Time-Dependent Corrosion Model for Suspension Bridge Main Cables

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Abstract Suspension bridge safety is a function of the strength of bridge cables in their deteriorated state. The prevailing methods for assessing suspension bridge safety — most notably, visual inspection of bridge cables at a few selected locations — provide limited information regarding the status of bridge wires and require the removal of the cable's external covering. In this paper, we present a time-dependent corrosion rate model for bridge wires that employs the monitored environmental inputs (e.g. temperature, relative humidity, etc.) from the cable interior. Machine learning methods are used to develop a long-term corrosion rate model from a corrosion database. This database is compiled using data from previous studies in the literature, as well as the results of cyclic corrosion tests on bridge wires that were subjected to varying levels of environmental variables as a part of this study. Finally, we use our model in a numerical example and demonstrate the evolution of cable strength of a new bridge cable composed of galvanized wires under typical environmental conditions. The method presented in this study can be used to evaluate the remaining strength of suspension bridge main cables in their deteriorated state in lieu of invasive and expensive inspections.

1 Introduction

In recent years, suspension bridge inspections revealed extensive corrosion of steel bridge wires in the main cables. Safety of suspension bridges depend heavily on the remaining strength of main cables. In the United States, current maintenance programs offer partial information on the status of bridge wires that make up the main cables. These inspections start with a visual inspection of the cable covering: if there are signs that point to corrosion of the cable, further inspections are then carried out at a few locations. These inspections require, at a minimum, local removal of the cable's protective covering. Bridge wires are then visually inspected, and a few samples may be taken for later testing. This inspection methodology falls short of providing sufficient data for determining the cable strength and how it changes over time: these inspections show the condition of the main cable only at the few inspected stations, and only at the time of the inspection. Main cable strength is calculated based on the limited data obtained from inspections. This data includes tensile test results of samples removed during the inspection and wires graded into various stages of corrosion visually [1]. This method is inherently uncertain it does not utilize data from the entirety of the cable. Furthermore, the evolution of cable strength due to deterioration of wires is not considered in the current methodology. Previous research, investigated: (a) utilizing NDT for direct measurement of corrosion damage to bridge wires and (b) making use of a sensor network to continuously check the internal cable conditions to determine wire deterioration over time [2,3].

This paper outlines a time-dependent corrosion model for suspension bridge main cables that relies on monitored environmental variables from the interior of the cable. This model can then be used to estimate the decline in the remaining cable strength. In developing this model, experimental data from past studies was analyzed to produce a set of environmental variables that can be monitored to produce the best prediction accuracy in determining the corrosion rate of bridge wires. To expand the literature, cyclic corrosion tests were carried out at various levels of the selected environmental variables. Finally, a model that predicts the annual corrosion rate of bridge wires as a function of the selected environmental variables is developed using an augmented dataset that includes both the data from past studies as well as test performed in this research effort. A numerical example is presented to illustrate the proposed approach, focusing on the evolution of cable strength of a hypothetical new bridge subjected to typical environmental conditions in a simulation.

1.1 Corrosion of High-Strength Bridge Wires

Bridge wires are classified as high-carbon steel and generally galvanized with zinc to offer protection from corrosion. The galvanization layer will corrode first, after with the steel wire starts to corrode, starting from the wire surface. Bridge wires are exposed to varying environmental conditions such as fluctuations of humidity and temperature. The most important environmental variables that affect the metal's corrosion rate are temperature, pH, contaminant concentration, humidity and wetness [4,5]. Moist air and rainwater enter the cable interior due to deficiencies in the cable covering, poor compaction of wires, cracks in the caulking [6]. The inspection reports on suspension bridges in the New York City area point out the occurrence of water in the cable interior, with pH values as low as 4 [7,8] reported presence of water inside the main cables of suspension bridges in Japan, after only a few years in service. The studies referred to above demonstrate that the natural conditions a bridge wire is exposed to depend not just on the geographic area of the bridge itself but also on the position of a wire, both within the cross-section and also along the length of the cable. This variation in the environmental conditions could be the main reason as to why wires removed from the same cable can exhibit very different levels of corrosion.

