



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 preser-

vative 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 elliotii*). 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 G198 test 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



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.

ground, and therefore the primary direction of moisture transport was in the radial direction.

Three of six wood specimens were treated with alkaline copper quaternary type D (ACQ-D) as specified in AWP 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 AWP 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 $24 \mu\text{m}$ 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) ($43^{\circ}02'42''\text{N}$, $89^{\circ}33'09''\text{W}$). 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

the temperature is below freezing, and furthermore, the combined hygrothermal-corrosion model enforces a no-corrosion condition when the wood temperature is below freezing, so the manner in which the rain gauge records snowmelt mimics how the model computes corrosion.

In addition to weather data, moisture content of the wood was measured 70 mm below the surface with an electrical resistance technique at two locations per board for six total measurements each for treated and untreated specimens. Wires were embedded into the wood with a conductive epoxy. The leads were connected to a Delmhorst Kil-Mo-Trol Plus K-1100 automated moisture content measurement system. Readings were corrected for temperature and species using a calibration curve developed especially for the experiment that used conductive epoxy embedded electrodes in untreated and ACQ-treated southern pine.

Immediately prior to testing, the fasteners were cleaned, dried, and weighed. The fasteners were cleaned in an ultrasonic bath with a soap solution for 5 min, rinsed under flowing reverse osmosis (RO) water, and placed in an ultrasonic bath filled with RO water for an additional 5 min, after which they were rinsed with acetone and dried under flowing air. After weighing the fasteners, they were driven into the wood, which had been preconditioned for several months at 22 °C and 60% RH, with a resulting moisture content of 12.5%. The specimens were then placed out-doors within a couple of hours of the fasteners being driven into the wood. The test was started on July 31st, 2012 and continued for 8760 h.

After testing, the fasteners were removed from the wood by sawing notches into the wood and breaking the wood around the fastener; this allowed the fastener to be removed from the wood without damaging the corrosion products with methods developed by Zelinka [45]. The fasteners were then photographed and the loosely-adherent corrosion products were brushed off and collected for X-ray diffraction (XRD) analysis. The remaining corrosion products were removed by chemically cleaning them in a bath comprised of 50 vol% EvapoRust (Orison, Abeleine, TX) and 50 vol% water in an ultrasonic cleaner for 60 min, dried and weighed. To correct for loss of the base metal by the cleaning procedure, uncorroded replicates were also cleaned with this procedure and it was found that they lost 2.8 mg. This was accounted for when calculating the mass loss caused by corrosion through the following formula

$$\Delta m = m_i - m_f - m_c \quad (2)$$

where m is the mass and the subscripts i and f stands for initial, and final, respectively, and subscript c stands for the mass change caused by cleaning (taken as -2.8 mg). The change in mass was then used to calculate the average corrosion rate (R , in $\mu\text{m year}^{-1}$) through

$$R = k \frac{\Delta m}{\rho a t} \quad (3)$$

where ρ is the metal density (7.87 g cm^{-3} for steel, 7.13 g cm^{-3} for galvanized steel), t is the time of the experiment (8760 h), k is a constant needed for unit analysis, and a is the surface area (cm^2)

of the fastener which was determined optically by the method of Rammer and Zelinka [46,47].

An attempt was made to characterize the corrosion products using powder X-ray diffraction (XRD). Corrosion products were removed, collected and XRD patterns were collected using an Inel (Artenay, France) CPS 120 wide angle diffractometer with a Cu K α source. However, there were not enough corrosion products to get a useable signal. Instead the chemical composition of the corrosion products were analysed with energy dispersive X-ray spectroscopy.

Cross sections of corroded fasteners were examined with scanning electron microscopy to characterize the depth of the corrosion attack. Two locations on the fasteners were examined; 5 mm below the fastener surface and 60 mm below the fastener surface. These locations were chosen as the simulations predicted a high amount of corrosion at 5 mm and relatively little corrosion at 60 mm.

2.2. Simulations

The results of the field test were compared against the results of a computer simulation which utilized the combined hygrothermal-corrosion model developed by Zelinka et al. [33]. The method used a finite element model with adaptive time stepping to calculate the wood moisture content at each node from hourly weather data and an empirical corrosion post-processor, which calculated the instantaneous corrosion rate at each hourly time step.

Simulations represented the field corrosion test where a nail was driven into the 40 mm face of a 40 by 90 mm wide piece of wood. To simulate the field exposure, a full set of boundary conditions was applied to the top surface with the nail head (i.e. rain, temperature, relative humidity, solar radiation, wind). Only temperature and relative humidity boundary conditions were applied to the other faces of the wood.

The simulations utilized a 2D computational domain. Since the ends of the wood beams were covered with an impermeable coating during the field tests, the beam was treated as semi-infinite and therefore the third dimension could be ignored in the simulation. A majority of the moisture movement was 1 dimensional (from a front of liquid water on the top of the board caused by rainfall); however, the drying was 2-dimensional and comparisons between 1D and 2D simulations showed up to a 20% difference. For the 2D simulations, a symmetry plane was used to reduce the mesh to a physical size of 20 by 90 mm. The mesh was non-uniform with a higher density of nodes near the surface exposed to the rain and was constructed with 2301 elements and 2400 nodes.

