

Corrosion of Embedded Metals in Wood: An Overview of Recent Research with Implications for Building Moisture Design

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ABSTRACT

ASHRAE Standard 160, Criteria for Moisture-Control Design Analysis in Buildings, specifies moisture design criteria in buildings to prevent moisture damage such as fungal activity and corrosion. While there has been much research on mold and decay fungi in wood buildings, it is often overlooked that wet wood is corrosive to the metal screws or nails used to fasten it. Currently, corrosion design in Standard 160 is based upon relative humidity criteria that were developed for atmospheric corrosion. However, the corrosion of metals embedded with wood is controlled by wood chemistry and moisture content rather than atmospheric relative humidity. This paper highlights recent research on the corrosion of metals in wood that may be of interest to those in the building moisture design community who develop codes, standards, and hygrothermal models to minimize the results of structure problems caused by fastener corrosion. The major design implications are that (1) corrosion of metals in wood is not the same as atmospheric corrosion, and (2) that the wood moisture content should be kept below 18%.

INTRODUCTION

Most of the research on moisture damage in wood has focused on mold, decay fungi, and insect attack. It is often overlooked that wet wood is corrosive, and that even a modestly sized residential building will have thousands of metal fasteners embedded in wood. While wood is not considered an especially corrosive environment, embedded fasteners corrode in the presence of the organic acids, water, and oxygen available in the wood (Packman 1960). Fastener corrosion can also be accelerated when preservative or fire-retardant chemicals are added to the wood.

Prior to 2004, the most common waterborne wood preservative in the United States was chromated copper arsenate (CCA). The corrosion of metals in CCA treated-wood was studied by several researchers who found that it was more corrosive than untreated wood and suggested that at a minimum, hot-dip galvanized fasteners should be used in treated wood. In 2004, CCA-treated wood was voluntarily withdrawn for use in residential construction in the United States and similar changes in regulation have decreased the use of CCA-treated wood in Europe and Australasia. At that time, several alternatives to CCA, such as alkaline copper quaternary (ACQ) and copper azole (CuAz), became commercially available. Like CCA, these preservatives used copper as one of the biocides, but in a higher concentration than CCA, and did not contain chromates or arsenates, which are known corrosion inhibitors. Shortly after this transition, anecdotal evidence of corrosion failures was found with these new preservative treatments (e.g. Mittendorf 2009).

Since the 2004 change in wood preservative regulation, numerous research projects have examined different aspects of fastener corrosion in wood. The findings from these studies suggest that fastener corrosion is not just a concern in outdoor construction (decks, playgrounds, boardwalks, etc.) but may also be a concern for fasteners embedded in wall assemblies, especially when the moisture loads are high and drying potential is low.

Despite the implications for buildings, the majority of the research, to date, has been published in journals that focus on either corrosion or wood science. The objective of this paper is to transfer fastener corrosion knowledge to the building community for effective moisture design. ASHRAE Standard 160 *Criteria for Moisture-Control Design Analysis*

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in *Buildings* lists corrosion as one of the moisture performance evaluation criteria, yet the requirements for the prevention of corrosion are based upon relative humidity (RH) criteria applicable to atmospheric corrosion. The corrosion of embedded metals is very different from atmospheric corrosion and, more importantly, does not depend directly upon atmospheric relative humidity. When corrosion of metals embedded in wood is a concern, risk evaluation criteria, such as those suggested by ASRHAE Standard 160, should focus on moisture content rather than RH.

The remainder of this paper reviews recent research on corrosion of metals in wood, highlighting aspects related to moisture design in buildings. The review is broken into three major topics: the differences between atmospheric corrosion and corrosion of embedded metals, the dependence of the corrosion rate on wood moisture content, and how corrosion of embedded metals affects the mechanical properties of the wood-metal connection.

DIFFERENCES BETWEEN ATMOSPHERIC CORROSION AND CORROSION OF FASTENERS IN WOOD

Most of the common sense precautions for corrosion control are based consciously or subconsciously on design strategies for atmospheric corrosion. Not only is atmospheric corrosion economically important, but nearly everyone has some sort of personal experience with atmospheric corrosion on his/her home or car. Therefore, it is not surprising that models of atmospheric corrosion and methods of protecting steel from atmospheric corrosion are often applied to fasteners used in wood by default. While the wood may be exposed to

the atmosphere, the corrosion of embedded fasteners is controlled by the wood chemistry and moisture, which has major implications for successful selection of fasteners and their joint design in wood.