Previous research on the corrosion of bridge wires reinforce the dependence of corrosion rate on environmental variables. Betti et al. performed cyclic corrosion tests on bridge wires subjected to corrosive environments [9]. Their results show that reduced pH level and increased chloride ion concentration both led to higher corrosion rates. Suzumura et al. published extensively on wire corrosion, revealing that: (a) corrosion occurs at very slow rates when relative humidity is below 60%; (b) corrosion rate is almost constant as long as environmental conditions are unchanged; (c) corrosion rate has an exponential dependence on temperature [10]. Because of the complexity of the underlying corrosion processes, analytical models developed to model corrosion rate are restricted to specific geographical region and limited in capturing the nonlinear nature of corrosion. The time-dependent corrosion rate of metals is generally expressed by the exponential expression

$$C(t) = At^{n} \tag{1}$$

where *C(t)* – cumulative corrosion loss (in terms of corrosion depth or loss of metal area from the cross-sectional area) after *t* years, *A* – annual corrosion rate of a metal, *n* – exponent which depends on the type of metal and surrounding environment, in the range [0-1]. Environmental conditions play a direct and fundamental part in the corrosion of bridge wires and thus have to be related to the corrosion rate expression in Eq. (1). This research utilizes a machine learning based methodology to establish the annual corrosion rate A in Eq. (1) as a function of environmental variables such as temperature (T), pH, RH, etc. so that the corrosion loss expression in Eq. (1) becomes

$$C(t, T, pH, RH, etc.) = A(T, pH, RH, etc)t^{n} \tag{2}$$

2 Methodology: Development of Corrosion Rate Model

In developing a method to estimate the remaining cable strength, it is vital to have a model that predicts the corrosion rate of individual wires within the cable. This rate depends upon the interaction of bridge wires with their environment that is typified by environmental variables such as T, pH, RH, etc.

Past research on bridge wires in the last 20 years by Betti et al. [7-9] and Nakamura et al. [10] provide a good understanding of the effects of environmental parameters on the corrosion of bridge wires. However, the data available from these studies is not adequate to develop a data-based predictive expression for the corrosion problem at hand. For this reason, an extensive database that consists of environmental variables as input and the associated annual corrosion rate as output was compiled to: (a) pick the environmental variables to be monitored in order to attain the greatest corrosion rate prediction accuracy; (b) develop the annual corrosion rate estimation model based on these environmental variables.

2.1 Most Relevant Environmental Variables and Model Development

Machine learning methods are algorithms that are frequently utilized to develop predictive models from measurements [11]. Supervised learning is a type of machine learning where datasets that include both input data and the known corresponding output values are used to build models that can predict the output value when presented with new input data. Since the goal of this study is to develop a predictive model from a database that consists of environmental variables (T, pH, RH, etc.) as the input and the corresponding measured annual corrosion rate A in Eq. (2) as the output, supervised learning methods are used in this study.

The machine learning based method to find the subset of environmental variables that leads to the greatest prediction accuracy can be summarized as: (a) generating combinations of environmental variables (e.g. (T, pH, RH)); (b) training predictive models for each combination using a learning algorithm; (c) testing the models on test data to find the best performing subset. Next, the chosen environmental variable subset is used to develop the model for estimating the annual corrosion rate of carbon steel.

Worldwide atmospheric corrosion tests performed on carbon steel is available in literature, providing an extensive database of corrosion rates for a wide range of environmental inputs. In these tests, carbon steel specimens were exposed to varying atmospheric conditions for a year. The database has a total of 309 records for the measured annual corrosion rate versus six recorded environmental variables: temperature (T), relative humidity (RH, %), time of wetness (period of time during which a surface layer of moisture is present on a metal, %), annual precipitation (mm), pH of rainwater, and chloride ion concentration (Cl^-, mg/L).