The simulations utilized wood material properties collected on the same parent material as the corrosion test specimens by Zelinka et al. [39] to calculate the wood moisture content from the weather data. The relationship between the wood moisture content and the corrosion rate used the empirical relationship in Eq. (1) applied with a temperature criterion. If the temperature at the wood-metal interface was less than or equal to 0 °C, it was assumed that no corrosion occurred during the hourly time step because of the lack of liquid water. Otherwise, Eq. (1) was applied to determine the corrosion rate for the time step, and an incremental amount of corrosion

Table 1
Values of A , B , and C used in the empirical Eq. (1) used to calculate the corrosion rate as a function of moisture content based upon a best fit to the corrosion data of Zelinka et al. [38].

		A ($\mu\text{m/year}$)	B (g/g)	C (g/g)
Steel	Treated pine	25.2	40.8	0.239
	Untreated pine	0.7 ^a	40.8 ^b	0.239 ^b
Galvanized steel	Treated pine	54.6	19.9	0.256
	Untreated pine	4.4 ^a	19.9 ^b	0.256 ^b

^a The asymptotic maximum corrosion rates for untreated wood were taken from measurements of fasteners embedded in wood and exposed to a 100% RH environment [2]. A better prediction can be obtained by using a value of 19.7 for steel and 14.6 for galvanized steel (see Section 4).

^b These parameters were not measured for untreated wood, but instead the values for treated wood were used for untreated wood.

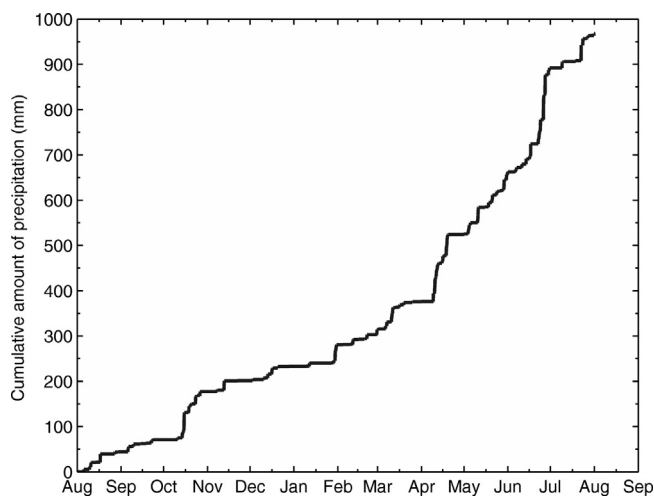


Fig. 2. Cumulative amount of measured precipitation during the 1 year exposure test and used in the simulation.

was calculated each hour and added to the cumulative amount of corrosion. The parameters *A*, *B*, and *C* were determined by running laboratory corrosion tests at several different fixed relative humidities for 1 year. The laboratory tests used the same nails and treated southern pine as the field tests and the results were presented previously [38]. For the untreated specimens, data were only available from a different study on southern pine where measurements were taken at 100% relative humidity [2]. The corrosion rate measured under these conditions was assigned to parameter *A* (the asymptotic maximum corrosion rate), and the parameters *B* and *C* were taken to be the same as those found in treated wood. The parameters used in the empirical corrosion models for steel and galvanized steel in treated and untreated wood are given in Table 1.

3. Results

3.1. Field test

The mean of the hourly temperature measurements was 7.4 °C over the year-long test. Of the 8760 hourly measurements, there were 6034 h where the temperature was above 0 °C. There was 0.97 m of precipitation (measured as liquid), and precipitation was recorded during 594 of the hourly measurements (Fig. 2).

The average corrosion rates, determined gravimetrically, are shown in Fig. 3. Similar to previous laboratory tests the hot-dip galvanized fasteners exhibited a higher corrosion rate than steel fasteners [38,48,49] in ACQ-treated wood.

The severity of the corrosion attack was also measured by examining the amount of the fastener that exhibited visible corrosion products (Fig. 4). The corrosion was unevenly distributed along the length of fasteners because the top of the block of wood was exposed to rain, so the nail head had more rust than the nail tip, which had no visible corrosion products. The amount of visible corrosion products were recorded by measuring the fasteners along their length from the head until the last visible corrosion product, and we refer to this as the corrosion length. The corrosion length was measured from calibrated images using *ImageJ*, a freely available software developed by the US National Institutes of Health [50]. The average corrosion length for the steel and galvanized fasteners was 32 and 35 mm, respectively, in the treated wood. For the untreated wood, the steel fasteners had an average corrosion length of 25 mm; the corrosion length could not easily be determined for the galvanized fasteners (Fig. 4d).