Corrosion Kinetics of Different Metals

It is common knowledge that galvanized steel has a longer life than uncoated steel when undergoing atmospheric corrosion. Zhang et al. (2003) summarized the literature and found steel exposed to outdoor atmospheric conditions, on average, corroded twenty times faster than zinc. However, for metals embedded in untreated and preservative-treated wood, Zelinka et al. (2010) observed that galvanized fasteners corroded more rapidly than steel fasteners (Figure 1). Because this finding is both counterintuitive and has important implications for materials selection and construction, it is worthwhile to discuss this further.

In atmospheric corrosion, zinc oxidizes to form hydrozincite $\{Zn_5(CO_3)_2(OH)_6\}$ and smithsonite ($ZnCO_3$) which passivate the zinc surface; that is, these oxidized species protect the metal from further corrosion. Conversely, steel forms goethite ($\alpha\text{-FeOOH}$), also called red-rust, in atmospheric conditions. Kinetically, hydrozincite and smithsonite are better at protecting the underlying metal than goethite; that is why zinc corrodes more slowly than steel in atmospheric conditions (Zhang 2003). It is known that in certain environments, such as immersion in saltwater (Zhang et al. 1998) or in environments with volatile acetic and formic acids (Knotkova-Cermakova and Vlckova 1971), different corrosion products form and zinc corrodes more rapidly than steel. In addition to measuring the corrosion

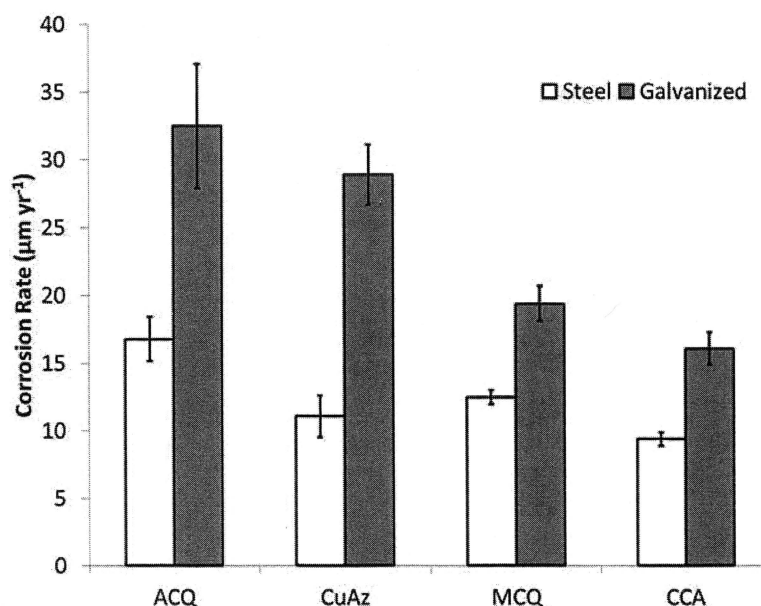


Figure 1 Corrosion rates of steel and galvanized steel measured in wood treated with different wood preservatives exposed to a 27°C (80°F), 100% RH environment. Zelinka et al. (2010).

rates, Zelinka et al. (2010f) examined the corrosion products on fasteners removed from steel and galvanized steel fasteners in wood using X-ray diffraction (Figure 2) and did not observe smithsonite on the zinc fasteners. Instead, they observed hydrozincite, namuwite $\{Zn_2(SO_4)(OH)_6 \cdot 4H_2O\}$, and simonkolleite $\{Zn_5(OH)_8Cl_2 \cdot (H_2O)\}$, which are consistent with the observed relative corrosion rates.

It should be noted that in other experiments on treated wood with different environmental conditions, zinc corroded more slowly than steel (Kear et al. 2009) although the corrosion products were not analyzed. Further testing is currently underway to understand the effect of the environment and wood treatment on the corrosion products.

