Comparing the Methodologies in ASTM G198 Using Combined Hygrothermal-Corrosion Modeling

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ABSTRACT

ASTM G198, "Standard test method for determining the relative corrosion performance of driven fasteners in contact with treated wood," was accepted by consensus and published in 2011. The method has two different exposure conditions for determining fastener corrosion performance in treated wood. The first method places the wood and embedded fasteners in a chamber at 95% relative humidity (RH), 32°C, for 120 days. The second method involves a cyclic fog, with 48 h of fog followed by 72 h of dry for 120 days. The corrosion rate of embedded metals is an extremely sensitive function of the wood moisture content. While the wood moisture content is well defined, and fixed, in the constant RH test, the moisture content fluctuates and there are moisture gradients in the cyclic fog test. As a result, the fasteners in the cyclic fog test experience non-uniform and constantly changing conditions, which may be more or less challenging than the steady-state test. This paper presents the results from a combined hygrothermal/corrosion model to explore how the moisture content and temperature at the fastener interface differs between these two methods and shows how these differences in moisture content affect corrosion.

KEY WORDS: ASTM G198, corrosion, hygrothermal modeling, preservative treated wood

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INTRODUCTION

Waterborne wood preservatives are added to wood used in outdoor residential construction to protect the wood from termites and decay fungi. Almost all commercially available waterborne preservatives contain copper and/or cupric ions in addition to other biocides. In January 2004, there was a change in how wood preservatives were regulated, and many new wood preservatives were introduced to the market.[1] Shortly afterward, corrosion of fasteners in wood treated with new preservatives became a concern as corrosion failures began to be observed in service. While it was widely understood that corrosion of embedded fasteners was an important consideration for wood preservatives, rapidly quantifying differences in corrosiveness between wood preservatives presented many challenges, not the least of which was that the mechanism of corrosion in treated wood was poorly understood at that time. Many different methods, involving high temperature, high humidity, and/or salt spray were used to rapidly quantify the corrosion of metals in treated wood, though there was little consistency between the different methods.[2] Because it was possible to manipulate the test to achieve the desired results, there was a need to develop a standardized test method for corrosion of fasteners embedded in wood.

When the regulations were changed in 2004, there was already one standard, American Wood Protection Association (AWPA) E12, for measuring the corrosion of metals in wood.[3] The AWPA E12 standard

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specifies that sheets of metal be sandwiched between two blocks of treated wood that are held together by nylon bolts. These assemblies are then placed at 49°C and 90% relative humidity (RH), which corresponds to approximately 19% moisture content (MC) for 240 h.[4]

Despite being the only standard on corrosion of metals in wood, there were many complaints against the method at industry meetings and tasks groups. It was not clear how the test could be related to embedded fasteners since the "sandwich" allowed water and oxygen to approach the metal from the outside. The applicability was also questionable because of the high temperature used in the test. While the intent of the high temperature was surely to accelerate the corrosion, at a given humidity, temperature and moisture content are inversely related, so the wood is actually at a lower moisture content than it would be at room temperature, and moisture content is a major driver of corrosion of metals in wood. Besides concerns about its relation to embedded fasteners, the wood and fastener industries also had concerns about inconsistencies in the method. Lacking a suitable standardized method, AWPA formed subcommittee G01.14.01, "Corrosion of Metals in Treated Lumber," in September 2005 to develop a test method for measuring the corrosion of fasteners in wood. The starting point for the proposed method was based on test methods developed by the International Staple, Nail, and Tool Association[(1)] (ISANTA). After six years, and many negative ballots, the committee produced standard ASTM G198 in 2011.[5] Through the balloting process, the standard ended up with two parallel methods to evaluate corrosion of fasteners in wood: a steady-state test where fasteners are held in a constant temperature (32°C), a constant humidity (95% RH) environment, and a cyclic-fog test, where fasteners are exposed to a liquid water fog for 48 h and then allowed to dry for 72 h to 120 h. The reason for including the cyclic fog test is that for atmospheric exposures, it is well known that galvanized steel performs better when it goes through wet and dry cycles, and that in real, outdoor exposures, the wood will surely go through wet and dry cycles.[6] However, it has recently been shown that the corrosion of metals in wood undergoes a completely different mechanism than atmospheric corrosion.[7] The fasteners form corrosion products not normally seen in atmospheric conditions, and the corrosion kinetics for galvanized steel do not decrease with time like they do in atmospheric conditions.[8-10] Furthermore, the reasoning for including the cyclic fog test ignores the fact that wood holds moisture and therefore acts as a moisture buffer; that is, even after it stops raining, the wood near the fastener remains wet for much longer.[11]