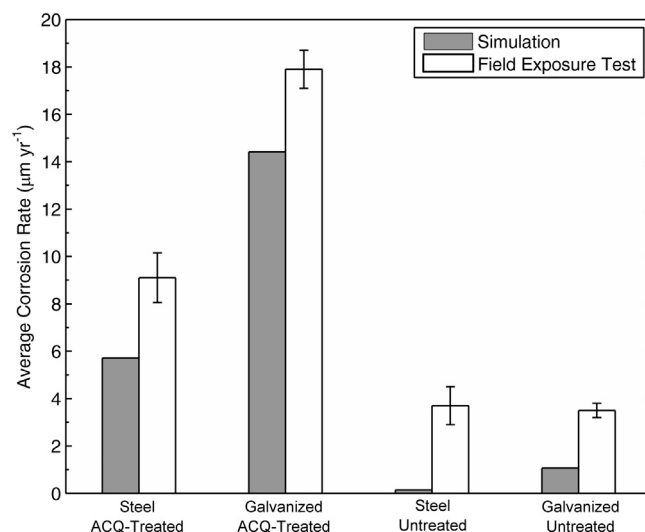


Fig. 3. Average gravimetric corrosion rates from the field test (grey) and predicted from the computer simulation (white) for steel and galvanized steel in untreated and ACQ-treated wood. Error bars represent the standard error.

Cross sectional scanning electron microscopy images (backscatter) are presented in Fig. 5. The images from the backscattered electrons provided more contrast between the steel fastener, galvanized coating, and the corrosion products than the secondary electron images. Fig. 5a and 5b shows the galvanized cross section at 60 mm and 5 mm below the wood surface, respectively. The thickness of the corrosion products at 60 mm ranges between 5 and 10 μm, and the galvanized coating thickness ranges between 45 and 60 μm. In the corrosion zone, the corrosion products were 30 μm thick and the galvanized coating thickness was between 20 and 25 μm. Figs. 5c and 5d shows the steel fastener cross sections at 60 mm and 5 mm below the wood surface. At 60 mm, corrosion products were less than 1 μm thick, and were between 45 and 50 μm thick at 5 mm below the wood surface.

Energy dispersive X-ray spectroscopy spectra are presented in Fig. 6 along with the electron micrographs of the surface. For the galvanized fastener (top), only Zn, O, and C could be detected. For the steel fastener, Fe, O, C, and Cu could be detected. The copper in the surface of the corrosion products represents reduced copper from the wood preservative. In previous, laboratory, experiments,



Fig. 4. Images of the fasteners after being removed from the 1-year field exposure test. (a) steel fastener in treated wood, (b) steel fastener in untreated wood, (c) galvanized fastener in treated wood, (d) galvanized fastener in untreated wood.

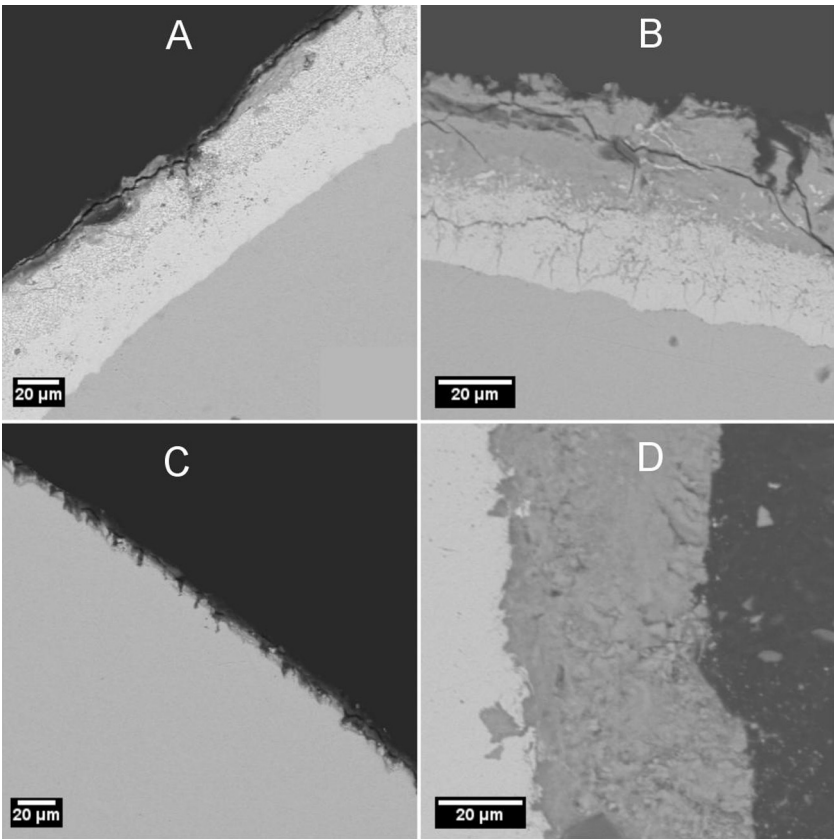


Fig. 5. Backscattered electron images of (A) galvanized fastener 60 mm below the surface of the wood (B) galvanized fastener 5 mm below the surface of the wood (C) steel fastener 60 mm below the surface of the wood (D) steel fastener 5 mm below the surface of the wood.