Variation of Corrosion Rate with Time

In order to predict how long fasteners will last, it is necessary to understand how fastener corrosion rate varies with time. This is another key difference between atmospheric corrosion and corrosion of fasteners in wood.

During atmospheric corrosion, in many cases the corrosion rate decreases with time because of passivation. Empirically, the kinetics are frequently described by

$$\Delta W = Kt^n \quad (1)$$

where ΔW is the change in weight, K is a constant (the one year corrosion rate), t is the time in years, and n is an exponent that controls the kinetics and describes passivation (Legault and Preban 1975). Theoretically, n should be bounded by 0.5, which represents complete diffusion control, and 1, which represents activation control, where the rate-determining step is the electron transfer reaction at the surface of the metal. Practically, in actual atmospheric exposures $n < 0.5$ is observed regularly; $n = 1$ appears to be both a theoretical and empirical limit (Legault and Preban 1975).

Corrosion of metals in wood is activation controlled, and exhibits a constant corrosion rate with time. Three different

experiments support this assertion. Baker (1992) ran a 17 year exposure test and found that the weight loss increased linearly with time (i.e., $n = 1$). In other work, kinetics were examined by electrochemically measuring the corrosion rate in a water extract of treated wood, where the diffusion coefficients would be much higher than in the solid wood (Zelinka et al. 2008). Corrosion rates measured in the extract were the same as those measured in a exposure test in solid wood at 100% RH (Zelinka and Rammer 2009). Finally, a zeroth order approximation of the diffusion rates necessary to sustain corrosion suggests that the reaction should not be diffusion controlled even in solid wood. Measured corrosion rates ranged between $5\text{--}60 \mu\text{m yr}^{-1}$ ($0.2\text{--}2.4 \text{ mil yr}^{-1}$) (Zelinka and Rammer 2009), which would correspond to a depletion zone of copper of less than 1 cm (0.4 in.) per year around the fastener and a copper concentration of 4 kg m^{-3} (0.25 lb ft^{-3}) in the wood. Based upon measured cupric ionic diffusivities in wood (Simons et al. 1998), we estimate that the cupric ionic diffusion distance is greater than 1.3 cm yr^{-1} (0.5 in. yr^{-1}) and could sustain an activation-controlled corrosion.

Practically speaking, the fact that fastener corrosion is activation controlled has two implications. The first is, activation control represents nearly a worst-case scenario for corrosion. The second is, fastener corrosion can be added quite easily to hygrothermal models because it represents an “on-off” criteria, and does not depend on the previous history of corrosion.

RELATIONSHIP BETWEEN MOISTURE CONTENT AND THE CORROSION RATE

The corrosion of embedded metals is strongly dependent upon moisture content. When the wood is dry, embedded metals do not corrode. The minimum moisture content (MC) at which embedded metals begin to corrode occurs between 15–18% MC (Baker 1987; Short and Dennis 1997). Above a certain moisture content, the corrosion rate plateaus at a constant value (Kear et al. 2009; Short and

