrow preexisting stress cracks may facilitate chloride penetration in otherwise sound high quality concrete was not known.

## OBJECTIVES

The primary objectives of this project included the following:

1. Improve forecasting abilities by updating information on the rate of chloride ion penetration, paying special attention to the effects of cracks, into the substructure of FDOT marine bridges constructed with the most promising concrete formulations.

2. Improve methods of predicting the length of the corrosion initiation and the corrosion propagation stages, which would then be integrated into a comprehensive forecasting model.

3. Evaluate the feasibility of electrochemical corrosion protection methods for extending the durability of new and existing structures.

Thirteen FDOT bridges were examined. Samples were analyzed to assess the presence and extent of chloride penetration, as well as the consequences of stress cracks. Laboratory experiments and computer calculations were conducted to supplement the information from the field and address the other issues.

# FINDINGS AND CONCLUSIONS

Analysis of the bridge samples confirmed that sound concrete, made per Section 346 of the FDOT Standard Specifications for Road and Bridge Construction, with high cement factor, low w/c, and pozzolanic cement replacement exhibits very slow chloride penetration in aggressive marine bridge substructure service. The best performing concrete, comparable to a Class V formulation and with w/c~0.32, showed an average value of D of about 0.01 $in^2/y$ (2 $10^{-9}$ $cm^2/sec$), at age 11 years and in the Tidal to 6 ft (1.8 m) above high tide (AHT) region. Results from the Sunshine Skyway Bridge suggest that D decreases with the age of the structure, which agrees with reports from other investigations of aging concrete with pozzolanic additions. The surface chloride concentration ($C_s$) appeared to reach relatively steady values early in the life of the substructures examined. A value of $C_s$ of about 30 pcy (18 $kg/in^3$) may be considered typical in the Tidal to 6 ft (1.8 m) AHT region. The surface concentration was not found to be a strong function of the salt content of the surrounding seawater.

Thin (typical width ~0.15 mm) cracks were found in many of the substructures examined. Many of these cracks in footers or piles reached down to the waterline and extended to at least the rebar depth. Crack incidence on the order of one crack every several meters of waterline perimeter was not uncommon. Even though the cracks were thin, there was substantial preferential chloride penetration immediately around the crack, as compared to the surrounding sound concrete, reaching levels that exceed commonly assumed values of the chloride initiation threshold. The effect was most marked in the splash evaporation zone. In spite of this enhanced chloride penetration, conspicuous indications of corrosion were not observed in any of the crack locations examined (the use of epoxy-coated rebar in some of the bridges may have masked or mitigated corrosion development there). Numerical models of chloride transport in the cracks reproduced the observed chloride penetration behavior. The analysis predicts that under moist substructure conditions, significant chloride penetration can occur even in extremely thin cracks, and that chloride buildup could be more severe when a crack terminates at a short distance from the surface than when it extends deep into the concrete.

Calculations of the penetration of chloride in sound concrete revealed that the rebar acts as an obstruction to the diffusional chloride flow, causing a local increase in concentration. That increase shortens the projected time for corrosion initiation ($t_i$) when compared to that which is evaluated assuming unrestricted diffusion. The effect can be strong (e.g., reductions in $t_i$ by as much as 40%), depending on the concrete cover, rebar diameter, and chloride threshold value. Derating factors to account for this effect were computed and proposed for use in durability estimates. Researchers created an integrated corrosion initiation model for sound concrete that takes into account the concrete mixture proportions, rebar cover and size, and system geometry (flat wall, 2- and 3-way corners, or cylindrical columns). Researchers created software which can perform a rapid calculation of $t_i$ , and which incorporates the initiation model and input values based on the field findings.

Experiments revealed that the amount of critical corrosion penetration needed to cause cover cracking was greater when corrosion was localized (as it may happen in an area of preferential chloride penetration) than when corrosion was more uniform (as in sound concrete). A quantitative relationship between critical corrosion penetration, rebar cover and diameter, and length of the corroding region was established. A theoretical analysis of localized corrosion at preexisting concrete cracks indicated that local corrosion rates could be about one order of magnitude greater than those occurring under more uniform conditions. The results agreed with independent experimental observations. Overall, these findings indicated that corrosion at localized active spots could still result in significant damage in a relatively short time after corrosion initiation.

An overall corrosion process forecast approach was formulated, based on the aforementioned findings. The durability projections obtained when applying this procedure to substructures built under present FDOT guidelines and with the highest concrete grades indicate a generally good prognosis for achieving the 75-year goal, as long as concrete away from stress cracks is considered. For locations where preexisting cracks are present, the forecast, although inherently conservative, indicates that a small but noticeable fraction of substructures built using the present design method could encounter localized corrosion damage in the near future. Specialized corrosion control procedures need to be developed in anticipation of this problem.

Researchers formulated a next-generation computational approach for forecasting durability of marine substructures that integrates the corrosion initiation and propagation stages with the evaluation of damage distribution over the entire elevation range of the substructure element. They also developed a detailed (rebar scale) predictive model to compute corrosion distribution. The model successfully reproduced in a laboratory system the throwing power of a galvanic system for cathodic prevention. The application of variations of the model to typical marine substructure conditions indicates that polarization levels on the order of 100 mV may be attained on passive steel in the area immediately above high tide with an immersed galvanic anode.

## BENEFITS

This research developed a design model that can be used to predict the service life of bridge substructures. FDOT designers will use this model to predict the service life of bridge structures based on materials selection, concrete cover, rebar location, and geometry.  This tool will enable the Department to save future maintenance costs by improving the service life of bridge substructures.

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