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A Study on Laboratory Corrosion to a Corrosion Lifetime for Wood Fasteners

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Abstract:

Determining a "corrosion-lifetime" for fasteners embedded in wood treated with recently adopted preservative systems depends upon successfully relating results of laboratory tests to in-service conditions. In contrast to laboratory tests where metal is embedded in wood at constant temperature and moisture content, the in-service temperature and moisture content of wood exhibit large fluctuations which affect the corrosion rate. The paper presents an approach for determining the corrosion lifetime of fasteners in which the calculated wood moisture content at the wood-fastener interface is used to predict the corrosion rate as a function of time through coupling two models. First, the moisture content across the wood component is calculated using a finite element code solving the coupled heat and mass transport equations with climatic data used as boundary conditions. Secondly, at the wood-fastener interface, the instantaneous corrosion rates are computed using an empirical corrosion model and integrated with time.

Keywords **-** *Corrosion, hygrothermal modeling, preservative treated wood*

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I. INTRODUCTION

One aspect of the durability of treated wood structures is the lifetime of metallic fasteners. Their corrosion rate depends on the moisture and temperature conditions on the metallic surface, which vary considerably Our corrosion model draws upon recent experimental work by which chromated copper arsenate (CCA) was replaced by alternatives such as alkaline copper quaternary (ACQ) and copper Azole (CuAz) for residential applications (Lebow, 2004). Evidence suggested that the alternative wood preservatives might be more corrosive to metal fasteners embedded in the wood than CCA (Burkholder, 2004; anon, 2008). From a practical perspective, this practical need motivated fundamental research with the ultimate goal of predicting the corrosion lifetime for metallic fasteners in treated wood. As a result, many tests were conducted to measure corrosion rates in wood treated with CCA alternatives. The corrosiveness of CuAz and ACQ has been evaluated by several different test methods. Most of the previous research has used the American Wood Protection Association AWPA E-12 standard, which places metal coupons between blocks of wood and subjects them to a high temperature (49°C) environment at 90% relative humidity (RH) for at least 240 hours (Freeman & McIntyre, 2008; Kear et al., 2009). Kear et al., (2009) exposed fasteners embedded in treated wood to 21°C at 3 different relative humidities ranging from 75% to 98% RH for 1 year. Zelinka and Rammer (2009) embedded fasteners in blocks of treated wood exposing them to 27°C and 100% RH for one year. In a novel test procedure, electrochemical tests in a water-extract of treated wood were found to have the same corrosion rates as those measured at the 27°C 100% RH condition (Zelinka et al., 2008). These tests show that ACQ and CuAz are more corrosive than CCA. It is widely known that the corrosion rate of metals in contact with wood depends strongly on the wood moisture content (MC). Below 15%-18% MC, embedded metals do not corrode (Baker, 1987; Short & Dennis, 1997). Above this threshold, the corrosion rate increases with increasing moisture content before eventually reaching a plateau (Kear et al., 2009; Short & Dennis, 1997). Therefore, it is necessary to know the moisture contents of exposed wood structures when predicting a corrosion lifetime. Recent reviews of studies that examined the in-service moisture content of wood decks have shown that wood used in exterior applications experiences large variations in moisture content (from 8% to 80%) depending on the environmental conditions (Lebow & Lebow, 2007; Glass & TenWolde, 2007). These changes in the wood moisture content affect the corrosion rate at the wood-fastener interface; therefore a steady-state approximation of the corrosion rate is not able to capture these changes and predict a corrosion lifetime. We use here an existing heat and moisture transport model (Janssen et al. 2007) to calculate conditions at the wood-fastener interface using a complete set of climatic data as boundary conditions which includes air temperature and relative humidity, solar radiation, cloud cover, rain precipitation and wind conditions. The coupling of the models is implemented by inputting the moisture content at the wood-fastener interface into a corrosion rate model that is dependent on MC. This paper presents preliminary work combining the corrosion and hygrothermal models, implemented on a simplified geometry.