While the mechanism of corrosion in treated wood is not fully understood, what is known is that the corrosion rate depends upon the wood moisture content, exhibiting nearly a Heaviside function centered around 24% MC.[12] The two methods in ASTM G198 will give different moisture contents and, therefore, different corrosion rates. In the steady-state test, the moisture content is well-defined and constant throughout the test; uniform corrosion has been observed in these tests under similar conditions.[8,10,13] However, in the cyclic fog test the moisture content at the fastener interface is different along the entire length of the fastener and constantly changing throughout the test. It is not clear whether the moisture content, on average, is more or less than in the steady-state test; it depends upon how fast the capillary uptake of liquid water occurs and how rapidly the water redistributes itself. Furthermore, the moisture content profile cannot easily be measured because traditional measurements of moisture content spatially average over at least a length scale of several centimeters.

Since the differences in moisture content between the two methods cannot easily be attacked experimentally, it makes sense to use computer modeling. By solving the partial differential equations governing heat and mass transport, the changes in moisture content caused by the cyclic fog conditions can be calculated and the resulting amount of corrosion can be determined. We have recently combined a validated finite element hygrothermal model[14] with a corrosion model to predict the corrosion of metals in wood exposed to different climates.[12] In this paper, this same methodology was used to compare the two methods in ASTM G198 by simulating a hot-dip galvanized fastener embedded in alkaline copper quaternary (ACQ)-treated wood. The goals of the paper were to compare the two methodologies in ASTM G198 and to examine the sensitivity of the corrosion to variations in the test conditions allowed by the tolerances given in the standard.

EXPERIMENTAL PROCEDURES

Combined Hygrothermal and Corrosion Model

This analysis uses a recently developed combined hygrothermal/corrosion model that calculates corrosion along the depth of fasteners embedded in wood.[12] Pertinent details of the model are detailed in the "Corrosion Model" section. For more complete information, the reader is directed to Reference 12. The hygrothermal model utilizes an existing, validated finite element code to solve the coupled heat and mass-transport equations using hourly climatic data as an input,[14] and outputs the wood temperature moisture content next to the fastener at each time step. Importantly, the model is able to handle both liquid water and water vapor transport. The wood temperature and moisture content are used as inputs into the corrosion model.

(1) The International Staple, Nail, and Tool Association (ISANTA), 512 W. Burlington Ave., Suite 203, La Grange, IL 60525-2245.

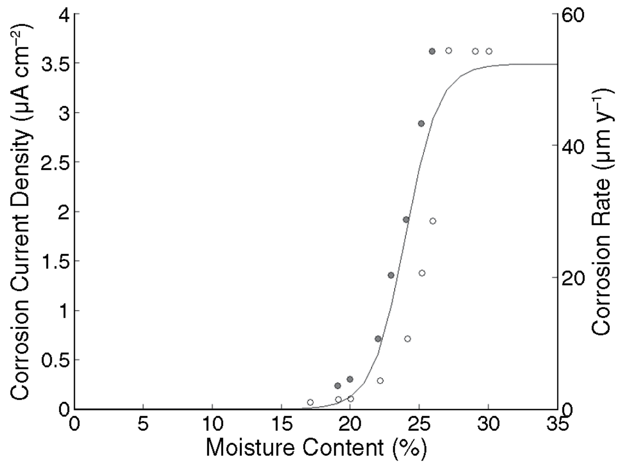

FIGURE 1. *Left axis: Corrosion current density as a function of moisture content (symbols) collected by Short and Dennis.[16] The filled symbols were collected from desorption conditions. Right axis: Model used in the simulations based upon the corrosion current density and the corrosion rate of galvanized steel in water extracts of treated wood (line).*

