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Comparison of the corrosion of fasteners embedded in wood measured in outdoor exposure with the predictions from a combined hygrothermal-corrosion model

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ABSTRACT

This paper examines the accuracy of a recently developed hygrothermal-corrosion model which predicts the corrosion of fasteners embedded in wood by comparing the results of the model to a one year field test. Steel and galvanized steel fasteners were embedded into untreated and preservative treated wood and exposed outdoors while weather data were collected. Qualitatively, the distribution of corrosion products along the length of the fastener were in agreement with the simulation results. Quantitatively, the combined hygrothermal-corrosion model predicted 20% less corrosion than measured in the exposure test for galvanized steel fasteners due to a lower simulated moisture content.

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1. Introduction

Metal fasteners, such as nails, screws, and bolts are an essential part of wood construction. Corrosion is rarely a design consideration and in most cases, carbon steel or galvanized fasteners are used with little or no corrosion problems. However, in preservative or fire retardant treated wood, corrosion can be a concern. A 2004 change in the regulation of waterborne wood preservatives highlighted the need for corrosion research. Prior to the regulation change, the most common wood preservative was chromated copper arsenate (CCA). Newer wood preservatives introduced to the market after the regulation change, such as alkaline copper quaternary (ACQ) were more corrosive, and in some case rapid failures were observed in service [1]. Further research has found that the corrosion rate in ACQ treated wood is 2–6 times greater than in wood treated with CCA [2–12]. This increase in corrosion rate has decreased the expected service life of a common decking nail by more than 90% [13].

The corrosion of metals in treated wood involves the reduction of cupric ions from the wood preservative, depends upon wood moisture content, and exhibits constant kinetics with time. It is thermodynamically favorable for cupric ions in the wood preservative to be reduced to copper metal in the presence of steel or zinc galvanized fasteners. Not surprisingly, research has shown that the corrosion rate depends upon cupric ion concentration [3,14]. The corrosion rate also depends upon wood moisture content exhibiting a sharp transition from zero at around 15% wood moisture content to a plateau at a maximum corrosion rate at roughly 30% moisture content [15,16]. Additionally, different wood species may exhibit different corrosion rates because they contain different amounts of acetic acid and tannins which are known to affect the corrosion rate [17–29]. Unlike atmospheric corrosion, where the corrosion kinetics slow down with time because of passivation [30,31], corrosion of metals embedded in wood exhibits a constant corrosion rate with time [32]. Therefore, the corrosion rate depends only on the wood moisture content, wood species, wood preservative, and fastener material but not the previous history. It follows that hygrothermal models used to predict the moisture content from environmental conditions can be further used to predict the amount of corrosion of embedded metals with some slight modifications.

Zelinka et al. used a combined hygrothermal corrosion model to predict the corrosion of embedded metals in seven different US climates [33]. The combined model has also been used to examine differences in standardized corrosion test methods [34]. The combined model utilized an existing, validated, two-dimensional finite element hygrothermal model to calculate moisture content of wood in response to environmental loadings [35]. Wood mate-

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rial properties came from the measurements of Zillig on Norway spruce [36]. At each time step, the instantaneous corrosion rate, R was calculated from the moisture content, M, through the empirical

$$R = \frac{A}{1 + e^{B(C-M)}} \quad (1)$$

where A, B, and C are fitting parameters [33]. Because of the shape of the equation, parameter A also corresponds with the asymptotic corrosion limit and was taken from electrochemical measurements of galvanized steel in water extracts of ACQ treated wood [37]. Parameters B and C were taken from a curve fit of polarization resistance measurements at different moisture contents collected by Short and Denis [15,16].

The original model provided insight into the relative amount of fastener corrosion that would be expected across different US climate zones, however it was unclear how accurate the predictions of the combined hygrothermal-corrosion model were. The model used hygrothermal properties of Norway spruce (*Picea abies*), which has very slow moisture transport, where the corrosion data was taken on southern pine (*Pinus* spp.), which has much different moisture storage and transport properties. Also, the empirical corrosion model used data from two different types of tests: the shape of the corrosion rate as a function of wood moisture content curve was taken from the measurements of Dennis et al. [15,16] but the asymptotic maximum corrosion rate was taken from measurements taken in a water extract of treated wood [37]. Furthermore, while the hygrothermal finite element model has been validated, it was unclear how the combined model compared to actual corrosion tests.