II. MODEL DEVELOPMENT

A. *Geometry of the physical problem*

We examine here the corrosion of the fasteners. The nails or screws must be made of hot-dip galvanized steel, stainless steel, silicon bronze, or copper and two fasteners must be used at each joist. The guide states that decking material should be made of dimension lumber 38 mm thick (nominal 2 inch thickness) and that the deck boards should be spaced approximately 3.2 mm apart, although the width of the deck board is not specified. Similarly, the joists must also be made of dimension lumber 38 mm thick and at least 190 mm in width. The guide allows a variety of species to be used. In this modelling, several simplifications are made to the configuration. The modelled geometry as well as the mesh are shown in Figure 1**.** The first simplification is that in the model, the fastener is embedded in a single wooden beam, which can be thought of as a joist with the deck board removed. The second simplification is that the problem can be treated two-dimensionally, which is equivalent to assuming that the fastener is in the middle of an infinitely long beam. Thirdly, the fastener geometry is modelled as a smooth cylinder, instead of an annularly or helically threaded fastener. Symmetry considerations were used so that only half of the width needed to be modelled. The two dimensional mesh is 20 by 90 mm and consisted of 1965 elements and 2064 nodes. The fastener width was taken as 3.2 mm based on the width of a smooth 8d fastener. Heat and moisture transport through the fastener was not modelled; instead, the fastener was represented in the model by a "no-flow" boundary condition.

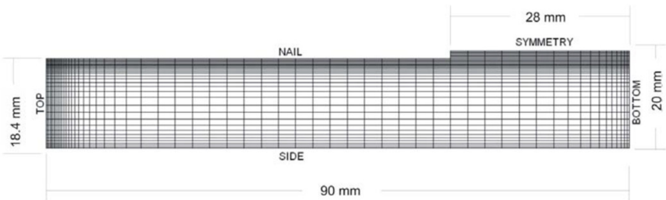

Figure 1: Mesh used for the hygrothermal model. Boundary conditions are explained in the Heat and Mass Transport Modelling section. The geometry describes one half of a "2 by 4" (38 mm by 90 mm) beam with an 8d nail, which is not included in the mesh

B. *Corrosion Modelling*

Short and Dennis used electrochemical techniques to measure the corrosion rate of zinc as a function of moisture content (Short & Dennis, 1997). They placed a small strip of CCA treated wood between the stainless steel counter electrode and the zinc working electrode. Two more pieces of wood were placed on the outside of the working and counter electrodes to create a "sandwich". The wood moisture content was adjusted by placing the assembly in various conditioning chambers and the corrosion rate was measured using polarization resistance. Short and Dennis found a sigmoidal dependence of the corrosion rate on moisture content: below 15% moisture content, there was no corrosion and above 27% moisture content, the corrosion rate was constant at its maximum value. Their data for the corrosion rate (R) as a function of the perecent moisture content, w (the ratio of the mass of water to the mass of ovendry wood). can be described by-

$$R = \frac{A}{1+e^{C-Bw}} \quad \text{...........(1)}$$

Where A, B and C are fitting parameters. The parameters B (0.835) and C (19.8) are taken from a curve fit of the published data of Short and Dennis (Short & Dennis, 1997). The parameter A, which is physically the asymptotic corrosion limit, is taken as 52.3 μm yr^{-1} from recent electrochemical measurements of hot-dip galvanized steel in an extract of ACQ treated southern pine (Zelinka et al., 2008). A graph of the corrosion rate as a function of moisture content is shown in Figure 2. It is noteworthy that no temperature dependence is included in the model at this stage; a further discussion of this is included in the "Future Work" section.

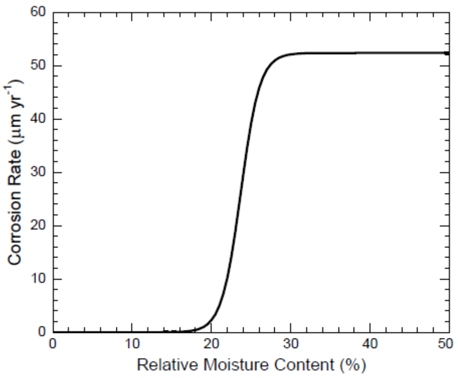

Figure 2: Corrosion model used in this study derived from (Zelinka et al., 2008) and (Short & Dennis, 1997).

C. Heat and Moisture Transport Modelling

The heat and moisture transport is calculated with a finite element code which uses capillary pressure as the driving potential for moisture transport and temperature for heat transport (Janssen et al., 2007). The model can handle the full range of moisture content of wood from dry to capillary saturation as it includes liquid transport. The non-linearity as well as the temperature and moisture content dependence of the material properties are implemented. In terms of boundary conditions, full atmospheric boundary conditions including air temperature and relative humidity, rain, wind, short-wave and long-wave solar radiation are applied on the top surface. On the "side" and "bottom" surfaces (Figure 1), only the air temperature and relative humidity are accounted for; the heat and mass transfer coefficients were taken as constant on these surfaces. The climatic data file comes from the hourly weather data collected at the Dane County Regional Airport (Madison, WI) from calendar year 2009. The solar radiation values were calculated from the model of Kittler (1981). The simulation is run from October 1 until September 30 to avoid having the simulation start in the middle of a season. The total precipitation is 1.106 m with maximum rainfall intensity of 51mm hr^{-1}. The temperature and moisture content of the wood at each node are written to an output file at one hour intervals.

