Fastener Corrosion: A Result of Moisture Problems in the Building Envelope

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Abstract

This paper reviews recent literature on the corrosion of metals embedded in wood and highlights the link between moisture accumulation in wood and fastener corrosion. Mechanisms of fastener corrosion are described including dependence upon wood moisture content. These fundamental concepts are applied to practical examples by explaining how hygrothermal models can be used to predict fastener corrosion in wood and showing how fastener corrosion affects the strength of wood-metal connections. The goal of the paper is to familiarize professionals in the wood design community with corrosion.

Introduction to Corrosion of Embedded Metals

Metal fasteners embedded in wood are subject to corrosion from organic acids present in the wood. When present, fire-retardant or preservative treatments may increase the corrosiveness. Over the last 10 years, there has been an increased interest in fastener corrosion because of a shift in commercially available wood preservatives. In January 2004, chromated copper arsenate (CCA) was voluntarily withdrawn from service for residential applications and newer wood preservatives such as alkaline copper quaternary (ACQ) and copper azole (CA) were introduced. Several years later, so called “micronized” formulations were introduced to the market. In these formulations, soluble copper is not injected into the wood; rather solid copper, copper oxide, or copper carbonate is ground into submicron particles (“micronized”) and suspended in solution prior to injection. Not surprisingly, the newer wood preservatives have varying degrees of corrosivity, and the lack of previous data onthe wood preservatives has caused some confusion and concern regarding the durability of metal fasteners embedded in wood.

The wood preservatives mentioned above use copper as a biocide, and for these treatments the corrosion mechanism of embedded fasteners involves the reduction of cupric ions introduced by the wood preservatives. The role of cupric ions in the corrosion mechanism was first hypothesized by Baker (1988) and later confirmed by work of Zelinka (Zelinka et al. 2010; Zelinka and Stone 2011) and Kear (Kear et al. 2008; Kear et al. 2009) through energy dispersive x-ray analysis, Pourbaix diagrams, and examinations of the role of cupric ion concentration and acidity. Several studies have also shown that as the copper concentration increases, so does the corrosion rate of embedded fasteners (Kear et al. 2009; Zelinka and Rammer 2011). Table 1 summarizes the composition and required retention for several wood preservatives and highlights the differences in copper concentration. CCA has the lowest copper concentration of the preservatives listed in Table 1 and is also the least corrosive.

An important difference between the corrosion of fasteners embedded in wood and atmospheric corrosion involves passivation. Passivation refers to the process through which corroding metals form a protective oxide or hydroxide layer (patina). In atmospheric corrosion, the corrosion kinetics of steel and zinc are affected by passivation and the corrosion rate decreases with time (Legault and Preban 1975; Legault and Pearson 1978). However, for metals embedded in wood, the corrosion rate has been found in multiple studies to be constant with time (Baker 1992; Zelinka and Rammer 2009). Another difference between atmospheric corrosion and embedded metals involves the relative corrosion rates of different metals. In atmospheric corrosion, zinc forms a passivating zinc carbonate layer that greatly reduces the corrosion rate; however, Zelinka et al. (2010) have examined the corrosion products of steel and zinc fasten-

Table 1: Summary of Some Waterborne Wood Preservatives and Above Ground Retentions Highlighting the Difference in Copper Concentration Between Preservatives. Data are Combined from ((Anon 2007; Lebow 2010)).

Preservative	Composition	Above ground retention (kg of preservative per m^3 of wood)	Copper Concentration (g of copper per m^3 of wood)
CCA	47.5% chromium trioxide 34.0% arsenic pentoxide 18.5% copper as copper oxide	4	591
ACQ	67% copper as copper oxide 33%DDAC	4	2141
CA-B	96.1% amine copper as Cu 3.9% Tebuconazole	1.7	1634
CA-C	96.1% amine copper as Cu 1.95% Tebuconazole 1.95% Propiconazole	1.0	961
ESR-1721 (MCA-B)	96.1% amine copper as Cu 3.9% Tebuconazole	1.0	961
ESR-1721 (MCA-C)	96.1% amine copper as Cu 1.95% Tebuconazole 1.95% Propiconazole	0.8	769
ESR-1980	67% copper as copper oxide 33%DDAC	2.4	1285
ESR-2240	96.1% copper particles 3.9% Tebuconazole	1.0	961

ers and found that embedded fasteners do not form zinc carbonate. This difference in corrosion products is consistent with observations that zinc galvanized fasteners corrode more rapidly than steel fasteners when embedded in wood (Zelinka 2007; Zelinka et al. 2008; Zelinka and Rammer 2009; Zelinka et al. 2010).