The environmental variables subset [T, RH, pH, Cl-] was determined as the relevant feature set for the corrosion rate modelling problem. The algorithm for selecting the most relevant environmental variables and development of the predictive model using machine learning methods from a corrosion database will be presented in detail in a future publication. Support vector regression (SVR) using a radial basis function (RBF) kernel produced the greatest prediction accuracy. The predictive model for determining the cumulative corrosion for a wire becomes:

$$C(t, T, pH, RH, Cl^-) = A(T, pH, RH, Cl^-)t^n \qquad 3$$

This dataset is complemented with bridge wire-specific data obtained from cyclic corrosion testing at different levels of the selected environmental variables. The final predictive model is then developed using this augmented dataset. Cyclic corrosion tests conducted in this study employ an array of solutions, ranging from mildly to highly corrosive, as fog sprays in a corrosion chamber to create environments at different levels of the selected environmental variables. Fog solutions are adjusted with acetic acid (CH_3COOH) to attain pH values of 3.0, 4.0, and 6.0. Cl^- ion content is regulated by NaCl to achieve 100 and 500 ppm Cl^- solutions and tests are run at 30, 35 and 45˚C. RH conditions are the same for all tests, at an average value of 80% over the duration of each test.

2.2 Long-Term Corrosion of Wires

In order to determine the exponent n in Eq. (1), the original and the deteriorated condition of a bridge cable after t years in service need to be established. To this end, the 1988 cable investigation program for the Williamsburg Bridge in New York, USA proves an excellent source of data [12]. In this effort, extensive tensile test data of bridge wires after 85 years in service exhibiting various levels of corrosion, as well as, wires in brand new condition with no loss of section that are representative of the original condition were when the bridge was opened to service in 1903 was gathered.

Original strength of the Williamsburg Bridge cable in 1903 is estimated using a random field-based methodology (RFM). Strength of a bridge cable can be estimated from tensile test data of individual bridge wires. In the standard approach, wires are cut into specimens of unit length and tested for tensile strength. The strength of a wire of prescribed length is the minimum of the *n* strengths of the *n* unit-length segments, which can be calculated based on the probability distribution of the unit-length specimen strength values [13]. Having obtained the strength of an individual wire of prescribed length by one of these approaches, strength of the entire cable cross-section is determined.

In the standard approach, strengths of the successive unit-length segments along a wire of prescribed length are assumed to be uncorrelated. In contrast, RFM shows that strength of bridge wires exhibit correlation along their length [14]. In RFM, the strength of wire along its length is modeled as a random field of which the minimum strength value along the prescribed length of the field (bridge wire) represents the overall wire strength. The strength value of each wire segment along the length is established through Monte Carlo simulation. In addition to the probability distribution of the wire segment strengths for the entire sample population, wire strength also depends on the correlation structure of the tensile strength along the length of individual wires. Strength of the bridge cable can be established in the same manner as the standard approaches; first finding the minimum strength value along the length of an individual wire to determine its overall strength and then determining the cable strength using strengths of individual wires.