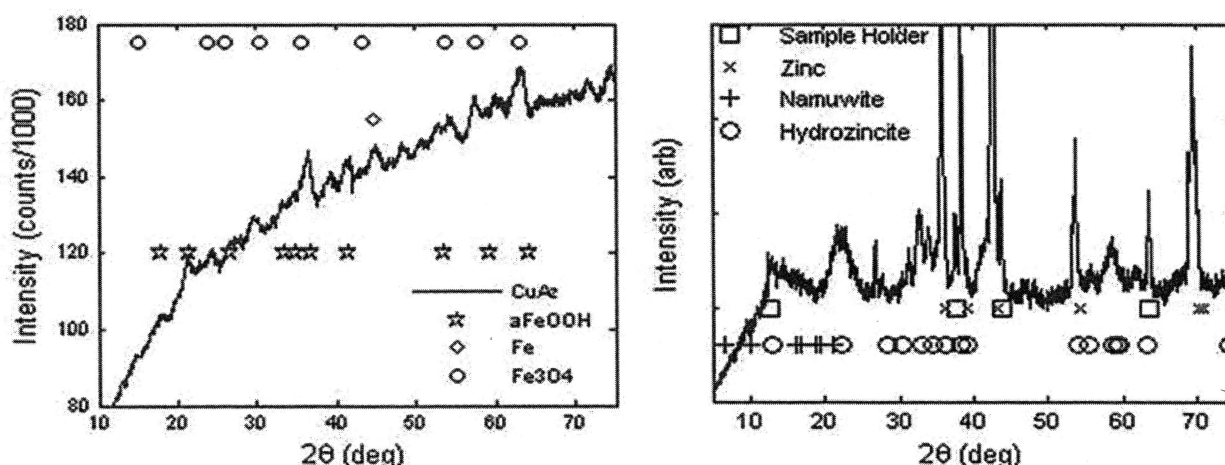


Figure 2 X-ray powder diffraction patterns from steel and galvanized steel exposed to wood treated with copper azole and micronized copper quaternary treated, respectively. Zelinka et al. (2010).

Dennis 1997). Using electrochemical corrosion measurements with solid wood as the electrolyte, Short and Dennis (1997) characterized the transition in corrosion rates as a function of moisture content and found the data had a sigmoidal shape. Their data of the corrosion current density (directly proportional to the corrosion rate) as a function of moisture content is shown in Figure 3. Surprisingly, the corrosion data exhibited a hysteresis, for which there is no known physical basis. Zelinka et al. (2011) recently fit the data, without hysteresis and scaled them so that the plateau corresponds with measured corrosion rates for hot-dip galvanized steel in ACQ-treated wood (Figure 4). It is known that the type of galvanization affects the corrosion rate (Zelinka and Rammer 2009; Baker 1992); in theory, it should be able to model these by scaling the data along the y-axis so that the plateau at the maximum moisture content occurs at the corrosion measured under saturated conditions. The data show the importance of controlling building moisture; the corrosion rate climbs from less than $1 \mu\text{m yr}^{-1}$ (0.04 mil) at 16% moisture content to more than $40 \mu\text{m yr}^{-1}$ (1.6 mil) at 26% MC. This is crucial because wood decay is not a concern until fiber saturation, and, while mold may be a concern in this range of MCs, it does not cause structure damage like decay or corrosion. Given the dependence of corrosion on the moisture content, the next logical step is to combine the corrosion rate data with hygrothermal models to predict fastener corrosion.

Using Hygrothermal Models to Predict Corrosion in Wood

Recently, Zelinka et al. (2011) combined the corrosion data in (Figure 4) with an existing, validated, two-dimensional

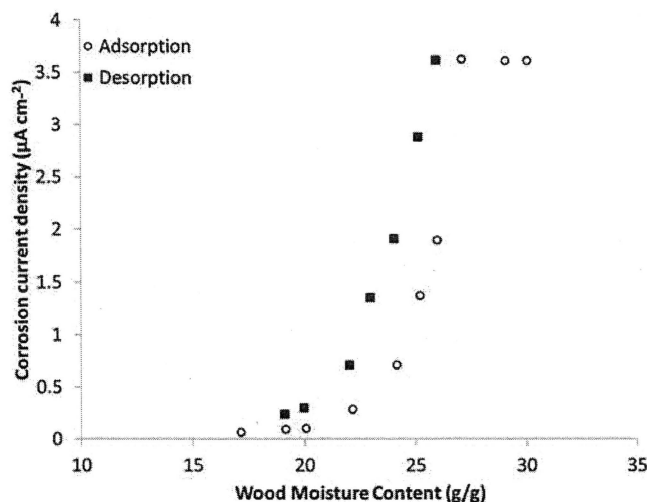


Figure 3 Corrosion current density, which is proportional to the corrosion rate, as a function of wood moisture content. Short and Dennis (1997).

finite element hygrothermal model (Janssen et al. 2007) to predict corrosion of embedded metals exposed to outdoor conditions. The geometry and boundary conditions were chosen to simulate a nail embedded in an exterior wood deck that was shaded (i.e. no solar radiation) but still received rain. Climatic data were obtained from the Solar and Meteorological Surface Observation Network (SAMSON) data set (NCDC 1993) and nine US cities were modeled with a reference year chosen based upon the number of hours with precipitation. The cities, information on the reference year, and the maximum amount of corrosion are shown in Table 1.