Role of wood moisture content in corrosion

How fast metals corrode in wood depends upon the wood moisture content. There is a threshold moisture content between 15-18% MC below which embedded metals do not corrode (Baker 1988; Dennis et al. 1995; Short and Dennis 1997). Above this threshold, the corrosion rate increases rapidly with MC, and possibly plateaus above fiber saturation (Dennis et al. 1995; Short and Dennis 1997).

Despite the importance of moisture, there has been little work examining the effect of moisture content on the corrosion of embedded metals because of experimental limitations. Gravimetric tests are limited because they take six months to a year to complete and the wood moisture content needs to remain constant for the entire test. Previous gravimetric measurements have included at most 3 different moisture conditions, all of which were in the hygroscopic moisture content range (which could be achieved by adjusting the relative humidity) (Baechler 1939, 1949; Kear et al. 2009). The most thorough examination of the moisture content used electrochemical tests where a piece of metal was sandwiched between two pieces of wood (Dennis et al. 1995; Short and Dennis 1997). The data of Dennis et al. (1995) are shown in Figure 1 which plots the corrosion current density (proportional to corrosion rate) as a function of wood moisture content.

Zelinka et al. (2011) fit the electrochemical data in Figure 1 to a simple model and scaled it so that the maximum corresponded with corrosion rates measured for hot-dip galvanized steel in ACQ-treated wood (Figure 2). Figure 2 can be used to estimate the corrosion rate as a function of the wood moisture content for hot-dip galvanized steel in ACQ-treated wood. Since the corrosion rate does not change with exposure time, this equation can be used to estimate the instantaneous corrosion rate when the moisture content of the wood is fluctuating. Therefore, it can easily be combined with a hygrothermal (heat and moisture) model that predicts the wood moisture content from temperature and relative humidity data to assess the risk of corrosion in different building assemblies.

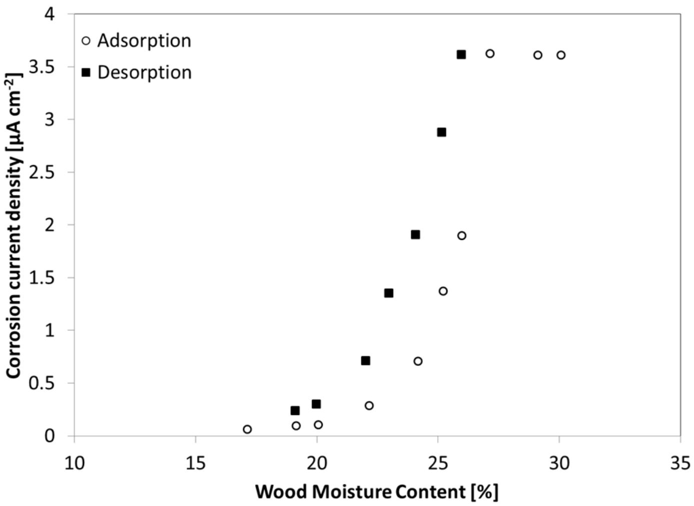

Figure 1: Corrosion Current Density of Galvanized Steel Sandwiched between CCA Treated Wood as Measured by Dennis et al. (1995).

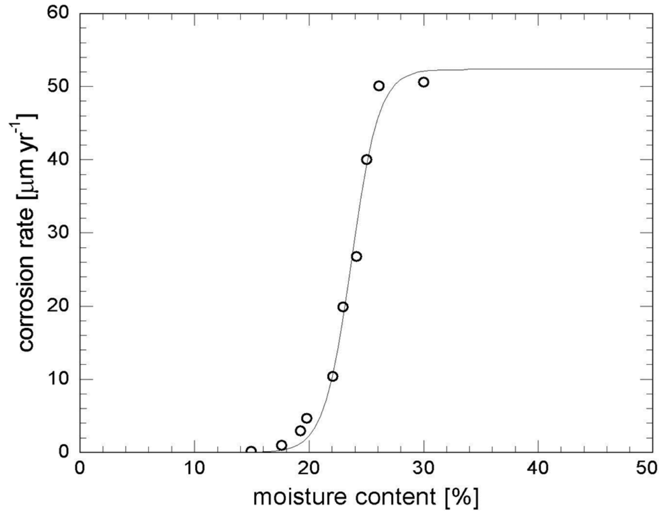

Figure 2: Dependence of the Corrosion Rate Upon the Wood Moisture Content Derived from the Data in Figure 1 and Corrosion Rates Measured by Zelinka et al. (2008) for Galvanized Steel in ACQ-Treated Wood.