Corrosion Model

It is known that the corrosion of metals in wood is dominated by the wood moisture content; below 15% to 18% moisture content, embedded metals do not corrode.[15] There has been little work on how the corrosion rate depends upon moisture content above the threshold because of experimental limitations. The most comprehensive data, collected by Short and Dennis, used polarization resistance measurements to examine the effect of moisture content on the corrosion rate of galvanized steel embedded in chromated copper arsenate (CCA)-treated wood.[16] Short and Dennis found that the corrosion current density exhibited a sigmoidal transition from no corrosion at 18% MC to a plateau at a maximum corrosion rate at approximately 30% MC.[16]

The measurements of Short and Dennis were used to construct the corrosion model; their measurements of the corrosion current density of galvanized steel in contact with treated wood as a function of wood moisture content are shown in Figure 1. The corrosion post processor was developed by fitting the corrosion current density data to:

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

and adjusting the parameter A, which physically represents the asymptotic corrosion rate so that it was equal to corrosion rates measured for galvanized steel in water-extracts of ACQ-treated wood.[17] This condition was chosen as an appropriate maximum since the water extract clearly represents a maximum in moisture content, and corrosion rates measured in water extracts have been shown to be statistically indistinguishable from those measured in wood conditioned at 100% RH.[17] The corrosion post-processor is shown in Figure 1 on the right y axis. The resulting simulations are based upon this equation and, therefore, represent hot-dip-galvanized steel in ACQ-treated wood. At this stage, the calculated corrosion rate is independent of temperature since there have been no studies on the effect of temperature on the corrosion rate of embedded metals.

Unlike atmospheric corrosion, where passivation oftentimes decreases the corrosion rate with time, the corrosion rate of metals embedded in wood has been found to be constant with time in tests that examined 10 different metal alloys, five wood preservative treatments, and two environmental conditions.[9-10] This is an important finding and is an implicit assumption that is the key to implementing the simulations, since it means that corrosion does not depend upon the previous history and can be calculated the same way at every time step.

The simulations involve the following steps:

—The wood moisture content and temperature are calculated at each hour of the ASTM G198 test from the climatic conditions specified in the standard.

—Equation (1) is applied to each node to give the hourly corrosion rate, and is multiplied by the length of the time step (1 h) to give the amount of corrosion that happened in that time step.

—These hourly corrosion amounts are then summed over the whole simulation to give the total amount of corrosion along the depth of the fastener.

Geometry of the Simulation

While heat and moisture transfer in wood is a three-dimensional (3D) problem, potentially requiring a 3D hygrothermal simulation, the nature of the ASTM G198 test allows us to simplify the simulations to 2D or possibly even 1D. The ASTM G198 test specifies that nails be driven into a 38 mm by 89 mm (nominal "2 x 4" in the U.S.) by 305 mm piece of wood on the 38 mm by 305 mm face with the fasteners spaced a distance of 10 times their diameter from each other. The standard specifies that cuts be made in the board along the 305 mm dimension in between fasteners to allow moisture to penetrate from the side. Because of the variability in the width of the cuts, we leave these out of the preliminary analysis and instead model the 305 mm dimension as continuous. For a common 8d nail (3.4 mm), the 10 diameter spacing represents 34 mm, and the entire 305 mm represents a nearly infinite dimension that would not affect moisture transport, easily allowing a simplification to 2D (along the depth of the fastener and the width of the board).