D. Material Properties

The accuracy, to which the hygrothermal model can predict the wood moisture content, and thus the corrosion rate, is dependent on appropriately determined material properties. The model requires a full moisture retention curve over both the hygroscopic (sorption isotherm) and over-hygroscopic regimes. Furthermore, the vapour and liquid water conductivities are needed. There are few published measurements on the hygrothermal properties of treated southern pine. Sorption isotherms of preservative-treated and untreated southern pine have recently been published (Zelinka & Glass, 2010) and there were only small differences between the isotherms of ACQ, CCA, and untreated southern pine. Two other papers have collected sorption isotherms of treated southern pine (Cao & Kamdem, 2004; Shupe et al., 2001). However, none of the papers have examined the vapour permeability of treated wood or characterized its over-hygroscopic regime. In the present work, the material properties have come from work on untreated Scots pine (*Pinus sylvestris*) (Zillig et al., 2006). While it is likely that there are differences in the hygrothermal properties of Scots pine and the southern pines, the data were chosen because of the quality and completeness of the data and because the data are from the same genus as the species group of interest. The moisture retention curve is shown in Figure 3. Volumetric moisture content, in kg m^{-3}, was based upon dry volume and this analysis thus ignores swelling and shrinkage. The liquid, vapour, and total permeabilities were taken from measurements in the tangential direction, and utilized the diffusivity approach presented by Carmeliet et al., (2007).

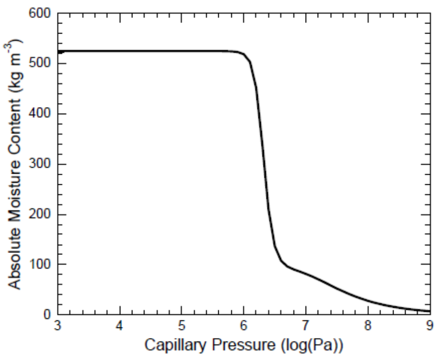

Figure 3: Moisture retention curve used in the hygrothermal model based on measurements from (Zillig et al., 2006).

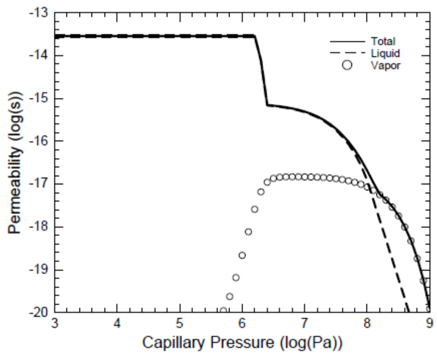

Figure 4: Liquid, vapor, and total permeabilities used in the hygrothermal model based on measurements from (Zillig et al. 2006) and the approach of (Carmeliet et al. 2007). The transition between 10^6 and 10^7 Pa corresponds to roughly 95% RH.

The permeability as a function of capillary pressure is given in Figure 4. Heat capacities and thermal conductivity values for loblolly pine (*Pinus taeda*) were taken from the Wood Handbook (Glass & Zelinka, 2010). The effect of temperature and wood moisture content on the heat capacity and thermal conductivity was ignored in this analysis.

III. COUPLING MODELS

Modelling the corrosion of fasteners in treated wood involves two steps; first, calculating the wood moisture content, and secondly, calculating the metal corrosion rate, which is dependent on this moisture content. We calculate the corrosion rate at each output time step (every hour) at each node along the wood-metal interface from Eq (1) and the wood moisture content. We assume the corrosion rate to be constant over the entire hour and independent of temperature. The total amount of corrosion is found by summing the hourly amounts.

IV. DISCUSSION

The cumulative corrosion along the length of the fastener after a one year simulation is shown in Figure 5. The corrosion was non-uniform along the fastener depth resulting from the non-uniform moisture contents. The maximum corrosion occurred approximately 2.5 mm below the surface which can be explained by the competing wetting and drying processes. After a rain event, the surface of the wood has the highest moisture content but is also the first to dry following the rain event because of wind and solar radiation. Practically no corrosion occurred at fastener depths greater than 15 mm; the calculated corrosion rates in this region did not change with time, which suggests that the wood moisture content in this region only experienced small changes within the first year and remained below the corrosion threshold.