Using Hygrothermal Models to Predict Corrosion

Recently, Zelinka et al. (2011) developed a post-processor that can be added to a hygrothermal model to predict corrosion of embedded metals. The corrosion post-processor was developed from the data in Figure 2 and relied upon the assumption that corrosion rate of embedded metals is constant with time as previous data suggest (Baker 1992; Zelinka and Rammer 2009). The two-dimensional finite element model took climatic data as inputs, calculated the wood temperature and moisture content hourly along the entire length of the fastener, and then calculated the instantaneous corrosion rate at each node from the wood moisture content. The instantaneous corrosion rate, which varied along the depth of the fastener, was multiplied by the time increment (an hour) to get the amount of corrosion that occurred during that time step. These hourly corrosion increments were then summed over the entire simulation to give the total depth of corrosion attack along the length of the fastener.

An example of the results of a combined hygrothermal-corrosion simulation is shown in Figure 3 and came from a 2D simulation of a hot-dip galvanized decking nail in ACQ-treated wood. The top surface of the wood was exposed to the full climatic conditions (including precipitation) and the sides and bottoms were exposed to changes in temperature and relative humidity only. The maximum amount of corrosion in the simulations occurred in the first centimeter below the surface of the fastener as this region of the wood remains the wettest for the longest period of time.

The combined hygrothermal-corrosion model is a tool that can be used to design more durable buildings and structures. Currently, the corrosion data are limited to hot-dip galvanized steel in ACQ-treated wood, although current research is underway to make the corrosion postprocessor more adaptable to various treatments and metal types. While the example simulation (Figure 3) showed how corrosion occurred in an outdoor structure, the combined hygrothermal-corrosion model can also be used to model building assemblies and find potential problem spots within the building envelope.

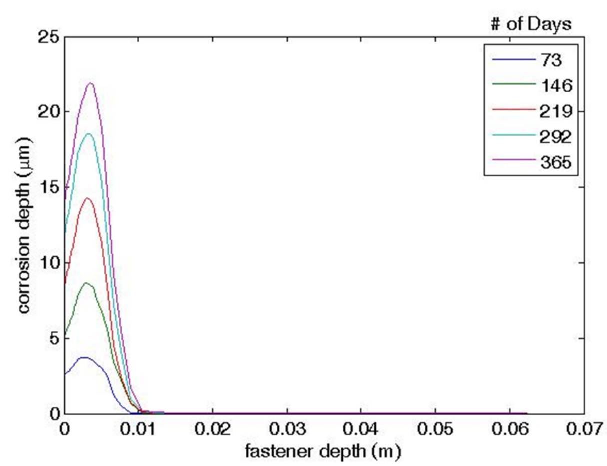

Figure 3: Example Result of a Combined Hygrothermal Corrosion Model Showing the Depth of Corrosion Attack as a Function of the Fastener Depth. The Simulation of a Decking Nail Embedded in ACQ-Treated Wood and Exposed Outdoors Used Climatic Data Collected in Baltimore From 1989.