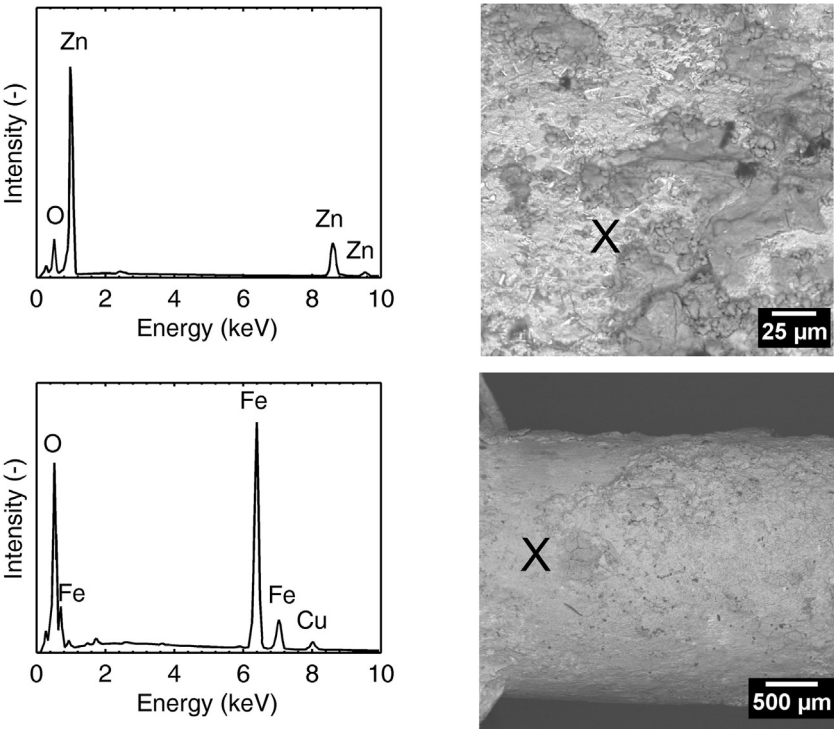


Fig. 6. Energy dispersive X-ray spectra with the corresponding scanning electron microscope image showing where the spectra were collected. Top: galvanized steel fastener. Bottom: steel fastener.

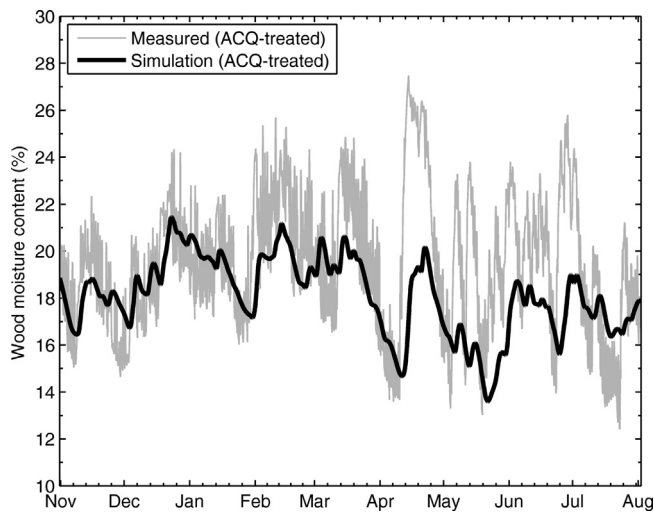


Fig. 7. Average measured moisture content of the ACQ-treated wood 70 mm below the surface compared with that predicted from the hygrothermal simulation.

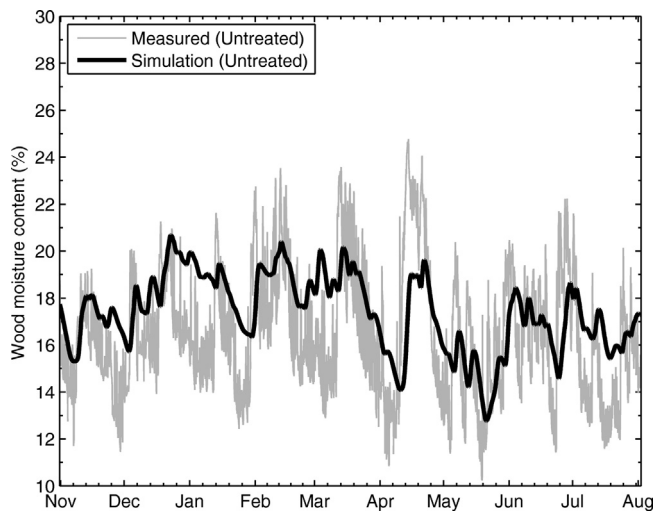


Fig. 8. Average measured moisture content of the untreated wood 70 mm below the surface compared with that predicted from the hygrothermal simulation.

copper had only been detected on fasteners placed in wood that had been saturated with liquid water, and not on fasteners placed in a humid environment [38].