In a previous publication,[12] we used 2D simulations to examine the corrosion of nails embedded in

2 x 4s exposed to rain; the simulations were similar to the ASTM G198 test in that the nail was orientated along the 89 mm direction. The mesh consisted of a "nail" with the thermal properties of steel and no moisture capacity, and the remainder of the mesh consisted of European spruce. We found that the moisture content at the nail surface (and thus the corrosion rate) in these simulations was nearly 1D, and the moisture content around the nail was not appreciably affected by the nail itself. To illustrate this, we reprint Figure 2, which illustrates the wood moisture content at the fastener surface (i.e., almost in the middle of the 38 mm dimension) along the depth of the nail (89 mm dimension). When there was a rain event, the wood would absorb water one dimensionally, since the rain was only striking the top surface. At the end of the rain event, the wood surface was saturated and there was a zone of high moisture content that had a fairly abrupt transition to the bulk, "pre-rain," moisture content. In most cases, this zone was less than 10 mm deep. Once the rain stopped, the wood dried from all sides. However, since the depth of the "wet zone" (<10 mm) was much smaller than the distance from the fastener to the side axis (~20 mm), practically all of the drying occurred from the top face. Therefore, we have simplified to 1D simulations (along the 89 mm dimension) in the current article, since this is sufficient to capture the physics and is much less computationally costly. Simplifying to 1D also assumes that the fastener does not affect moisture uptake, which is also justified by the previous simulations.

The 1D mesh consists of 80 linear elements (81 nodes). The first nine nodes to the interface receiving the fog are spaced 50 μm apart. The elements then progressively increase in size until element 58, at which point they begin to decrease in size until they reach 1 mm at the other boundary (Figure 3).

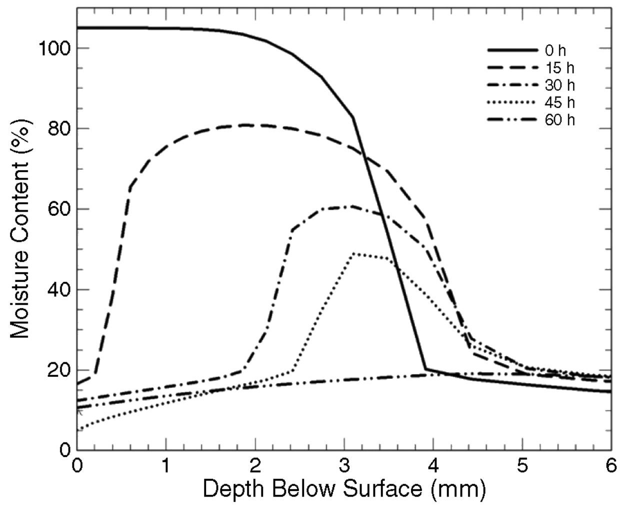

FIGURE 2. *Moisture content profile after a rain event from 2D simulations conducted by Zelinka, et al.;[12] the different curves show how the profile changes with time after the rain stops. Note that the maximum depth of water ingress (~4 mm) is much less than the width of the specimen (~40 mm).*