The corrosion model was coupled to the hygrothermal model by first calculating wood MC and temperature at the interface and then calculating the metal corrosion rate at each output time step (every hour) at each node along the wood-metal interface. The hourly corrosion rate was calculated from the data in Figure 4 and was assumed constant over the entire following hour. Although the detailed temperature dependence of corrosion is not known, an on/off condition was applied, setting the corrosion to zero if the wood was below freezing. The total amount of corrosion during the simulation was found by summing the hourly amounts.

Figure 5 plots the results of example simulations; the depth below the wood surface is the ordinate and the cumulative amount of corrosion is the abscissa. The shape of the curves is similar for each city and can be explained by the geometry and boundary conditions. During a rain event, the wood surface quickly saturates and corrosion begins; the depth of this corrosion region is dependent on the amount and duration of the rain event. Far below the surface the moisture content never climbs above the corrosion threshold. After the

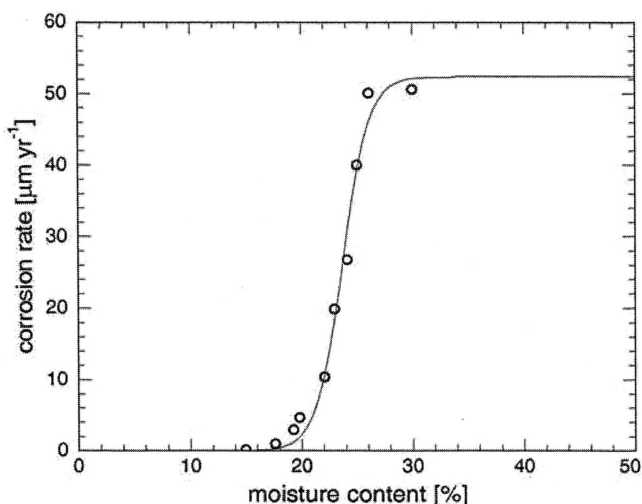


Figure 4 Corrosion model used in the hygrothermal simulations of Zelinka et al. (2012). The curve was generated by transforming the data in Figure 3 and scaling them so that the asymptotic corrosion rate corresponds with empirical data. Zelinka (2011).

Table 1. Cities, Reference Year Chosen, Pertinent Climatic Details, and the Maximum Amount of Corrosion as Determined in Hygrothermal Simulations

Zone	City	State	Year	Maximum predicted corrosion depth μm (mil)	Yearly		Total number of hours with	
					Mean Temperature $^{\circ}\text{C}$ ($^{\circ}\text{F}$)	Total Rainfall m (ft)	$T > 0^{\circ}\text{C}$ (32°F)	Rain
1	Hilo	HI	1990	45(1.8)	23.0 (73)	5.36 (17.5)	8760	2213
1	Miami	FL	1968	12(.47)	23.4 (74)	2.12 (6.96)	8760	588
2a	New Orleans	LA	1961	20(.79)	19.6 (67)	2.12 (6.96)	8715	593
2b	Phoenix	AZ	1978	5(.20)	23.3 (74)	0.39 (1.28)	8734	284
3a	Atlanta	GA	1975	17(.67)	15.9 (61)	1.68 (5.51)	8440	699
4a	Baltimore	MD	1989	16 (.63)	12.6 (55)	1.32 (4.33)	8127	794
4c	Seattle	WA	1971	26 (1.0)	10.1 (50)	1.10 (3.61)	8422	1205
5a	Chicago	IL	1983	11 (.43)	9.7 (49)	1.25 (4.10)	6691	739
6a	Minneapolis	MN	1983	12 (.47)	7.8 (46)	0.99 (3.25)	6217	731

Zelinka et al. (2011).