3.2. Simulations

The simulated wood moisture content at 70 mm below the surface of the wood is shown in Figs. 7 and 8 for the treated and untreated wood, respectively. The measured moisture content overlaid. For the treated wood, the simulated moisture content moves in the same direction as the measured moisture content and is mostly within the variation of the measured moisture contents from November, when the moisture content readings started until April. Starting in April, the measured moisture contents have larger fluctuations than the simulated data and in general, the simulated moisture content is less than the measured moisture content during this time period.

The combined hygrothermal-corrosion model output the amount of corrosion (in μm) as a function of position below the wood surface (Fig. 9). The shape of the curves in Fig. 9 shows a maximum corrosion attack about 10 mm below the surface. The maximum at 10 mm below the surface is a result of liquid water

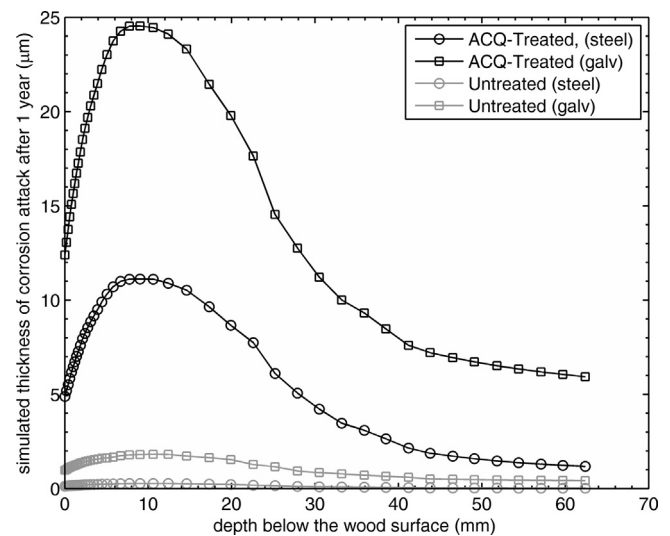


Fig. 9. The thickness of corrosion attack (depth of corrosion penetration) as a function of the fastener position below the wood surface.

movement through the wood during rain events. The top surface saturates during a rain event, and a wet zone advances into the wood. When the rain event is over, the wood dries predominantly from the top surface, resulting in the area just below the surface remaining the wettest for the longest period of time and having the most corrosion attack.

From the data in Fig. 9 the average corrosion rate could be calculated by a trapezoidal integration of the curve and dividing by the length of the fastener. The simulated average corrosion rates during the one year test were 14.4 and 5.7 $\mu\text{m year}^{-1}$ for the galvanized steel and carbon steel fasteners embedded in treated wood. For the untreated wood, the average corrosion rates were 1.07 and 0.14 $\mu\text{m year}^{-1}$, respectively. These data are included in Fig. 4 for a comparison.

Qualitatively, the shape of the curves in (Fig. 9) is similar to the behavior exhibited by the fasteners embedded in wood where the visual corrosion products are near the head of the fastener and the fastener tip appears relatively unaffected by the corrosion. The simulations show a large decrease in the amount of corrosion approximately 30–40 mm below the wood surface, which is similar to the amount of fastener that showed visible corrosion products (Fig. 4). However, it is difficult to quantitatively compare the depth of the corrosion attack visible in Fig. 4 to the simulations in Fig. 9 since the simulations do not reach zero corrosion. It is possible that there was some very slight corrosion attack on the bottoms of the fasteners that it did not result in a visible patina.

4. Discussion

The purpose of this paper was to examine how well a recently developed combined hygrothermal-corrosion model could predict the amount of corrosion exhibited by fasteners in a field exposure test. Steel and hot-dip galvanized steel fasteners were embedded in untreated and ACQ-treated wood and exposed for one year. The corrosion model had been developed for steel and galvanized steel in ACQ-treated wood; similar parameters were used for untreated wood to see if the combined model could be used for untreated wood (Table 1). Not surprisingly, the model predicted the corrosion of fasteners in treated wood much more accurately than it did in the untreated wood. Comparisons between the model and the field test can be made both in the total average amount of corrosion and the distribution of the corrosion with respect to the wood surface.

The simulations slightly underestimated the total yearly amount of corrosion for the steel and galvanized steel fasteners in ACQ-treated wood. The simulations predicted an average corrosion rate of $5.7 \mu\text{m year}^{-1}$ for the steel fastener and $14.4 \mu\text{m year}^{-1}$ for the galvanized fastener compared to the measured 9.1 and $17.9 \mu\text{m year}^{-1}$, respectively. Interestingly the absolute difference between the simulated and measured corrosion rates are nearly identical for the steel and galvanized steel at 3.4 and $3.5 \mu\text{m year}^{-1}$, respectively.

The most probable explanation for the difference between the simulated and measured corrosion rates is that the simulation under-predicted the wood moisture content from April until the end of the field test on July 31st (Fig. 7). The simulations only took into account for rain striking the top surface of the board, and ignore wind-driven rain striking the sides of the board, and also ignore potential runoff from the surface onto the sides of the board. It is likely that the differences between the measured and simulated moisture content are related to the model's assumption that there is no rain deposition on the sides of the board.