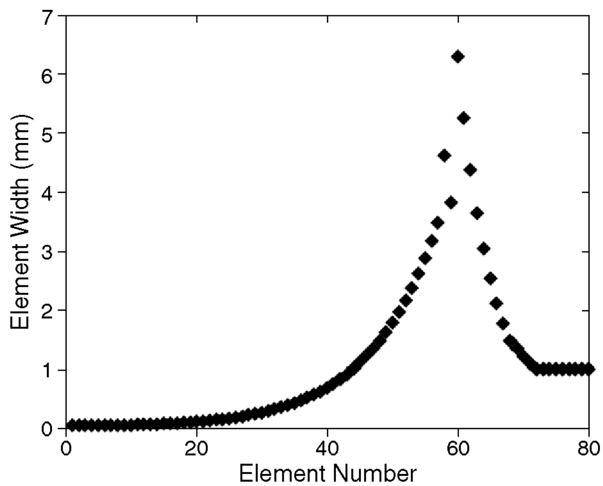

FIGURE 3. *Physical dimensions of the elements used in the simulations.*

Material Properties

The hygrothermal material properties of the wood were implemented based on measurements taken on European spruce (*Picea abies*).[18] ASTM G198 specifies that the test specimens shall be made from southern pine sapwood (*Pinus spp.*); however, southern pine could not be implemented in the hygrothermal model because there have not been sufficient measurements of the moisture retention curve and capillary absorption kinetics. This lack of data also precludes a full comparison of the hygrothermal properties of these two wood species, but we expect that the spruce used in this model to have an appreciably slower liquid transport. The resistance to liquid transport in spruce may have the effect of underestimating the modeled corrosion rate in the simulations presented. Zelinka and Glass have shown that preservative treatments such as ACQ only cause small changes in the amount of moisture held by wood at a given RH (less than 2% MC); by using data for untreated wood, this work implicitly assumes that the treatment does not affect hygrothermal properties.[19]

Boundary Conditions

ASTM G198 specifies a "wet/dry" cycle that consists of 48 h of fog, followed by a minimum of 72 h and a maximum of 120 h of drying time. A note in the standard states, "The drying time is intended to be 72 h as a standard with the allowance of an extra 48 h for weekends and holidays." However, the test could be entirely run with 120 h dry cycles and still be within conformance. The fog cycle is defined as having 1.0 mL to 2.0 mL per hour of fog hitting an 8,000 mm^2 collection area with a temperature of

TABLE 1
Experimental Parameters Examined in the Sensitivity Analysis and the Resulting Average Corrosion from the Simulation

Variable	Value	Avg. Corrosion (μm)
Defaults	Cyclic Fog	5.65
	Steady State (32°C, 95% RH)	5.20
Dry Cycle RH (default = 0.7)	0.67 (low)	5.52
	0.73 (high)	5.78
Rain Intensity (default = 0.1875)	0.125 (low)	5.52
	0.25 (high)	5.69
Dry Cycle Duration (default = 24 short)	1 long, 22 short	5.46
short = 72 h	10 long, 10 short (alternating)	4.90
long = 120 h	10 long followed by 10 short	4.54
	17 long	4.24

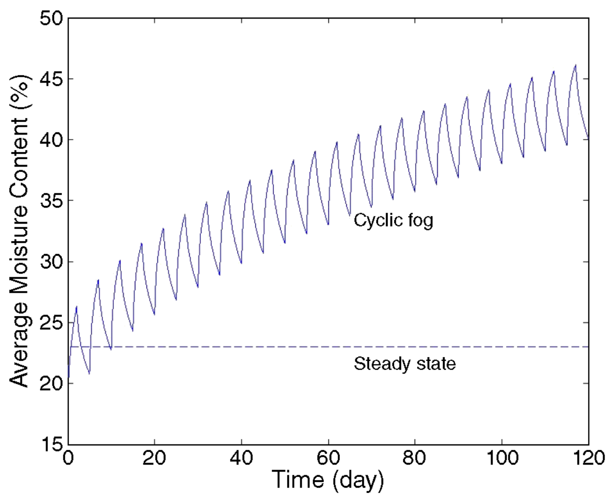

FIGURE 4. *Average moisture content of the default simulation throughout the 120 day test. Note the specimen is accumulating moisture throughout the test.*

24±3°C. This precipitation is equivalent to 0.125 mm to 0.25 mm per hour (0.0005 to 0.001 in per hour). During the fog cycle, the RH is fixed at 100% due to the presence of both liquid water and water vapor at atmospheric pressure. During the dry period, the relative humidity is kept at 70±3% RH.

To simulate the ASTM G198 test, we have taken the value in the middle of the tolerances as the default case—that is, 0.1875 mm per hour of precipitation during the wet cycle and 70% RH during the 72 h dry cycle. Furthermore, we have explored the sensitivity of fastener corrosion to the tolerances within the standard by running a simulation where one of the variables was changed, holding all others constant. A summary of the boundary conditions used in all simulations is given in Table 1.