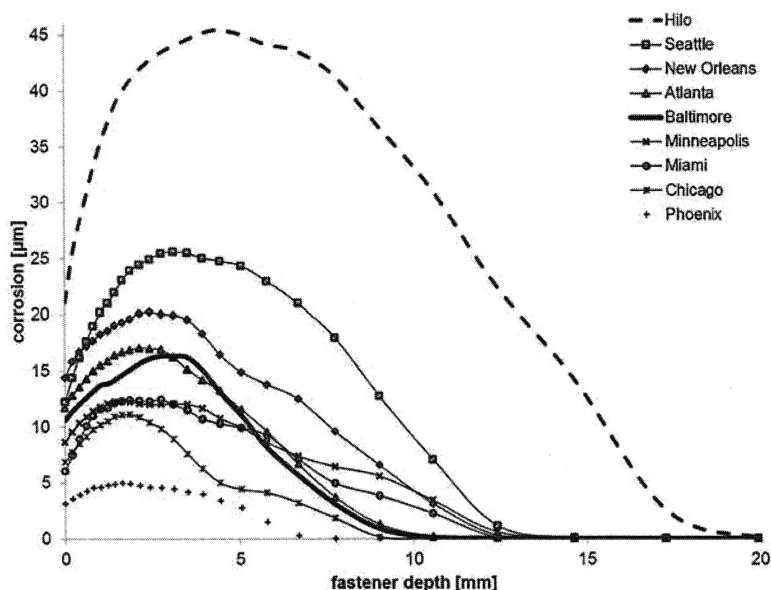


Figure 5 Example results for several cities in the US from the combined hygrothermal and corrosion model showing the amount of corrosion after one year as a function of depth below the wood surface. Zelinka et al. (2011).

rain stops, the wood begins to dry out from the surface. As a result, the region a few millimeters below the surface remains above the corrosion threshold for a longer time than the surface and this is where the maximum amount of corrosion is observed.

These simulations were included to show how hygrothermal models can be used to predict corrosion of embedded

metals in wood. However, the corrosion profile (Figure 5) and amount of corrosion will be completely different for wood used in buildings where the boundary conditions are different. In the preliminary development of the combined model, it was found that design reference years that were challenging for wall assemblies (such as Cornick et al. 2003; David et al. 2010; Salonvaara et al. 2010; Zhu et al. 1995; etc.) were not chal-

lenging for outdoor structures. Given that modeling is relatively inexpensive, it may make sense to massively model many different building assemblies in different climates to search for where fastener corrosion may be a concern in buildings.

THE EFFECT OF CORROSION ON THE STRUCTURAL CAPACITY OF THE JOINT

While the previous aspects of this paper have focused on how fast embedded metals corrode, what is ultimately important is whether corrosion affects structural soundness of the joint. Recently, Zelinka and Rammer (2012) combined yield theory with quantitative corrosion data to illustrate how corrosion affects the lateral strength of connections. The structural performance depends upon the joint geometry, fastener diameter, dowel bending yield strength, dowel-bearing strength, and direction of load to the grain. The effect of corrosion on lateral strength was analyzed using the yield theory expressions of Johansen (1949), which is now the standard method for connection design and is applicable to all types of dowel fasteners—nails, lag screws, and bolts.

The yield theory selects the worst case of yield modes based on different possibilities of wood bearing and nail bending. The lateral design load of a joint is determined by calculating the load for each failure mode and using the lowest calculated value. For a given joint geometry, wood species, and fastener bending yield stress, the equations depend only on the fastener diameter, which is a function of the corrosion rate.

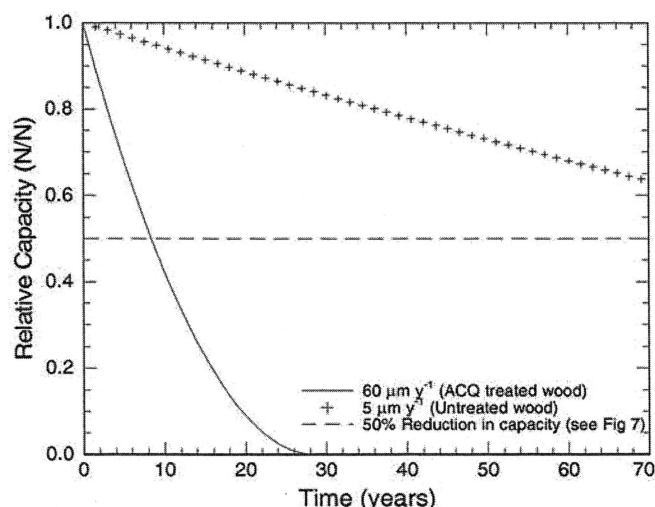


Figure 6 Reduction in capacity of an 8d galvanized decking nail exhibiting a Mode IV failure (wood bearing failure with two plastic hinges) for two different corrosion rates. Baker (1992).