In this paper, we present a further refined hygrothermal-corrosion model, and compare simulation results to the results of a field test where fasteners were embedded in wood and placed outside for a year. The refined model represents a culmination of several recent works examining the relationship between wood moisture content and the corrosion rate [38] as well as refined measurements of the moisture storage and transport properties of southern pine [39]. The comparison presented herein illustrates the potential usefulness of the combined model for predicting corrosion in wooden building components.

2. Methods and materials

The experimental work consisted of conducting an outdoor corrosion field test developed to compare and validate the combined hygrothermal-corrosion model. Throughout the field test, weather data were collected directly adjacent to the corrosion specimens and these data were used as boundary conditions in the simulations. An explanation of the experimental field test will be presented first, followed by the details of the simulation.

2.1. Field test

The wood specimens used in the field tests were cut from a single large beam from the southern pine species group. Although the exact species could not be determined, it was harvested from a plantation where over 90% of the trees were slash pine (*Pinus elliottii*). Southern pine was chosen as over 70% of the southern pine harvested is treated with waterborne preservatives [40]. Specimens were cut along the anatomical directions of the wood to 40 mm (tangential) by 90 mm (radial), approximately the size of a nominal US "2 × 4". The length of the boards of 610 mm (longitudinal), to match the geometry of the ASTM G198test specimen [41]. The end-grain was sealed with paraffin wax so that transport along the longitudinal direction could be ignored. Nails were driven into the 38 mm by 610 mm face, which was the tangential surface (see Fig. 1). This face was exposed outdoors pointing up, parallel to the ground, and therefore the primary direction of moisture transport was in the radial direction.

Fig. 1. Photograph of the untreated (left) and treated (right) specimens at the beginning of the 1-year exposure test. The "R" and "L" arrows denote the radial and longitudinal directions, respectively; the tangential direction is perpendicular to the radial direction on the front face. The tangential surface is on the top of the board and cannot be seen in these images.

Three of six wood specimens were treated with alkaline copper quaternary type D (ACQ-D) as specified in AWPA standard P5 [42]; the other half were tested in the untreated condition. ACQ-D consists of 66.7% copper oxide and 33.3% didecyldimethylammonium carbonate dissolved in ethanolamine. The treatment was performed by submerging the wood in the treatment solution pulling a vacuum for 30 min, followed by applying pressure (1034 kPa) for 60 min. The solution concentration was 0.7% to reach the target retention of 4 kg m^{-3}. This retention level corresponds with applications outdoors but not in contact with the ground as specified in AWPA U-1 [43].

Plain carbon steel fasteners and hot-dip galvanized steel nails were tested. To minimize other differences between the fasteners and focus solely on the effect of galvanization, the fasteners were produced in the same production run from a manufacturer of hot-dip galvanized fasteners, and the carbon steel fasteners were pulled from the production line immediately prior to galvanization. The fasteners were approximately 3.4 mm in diameter and 64 mm in length (nominal "8d" size). The thickness of the hot dip galvanized coating ranged from 10 to 24 μm deep.

Fasteners were driven into wood, with a spacing of 38 mm from the end and 33 mm between fasteners according to the geometry specified in ASTM G198, which resulted in 16 nails per board. The boards were then placed on posts that were 1.2 m above ground at the Forest Products Laboratory experimental testing site, in southern Wisconsin (USA) (43°02′42″N, 89°33′09″W). The posts were located about 2 m away from a building housing the data acquisition system, and specimens were on the south side of the building.

Weather data was recorded so that the simulation could use these directly as inputs. Wind speed, wind direction, temperature, relative humidity and precipitation were measured at the test site. Solar radiation was obtained from the nearby ISIS Network MSN station [44]. Cloud cover was calculated from data obtained from the KMSN (local airport) cloud conditions. Temperature and relative humidity were measured with a Vaisala HMP233. The mast of the wind sensor was 7.6 m high and located 15 m from the nearest obstruction. Precipitation was measured with a rain gauge that was surrounded by a wind shield at the base of the mast of the wind sensor. The rain gauge was not heated, which resulted in snow not being included in the precipitation measurements until it melted. While this method may underestimate the amount of precipitation, it is unclear whether snow covered wood absorbs moisture when