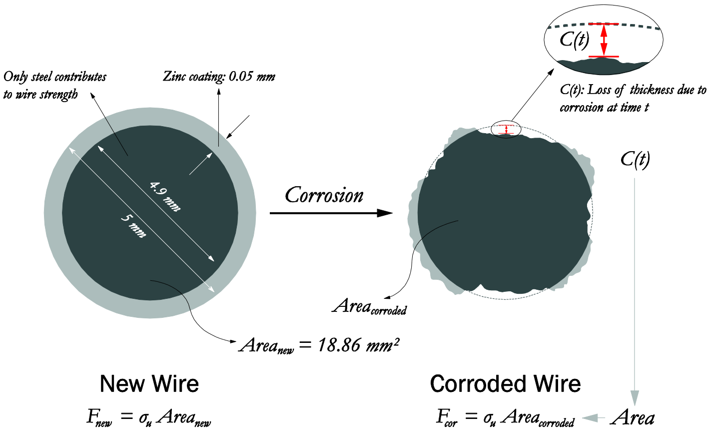

Fig. 1. Strength of a Corroded Wire

The loss of cable strength is then established as the difference between the 1988 cable strength results published by Shi et al. [14] and the estimated 1903 strength. Next, cumulative corrosion of each wire is calculated using Eq. (3). Environmental inputs along the cable cross-section are generated based on the developed internal distribution and historical records applied for the duration of 85 years, starting with brand new wires in 1903. Next, using the environmental inputs developed, the remaining strength of each wire in the cable cross-section is calculated for a range of *n* values. In this step, the remaining wire area for a wire is estimated first from Eq. (1) and then the remaining wire strength is calculated by multiplying the remaining wire area with the wire ultimate tensile stress (Figure 1). The *n* value that results in the same cable strength loss as the one estimated earlier using RFM is selected to be used Equations (1) and (2).

3 Results

The exponential constant *n* in Eq. 3 is determined as 0.*38* using RFM. This value falls between the values reported by Briggs [15] (*n*=0.25-0.41) and Feliu et al. [16] (n=0.59) for industrial and rural-industrial atmospheres. Note that, *n* could be seen as an index on the presence and physico-chemical behavior of the corrosion product layer, and the reactions of this layer with various environmental factors [17]. Once the corrosion process has begun, the rate of corrosion will be controlled by the corrosion product layer's (a) thickness, (b) porosity, and (c) chemical composition and distribution. The estimated *n* value is below 0.5, reflecting the presence of the so-called ideal diffusion-controlled corrosion mechanism. In this regime, which is realized with decreasing diffusion coefficient, all corrosion products remain on the metallic surface as an unperturbed layer. If the diffusion process is accelerated by removal of the corrosion products layer via erosion, dissolution, cracking, etc., the exponent *n* will attain a value higher than 0.5, up to the limiting value of 1.0. Thus, the results suggest that a corrosion layer that slows down the corrosion rate with time is formed on the surface of bridge wires and that there is minimal removal of this rust layer due to any erosion or dissolution processes.

3.1 Case Study

In this section, the estimated long-term exponential constant *n=0.38* is used to simulate the evolution of the remaining cable strength for a hypothetical, new bridge cable composed of 7,696 new galvanized wires (same number of wires as the Williamsburg Bridge cable). In this example, the hourly environmental inputs for T, RH, pH, and Cl^- concentration for a bridge cable in the New York City region are estimated from historical records.

The main difference between the Williamsburg Bridge cable and the hypothetical cable studied here is the presence of a galvanization layer surrounding each wire; steel corrosion and the associated loss in cable strength begin only after the zinc layer is depleted. Most long-span suspension bridges are constructed with wires protected by a coating that has a coating weight of 300 g/m^2 [6]. ASTM publication STP 435 [15] indicates that the corrosion rate of zinc in most environments is, at least, ten times lower than that of e. A power curve fitted to the steel versus zinc corrosion data in STP 435:

$$A_{zinc} = 0.392 \times A_{steel}{}^{0.561} \qquad 4$$

where A_{zinc} and A_{steel} are the annual corrosion rate of zinc and steel, respectively. The $n = 0.92$ value reported by Feliu et al. [16] for the corrosion of zinc in urban-industrial atmospheres will be used in Eq. (3) to calculate A_{steel} values when estimating zinc corrosion rates from Eq. (4).