Figures 6 and 7 illustrate how the relative capacity of a nailed joint decreases with time for several different corrosion rates. The figure was constructed for an 8d nail (length 63 mm [2.5 in.], $D = 3.4$ mm [0.13 in.]) exhibiting a Mode IV failure (side member greater than or equal to 21 mm (0.8 in.), a wood bearing failure where the fastener exhibits two plastic hinges). The corrosion rates were chosen to correspond to those measured for galvanized steel embedded in untreated wood ($5 \mu\text{m yr}^{-1}$ [0.2 mil]), and ACQ-treated wood ($60 \mu\text{m yr}^{-1}$ [2.4 mil]) exposed to humid conditions (Zelinka and Rammer 2009). For Mode IV failures, the yield strength is inversely related to the square of the diameter, which results in the lateral capacity decreasing rapidly with time as corrosion rate increases (Figure 6). If an arbitrary failure criteria were applied (for instance, 50% of the original capacity), then a time to failure can be calculated. Figure 7 graphically shows how changes in the corrosion rate, which may arise from fluctuations in moisture content or different treatment chemicals, affect this time to failure. It is important to note that measured corrosion rates are on the steepest part of this curve. Therefore, even small changes in the wood moisture content have can have potentially large effects in the service life of fasteners embedded in wood.

SUMMARY AND CONCLUSIONS

This paper was intended to introduce and summarize information on the corrosion of metals in wood for the building design community. Most of the research presented pertained to preservative-treated wood, although several of the trends, such as the kinetics as a function of time and the effect

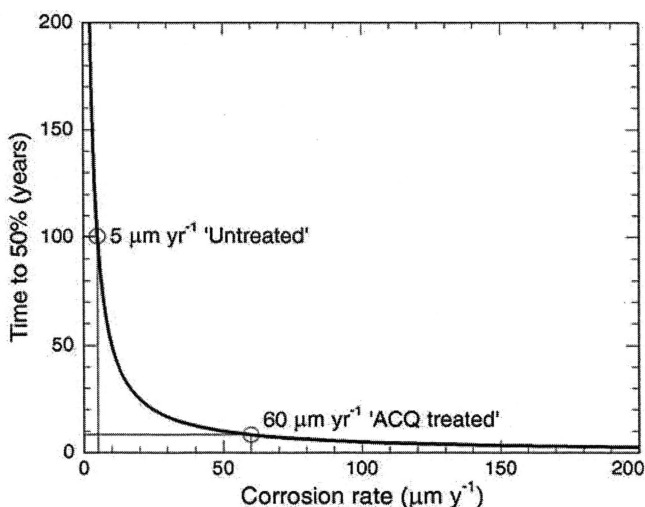


Figure 7 Illustration of how the “time to failure,” in this case arbitrarily set to 50% of the original strength of the joint, changes with corrosion rate for the 8d galvanized decking nail shown in Figure 6. The corrosion rates from Figure 6 are highlighted on the curve.

of moisture content on corrosion rate likely apply for fire-retardant treated wood as well. Many different examples were given for illustration, however the most important considerations for materials selection and design can be summarized in two, short phrases:

Corrosion in wood is not atmospheric corrosion: Corrosion in wood is different from atmospheric corrosion. There are different thermodynamics, different kinetics, and different corrosion products form. It is not safe to assume that just because a solution works for atmospheric corrosion that it is a good idea to apply it to fastener corrosion in wood.

Keep the wood moisture content below 18%: The corrosion of metals in wood is aqueous. The threshold moisture content at which moisture content occurs is between 15–18%, and the corrosion rate experiences a steep transition around 20% MC. The structural degradation of the joint depends strongly upon the corrosion rate, so even a few percent moisture content difference can make a large difference in the service life of the fasteners.

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DISCUSSION

Kelly Kissock, Professor, University of Dayton, Dayton,

OH: If galvanized nails corrode faster than steel nails, why use galvanized nails?

Samuel L. Zelinka: The corrosion rate is just one design consideration. When iron corrodes, it releases iron ions into the wood which break down the cellulose through a Fenton reaction and weakens the wood surrounding the nail (so called "nail sickness"). Zinc ions (from the corroded galvanized fasteners) do not break down cellulose.