Given these discrepancies in the moisture content, the simulations appear to do an adequate job of predicting the amount of corrosion that embedded steel and galvanized steel fasteners may exhibit in treated wood. However, the simulations greatly underestimated the amount of corrosion that occurred in the untreated field test by predicting essentially no corrosion for the steel fastener and only $1 \mu\text{m year}^{-1}$ for the galvanized steel fastener. Assuming the combined model can be adapted to untreated wood, there are two possible explanations for this discrepancy. The first is that the simulations were predicting too low of a moisture content, and the second is that the corrosion post-processor did not have the correct relationship between the wood moisture content. Fig. 6 shows that the model was able to predict the correct wood moisture content, which suggests that it is likely that the corrosion post-processor was not able to predict the amount of corrosion for untreated wood.

The corrosion post-processor used the same functional dependence of the corrosion on the wood moisture content for both the treated and untreated wood. The only difference in the models was parameter "A" which represents the asymptotic maximum moisture content, which for the untreated wood was taken from a study where fasteners were embedded in wood and equilibrated at 100% relative humidity. It is clear that the values of "A" used in the model for untreated wood were too low; the steel fastener in the exposure test exhibited a higher corrosion rate than the value of A used in the model. Since A represents the maximum amount of corrosion expected when the wood remains saturated all of the time, clearly the results of the field test should not be greater than A.

In previous work measuring the moisture content dependence in treated wood, measurements were also attempted in untreated wood; however, these measurements were not successful. The "solution" resistance of untreated wood at low moisture contents is too high (on the order of $10^8 \Omega \text{m}$) to take electrochemical measurements [51]. Gravimetric corrosion rate measurements are also difficult; the corrosion rates measured in wood in equilibrium with 100% relative humidity were barely measureable at less than $1 \mu\text{m}$ per year, so the dependence at even lower moisture contents is unlikely to yield reliable results. Realistically, the model could only be improved by developing an accurate prediction for the maximum corrosion rate (parameter A) and using the shape of the curve found for treated wood.

Given these difficulties in independently obtaining data that can be used to determine the model parameters for untreated wood, it may be useful to use the field test to determine a value of parameter A that can be used for practical modeling purposes. To do this, we took the untreated moisture content as a function of time as determined from the model and repeatedly ran it through the post processor with different values of parameter A and compared the average corrosion rate to the amount of corrosion measured in the

field test. The best agreement between the model and the field tests occurred when parameter A was set to $19.7 \mu\text{m year}^{-1}$ for steel fasteners and $14.6 \mu\text{m year}^{-1}$ for the galvanized fastener. While more data would be beneficial in refining the model for untreated wood, these values for parameter A should give reasonable predictions for simulations predicting the amount of corrosion that could be expected in untreated wood.

5. Conclusions

Here we conducted a one year field exposure test of steel and galvanized fasteners embedded in untreated and ACQ-treated wood and compared the results to a combined hygrothermal-corrosion model developed for predicting when fastener corrosion might cause problems in building applications. The following conclusions could be drawn:

1. The simulated moisture content was correlated with the measured moisture content. However, the simulation did not have as high of moisture contents as the measured moisture contents.
2. Qualitatively, the simulated amount of corrosion along the length of the fastener matched the patterns of the visible corrosion products.
3. For the treated wood, the combined hygrothermal-corrosion model slightly underestimated the amount of corrosion for steel and galvanized steel fasteners. However, the model correctly captured the relative differences between the amount of corrosion in the steel and galvanized steel fasteners. The underestimation in the predicted corrosion is most likely related to the underprediction of the moisture content during the high wetting periods.
4. When literature values were used in the model, the model was unable to reliably predict the corrosion of fasteners in untreated wood. This was attributed to quality of the data used to construct the corrosion post-processor. Because there were relatively few data available, the field data was used to determine appropriate parameters for the corrosion post processor for untreated wood. The model agrees with the field test when parameter A is set to $19.7 \mu\text{m year}^{-1}$ for steel fasteners and $14.6 \mu\text{m year}^{-1}$ for untreated fasteners.

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References

- [1] M. Burkholder, CCA, NFBA, and the post-frame building industry, Frame Building News, 16, 2004, 6–12.
- [2] S.L. Zelinka, R.J. Sichel, D.S. Stone, Exposure testing of fasteners in preservative treated wood: gravimetric corrosion rates and corrosion product analyses, Corros. Sci. 52 (2010) 3943–3948.
- [3] G. Kear, H.-Z. Wu, M.S. Jones, Weight loss studies of fastener materials corrosion in contact with timbers treated with copper azole and alkaline copper quaternary compounds, Corros. Sci. 51 (2009) 252–262.
- [4] Anon, Preservative treated wood. Simpson Strong-Tie Technical Bulletin No. T-PTWOOD08-R, Simpson Strong Tie, Pleasanton, CA, 2008.
- [5] G. Kear, M.S., Jones, P. Haberecht, Corrosion of mild steel, HDG steel, and 316 stainless steel in CCA, CuAz and ACQ-treated *Pinus radiata*, in, Beijing China, 2005.
- [6] G. Kear, M.S., Jones, P.W. Haberecht, Corrosion of mild steel HDG steel and 316 stainless steel in CCA CuAz and ACQ treated *Pinus radiata*, in, Gold Coast, Australia, 2005.
- [7] G. Kear, H. Wu, M.S. Jones, F.C. Walsh, Direct-current methods for the estimation of corrosion rates in aqueous timber preservatives, Aust. J. Chem. 61 (2008) 455–465.