An initial zinc coating thickness of 42μm is used for all wires – this value corresponds to the thickness required to achieve the coating weight of 300 g/m^2 for the uncoated steel wire diameter of 4.9-mm used in this study. For each wire segment, cumulative zinc corrosion depth is calculated until this value reaches the thickness of the initial coating. At this point, t=0-years is assigned to that wire segment and cumulative steel corrosion is calculated for the remaining duration of the simulation. Since the internal distribution of environmental variables varies across the cable cross-section, steel corrosion starts at a different time for each wire segment. Following the onset of steel corrosion, cumulative steel corrosion depth values are calculated by summing the incremental corrosion values and the remaining strength of each wire is calculated. Finally, remaining cable strength is obtained by summing the individual wire strengths (in kN) using the ductile-wire model that assumes that all of the wires in the cable share the cable force until the entire cable fails:

$$Y(t) = \sum_{i=1}^{n} F_i(t) \qquad 5$$

where *Y(t)* is the strength of the entire cable consisting of *n* wires at time *t,* and $F_i(t)$ denote the strength of wire *i* at time *t,* both *Y* and *F* in force units. Figure 2 displays the evolution of the remaining cable strength. The reduction in cable strength for 100-years in service is estimated as 7.93% (257,222kN to 236,833kN) for the determine *n* value of *0.38*.

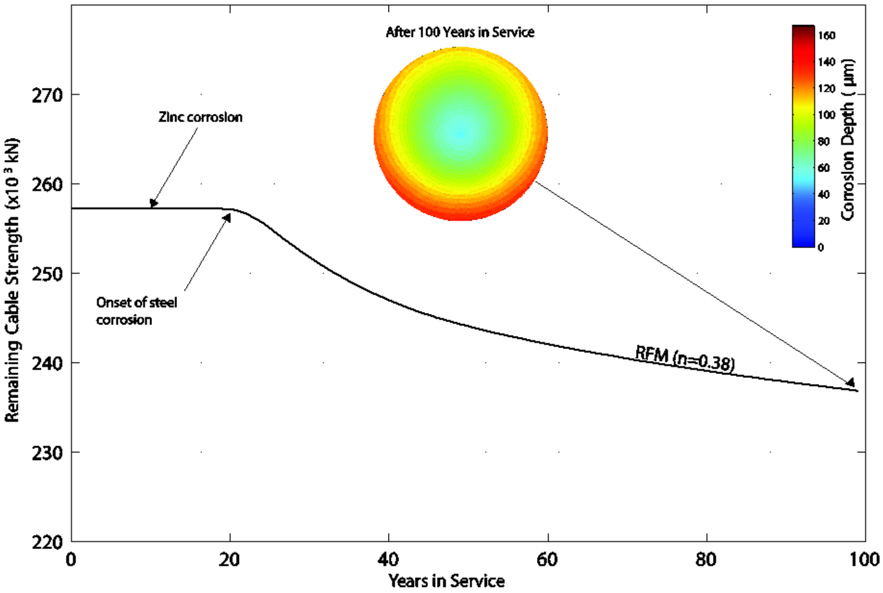

Fig. 2. Hypothetical, New Bridge Cable – Evolution of the remaining cable strength

4 Conclusions

Long-term corrosion of bridge wires can be estimated from monitored environmental parameters. This is particularly useful as it provides a means to determine the strength of bridge cables in their deteriorated state. The method presented in this paper offers a straightforward way of estimating the long-term corrosion depth of bridge wires, using only a number of monitored environmental inputs. Compared to the currently used cable inspection methods that reveal the condition of wires at only a selected few locations and only at the time of the inspection, estimating the remaining cable strength from monitored parameters offers a continuous and complete picture of the cable condition.

The numerical example presented on a new bridge cable composed of galvanized wires demonstrates how the evolution of cable strength can be predicted in the long-term from monitored environmental inputs. While the example provided is limited to a single location and use the ductile-wire model in strength estimation for its simplicity, the procedure can easily be extended to cover the entire length of the cable and to use a more appropriate strength estimation method such as the brittle-ductile model.

One of the remaining questions is whether the exponent n follows the exponential trend throughout the service life of a suspension bridge. We recommend that the n value estimated again for the Williamsburg Bridge when future inspections provide another data point in time. Another question is “how dependent is the exponent n on the specific suspension bridge and bridge locality?” We suggest that n values be calculated for different bridges as inspection data becomes available. It is, in any case, clear that the problems discussed here in this study will remain as some of the most crucial with regard to the safety of suspension bridges.

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