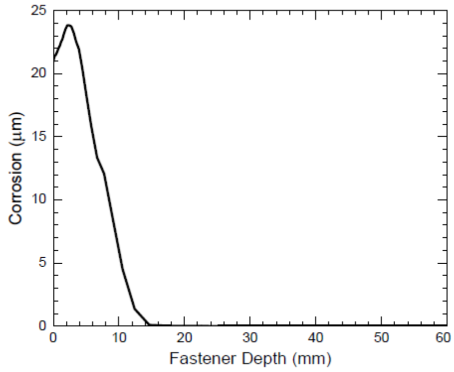

Figure 5: Corrosion rate as a function of depth for the "baseline" case.

➢ **Sensitivity Study: -** An analysis was conducted to examine the effects of several of the parameters in the model on the corrosion rate. Parameters were examined by running a 1-year simulation with the parameter in a "low" state, in which the parameter was halved, or a "high" state where the parameter was doubled. The parameters tested were: starting moisture content, heat capacity, thermal conductivity, solar radiation, and rainfall. The thermal properties were examined in particular since they were assumed to be independent of temperature and moisture content in all simulations. The solar radiation and rainfall were varied by multiplying the hourly values by 0.5 or 2, which changed both the intensity and total annual amount. An additional examination of rainfall was made by changing the climate file so that each rain event was half of the intensity of the baseline but had twice the duration. This simulation had the same annual rainfall as the baseline simulation but two times the number of hours during which precipitation occurred. The mesh sensitivity was examined by running a mesh with roughly half the number of elements (903 instead of 1965). Figure 6a gives the corrosion depth profile for several of the simulations from the sensitivity study. The maximum depth shown has been reduced to 10 mm so that y-axis could be scaled to highlight differences. Data from the simulations on heat capacity, mesh, and starting moisture content are not shown as they are too similar to the baseline case to be differentiated clearly at this scale. The differences due to changing thermal conductivity and solar radiation highlight the importance of solar drying on the top surface of the beam. The baseline value of 0.11 W m^{-1} K^{-1} corresponds to dry wood (0% MC) at room temperature. At a value of 25% MC the thermal conductivity would increase to about 0.17 W m^{-1} K^{-1} (a 55% increase). Given that a 100% increase in the thermal conductivity caused a 7% change in the maximum corrosion rate, it appears that the results could be improved slightly by implementing the dependence of moisture on the thermal conductivity.

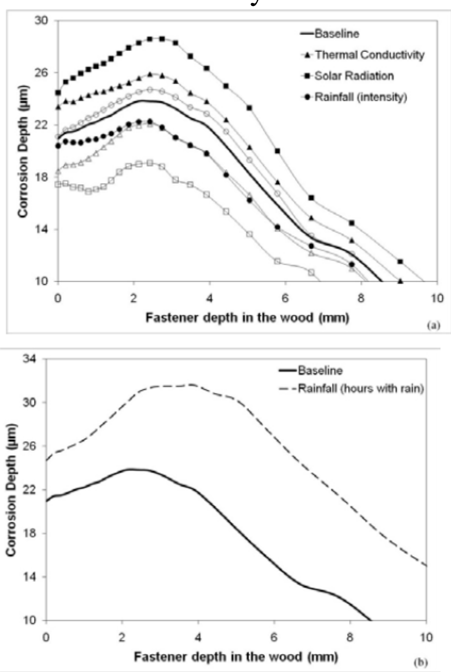

Figure 6(a): Selected results of the sensitivity study. The filled shapes represent scaling the parameter by a factor of 0.5 and the open shapes by a factor of 2. 6(b): Comparison of the baseline to the simulation in which the number of hours of rainfall was doubled (note the difference in scale).

V. CONCLUSIONS

This paper presents a preliminary modelling investigation coupling a heat and mass transport model and a corrosion model to assess the corrosion of fasteners embedded in wood. Using this model, the corrosion profile after one year of exposure was simulated for a steel nail embedded in ACQ wood. The maximum amount of corrosion occurred between 2 and 4 mm below the wood surface. Practically no corrosion occurred at depths greater than 15 mm below the surface. This corrosion profile was calculated from a corrosion rate that depends only on moisture content, and therefore the differences in corrosion with depth result only from the wood moisture content profile. An initial sensitivity study showed that the amount of corrosion was most sensitive to the number of hours of rain. The amount of corrosion was not sensitive to the starting moisture content (below 20%) or the heat capacity of the wood. Future work will focus on including the temperature dependence of the corrosion rate, including heat transfer through the fastener, and using material properties measured in treated southern pine.

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