- [8] G. Kear, H.Z. Wú, E.W. Bruce, C. Kane, M.S. Jones, Metallic materials selection for timbers treated with non-CCA-based, copper-rich preservatives: implications for Australasia, *Corros. Mater.* 32 (2007) 16–21.
- [9] G. Kear, H.Z. Wú, M.S. Jones, Corrosion of ferrous- and zinc-based materials in CCA, ACQ, and CuAz timber preservative solutions, *Mater. Struct.* 41 (2008) 1405–1417.
- [10] G. Kear, H.Z. Wú, M.S. Jones, The corrosion of metallic fastener materials in untreated, CCA-, CuAz0 and ACQ-based timbers, in: *BRANZ, Porirua City, New Zealand*, 2006, pp. 281.
- [11] G. Kear, H.Z. Wú, M.S. Jones, Non-Accelerated weight loss studies of fastener material corrosion in contact with CCA, CuAz, and ACQ-treated timbers, in: *Hobart Australia*, 2006.
- [12] G. Kear, H.-Z. Wu, M.S. Jones, F. Walsh, Impedance spectroscopy studies of the dissolution of ferrous- and zinc-based materials in aqueous timber preservatives, *J. Appl. Electrochem.* 38 (2008) 1599–1607.
- [13] S.L. Zelinka, D.R. Rammer, Modeling the effect of nail corrosion on the lateral strength of joints, *Forest Prod. J.* 62 (2012) 160–166.
- [14] S.L. Zelinka, D.R. Rammer, Synthesis of published and unpublished corrosion data from long term tests of fasteners embedded in wood: calculation of corrosion rates and the effect of corrosion on lateral joint strength, in: *CORROSION 2011, NACE International, Houston, TX*, 2011, pp. 11163.
- [15] J.K. Dennis, C. Zou, N.R. Short, Corrosion behaviour of zinc and zinc alloy coated steel in preservative treated timber, *Trans. Inst. Met. Finish* 75 (1995) 96–101.
- [16] N.R. Short, J.K. Dennis, Corrosion resistance of zinc-alloy coated steel in construction industry environments, *Trans. Inst. Met. Finish* 75 (1997) 47–52.
- [17] J. Gust, J. Bobrowicz, Sealing and anti-corrosive action of tannin rust converters, *Corrosion* 49 (1993) 24–30.
- [18] P.E. Hazlewood, P.M. Singh, J.S. Hsieh, Role of wood extractives in black liquor corrosiveness, *Corrosion* 62 (2006) 911–917.
- [19] R.G. Kelly, P.J. Ambrose, R.C. Wilson, K.A. Jefferies, S. Kannan, Results of corrosion coupon exposures of ferrous materials in black liquor, *Tappi J.* 79 (1996) 148–154.
- [20] J. Mabrou, M. Akssira, M. Azzi, M. Zertoubi, N. Saib, A. Messaoudi, A. Albizane, S. Tahiri, Effect of vegetal tannin on anodic copper dissolution in chloride solutions, *Corros. Sci.* 46 (2004) 1833–1847.
- [21] G. Matamala, W. Smeltzer, G. Droguett, Comparison of steel anticorrosive protection formulated with natural tannins extracted from acacia and from pine bark, *Corros. Sci.* 42 (2000) 1351–1362.
- [22] M. McDonald, I. Mila, A. Scalbert, Precipitation of metal ions by plant polyphenols: optimal conditions and origin of precipitation, *J. Agric. Food Chem.* 44 (1996) 599–606.
- [23] A.A. Rahim, E. Rocca, J. Steinmetz, M.J. Kassim, Inhibitive action of mangrove tannins and phosphoric acid on pre-rusted steel via electrochemical methods, *Corros. Sci.* 50 (2008) 1546–1550.
- [24] C.A. Smith, Corrosion of metals by wood, *Anti-Corros. Methods Mater.* 29 (1982) 16–17.
- [25] H. Winkelmann, E. Badisch, S. Ilo, S. Eglsaer, Corrosion behaviour of tool steels in tannic acids, *Mater. Corros.* 60 (2009) 192–198.
- [26] H. Winkelmann, E. Badisch, M. Roy, H. Danninger, Corrosion mechanisms in the wood industry, especially caused by tannins, *Mater. Corros.* 60 (2009) 40–48.
- [27] S.L. Zelinka, D.S. Stone, The effect of tannins and pH on the corrosion of steel in wood extracts, *Mater. Corros.* 62 (2011) 739–744.
- [28] M.V. Fiori-Bimbi, P.E. Alvarez, H. Vaca, C.A. Gervasi, Corrosion inhibition of mild steel in HCL solution by pectin, *Corros. Sci.* 92 (2015) 192–199.
- [29] P. Mourya, S. Banerjee, M. Singh, Corrosion inhibition of mild steel in acidic solution by *Tagetes erecta* (Marigold flower) extract as a green inhibitor, *Corros. Sci.* 85 (2014) 352–363.