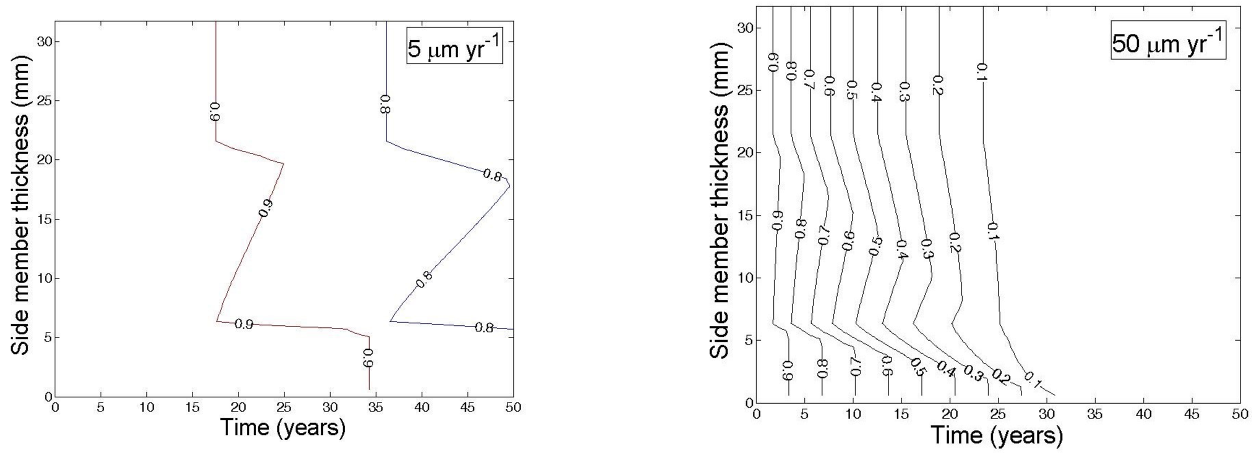

Figure 4: Reduction in Lateral Joint Strength (Contours) for an 8d Nail as a Function of the Joint Geometry and Exposure for Two Different Corrosion Rates. Each Contour Represents a 10% Reduction in Capacity.

Reduction in Mechanical Strength Caused by Corrosion

Most of the research on the corrosion of metals embedded in wood has focused on determining the corrosion rate; however, the magnitude of the corrosion rate is in some ways less important than how the corrosion affects the mechanical property of the joint. Zelinka and Rammer (2012) have used yield theory to examine how corrosion reduces the lateral strength of connections. The fastener connection performance can be calculated by the yield theory developed by Johansen (1949) which treats both the wood and metal as elastic/perfectly plastic materials. The lateral design load, Z (in N), is determined by

$$Z = \min \begin{cases} \dfrac{DT_s F_{es}}{2.2} & (\text{Mode I}_s) \\ \dfrac{k_2 D l_p F_{em}}{2.2(1+2R_e)} & (\text{Mode III}_m) \\ \dfrac{k_3 D T_s F_{em}}{2.2(2+R_e)} & (\text{Mode III}_s) \\ \dfrac{D^2}{2.2}\sqrt{\dfrac{2F_{em}F_{yb}}{3(1+R_e)}} & (\text{Mode IV}) \end{cases} \qquad (1)$$

where

$$k_2 = -1 + \sqrt{2(1+R_e) + \frac{2F_{yb}(1+2R_e)D^2}{3F_{em}l_p^2}}$$
$$k_3 = -1 + \sqrt{\frac{2(1+R_e)}{R_e} + \frac{2F_{yb}(2+R_e)D^2}{3F_{em}T_s^2}}$$
and
$$R_e = F_{em}/F_{es} \qquad (2)$$

where D is the dowel diameter (mm) $F_{e\_}$ is the dowel bearing stress of the main ($_m$) or side ($_s$) member (MPa), F_{yb} is the bending yield stress of the nail (MPa), l_p is the length of penetration in to main member, and t_s is the thickness of the side member. Since corrosion does not affect the joint geometry, wood dowel bearing stress, or the bending yield stress of the uncorroded fastener, the design load becomes a function of fastener diameter only. If it is assumed that the corrosion products are not structural, then the effect of corrosion can be treated as a reduction in fastener diameter calculated from the corrosion rate.

Figure 4 is a graph of the lateral strength of a connection with an 8d nail (3.4 mm diameter) as a function of joint geometry and time for two different corrosion rates. Each contour in Figure 4 represents a 10% reduction in capacity. The kinks in the contours represent the geometry at which the failure mode changes. From Eq. (1) it can be seen that the Mode IV failure represents a worst case scenario. Figure 5 shows the reduction in capacity as a function of time for many different corrosion rates based upon a Mode IV failure. It can be seen that reduction in capacity of fasteners drops extremely quickly over the range of measured corrosion rates in wood (2-113 micron per year).

Summary

This paper presented a brief overview of the corrosion of metals embedded in wood. Importantly, the corrosion of embedded metals has a different mechanism than atmospheric corrosion. The difference in mechanism explains the relative corrosion rates of steel and galvanized steel observed in wood and also the observation that the corrosion kinetics remain constant with time. The corrosion rate depends strongly on the wood moisture content.

Below 15-18% MC, metals do not corrode; however, once this threshold is crossed, the corrosion rate rapidly increases. This is important as the residual capacity of the joint decreases rapidly with increasing corrosion rate. Finally, a combined hygrothermal and corrosion model was illustrated that predicts the amount of corrosion that will occur in building assemblies. This tool may also be used to determine whether the conditions may warrant selecting a more expensive (corrosion resistant) fastener.

In addition, the following best practices can be used to minimize corrosion of metals in contact with treated wood:

- Keep the wood moisture content below 18%.
- Do not combine dissimilar metals (for example, using a galvanized fastener with a stainless steel joist hanger). This will result in accelerated corrosion.
- When using metals that are protected by paints or other non-metallic coatings, do not damage the coating during installation.

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