- [30] R.A. Legault, V.P. Pearson, Kinetics of the atmospheric corrosion of galvanized steel, in: S.K. Coburn (Ed.), *Atmospheric Factors Affecting the Corrosion of Engineering Metals*, ASTM STP646, American Society for Testing and Materials, West Conshohocken, 1978, pp. 83–96.
- [31] R.A. Legault, A.G. Preban, Kinetics of the atmospheric corrosion of low-alloy steels in an industrial environment, *Corrosion* 31 (1975) 117–122.
- [32] A.J. Baker, Corrosion of nails in CCA- and ACA-treated wood in two environments, *Forest Prod. J.* 42 (1992) 39–41.
- [33] S.L. Zelinka, D. Derome, S.V. Glass, Combining hygrothermal and corrosion models to predict corrosion of metal fasteners embedded in wood, *Build. Environ.* 46 (2011) 2060–2068.
- [34] S.L. Zelinka, Comparing the methodologies in ASTM G198: is There an easy way out? in: *CORROSION 2013, NACE International, Orlando, FL*, 2013 (p. 2507).
- [35] H. Janssen, B. Blocken, J. Carmeliet, Conservative modelling of the moisture and heat transfer in building components under atmospheric excitation *Int. J. Heat Mass Transfer* 50 (2007) 1128–1140.
- [36] W. Zillig, Moisture Transport in Wood Using a Multiscale Approach. Ph.D. Dissertation, Katholieke Universiteit Leuven Leuven, Belgium, 2009.
- [37] S.L. Zelinka, D.R. Rammer, D.S. Stone, Electrochemical corrosion testing of fasteners in wood extract, *Corros. Sci.* 50 (2008) 1251–1257.
- [38] S.L. Zelinka, D. Derome, S.V. Glass, The effect of moisture content on the corrosion of fasteners embedded in wood subjected to alkaline copper quaternary treatment, *Corros. Sci.* 83 (2014) 67–74.
- [39] S.L. Zelinka, S.V. Glass, C.R. Boardman, D. Derome, Moisture storage and transport properties of preservative treated and untreated southern pine wood, *Wood Mater. Sci. Eng.* (2014) 1–11.
- [40] R.P. Vlosky, Statistical Overview of the U. S. Wood Preserving Industry 2007, North American Wood Pole Council, Vancouver, WA, 2007, pp. 2009.
- [41] Anon, ASTM G198-11: Standard Test Method for Determining the Relative Corrosion Performance of Driven Fasteners in Contact with Treated Wood, ASTM, International, West Conshohocken, PA, 2011.
- [42] Anon, AWP A P5: Standard for Waterborne Preservatives, American Wood Preservers' Association, Granbury, TX, 2007.
- [43] Anon, AWP A U1-06: Use Category System, American Wood Preservers' Association, Granbury, TX, 2007.
- [44] B. Hicks, J. DeLuisi, D. Matt, The NOAA integrated surface irradiance study (ISIS)—a new surface radiation monitoring program, *Bull. Am. Meteorol. Soc.* 77 (1996) 2857–2864.
- [45] S.L. Zelinka, Uncertainties in corrosion rate measurements of fasteners exposed to treated wood at 100% relative humidity, *ASTM J. Test. Eval.* 35 (2007) 106–109.
- [46] D.R. Rammer, S.L. Zelinka, Analytical determination of the surface area of a threaded fastener, *ASTM J. Test. Eval.* 36 (2008) 80–88.
- [47] D.R. Rammer, S.L. Zelinka, Optical method for measuring the surface area of a threaded fastener, *Exp. Tech.* 34 (2010) 36–39.
- [48] S.L. Zelinka, D.S. Stone, Corrosion of metals in wood: comparing the results of a rapid test method with long-term exposure tests across six wood treatments, *Corros. Sci.* 53 (2011) 1708–1714.
- [49] S.L. Zelinka, D.R. Rammer, Corrosion rates of fasteners in treated wood exposed to 100% relative humidity, *ASCE J. Mater. Civil Eng.* 21 (2009) 758–763.
- [50] C.A. Schneider, W.S. Rasband, K.W. Eliceiri, NIH Image to ImageJ: 25 years of image analysis, *Nat Meth* 9 (2012) 671–675.
- [51] S.V. Glass, S.L. Zelinka, Moisture relations and physical properties of wood, in: R.J. Ross (Ed.), *Wood Handbook. Wood as an Engineering Material*, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 2010.