Finally, ASTM G198 also offers a "steady-state" moisture exposure, where wood is conditioned and maintained at 32°C and 95% RH. According to the material properties used in this study, the resulting moisture content would be constant and 18%. This is unusually low and would give a misleading underestimation of corrosion.[4] Instead, we used available measured data for ACQ-treated southern pine; the measured moisture content at 95% RH (25°C) is 23%.[18]

RESULTS

The simulations uncovered three significant results, which will be explored independently:

—The cyclic fog test causes the wood to accumulate moisture throughout the duration of the test.

—The cyclic fog test is much more severe than the steady-state test.

—The corrosion that occurs during testing is relatively insensitive to the allowed tolerances in the standard.

Figure 4 shows the "average moisture content" of the wood as a function of time in the cyclic fog test using the "default" conditions (Table 1). The average moisture content was calculated by taking an average of the moisture content at each node weighted by the physical length of the element preceding the node. Prior to exposure, the wood was conditioned at 95% RH, which resulted in a uniform moisture content of 18.1% MC. With the first fog cycle, the moisture content rises rapidly; the average moisture content reaches a maximum of 26.3% before beginning to decrease. However, during the dry cycle, the wood cannot dry to the starting moisture content; it reaches a minimum of 20.8% before the next fog cycle begins and the wood moisture content rises.

In fact, the wood continues to accumulate moisture during each consecutive fog cycle throughout the duration of the test. It never reaches a steady state where the moisture lost during the dry cycle is equal to the moisture gained during the fog cycle. To see how long it takes for steady state to be reached, additional simulations were run for durations of up to 4 years; the results of a 1 year simulation are shown for reference (Figure 5). The specimen continues to gain moisture with each cycle even at the end of 4 years; though the amount gained at the end of 4 years is quite small (0.01% MC per cycle).

It is important to note the limitations of examining the average moisture content in terms of calculating the corrosion rate. While Figure 4 shows that wood is accumulating moisture throughout the test and that the average moisture content in the cyclic fog test is always higher than in the steady-state test, it does not tell the entire story for corrosion since the moisture is not evenly distributed and the corrosion rate does not depend linearly on moisture content (Equation [1]). For example, Figure 6 shows the moisture content at the wood near the head and tip of the nail in the same simulation as Figure 4. The wood near the head of the nail quickly saturates during the wet cycle and then almost immediately dries out during the dry cycle. The bottom side of the wood near the nail tip actually dries out during the test, and the small fluctuations are caused by changes in RH in the wet and dry cycles. This suggests that while the block of wood, on average, is gaining moisture throughout the test, most of this moisture accumulation is occurring near the top of the block of wood.

Figure 7 shows how the moisture accumulation progresses throughout the test by plotting the moisture content at different depths below the fastener surface as a function of time. Unlike the head of the fastener (Figure 6), the wood at a depth of 1 cm never dries out completely after the first moisture cycle and continues to gain moisture, and eventually exhibits oscillations with the wet and dry cycles. A similar behavior is observed at a depth of 1.5 cm, but the moisture content increases more slowly and the oscillations are damped. At a depth of 3 cm, the moisture content of the wood is hardly changed until near the end of the test. The wood near the fastener in the 1 cm to 3 cm range does not dry out during the cyclic fog test, but instead accumulate moisture from the starting conditions. The moisture accumulation during the test that is visible in Figure 3 is essentially an increasing "wet-zone" deeper into the wood. This is important since the corrosion model (Figure 1) is nearly an "on-off" criteria, and the total amount of moisture is not as important as the amount of wood with a moisture content of above approximately 20%.

Given the differences in moisture content between the steady-state and cyclic fog tests, it is not surprising that the hygrothermal model predicts more corrosion in the cyclic fog test than the steady-state moisture content test. Using actual material properties from ACQ-treated southern pine, the moisture content

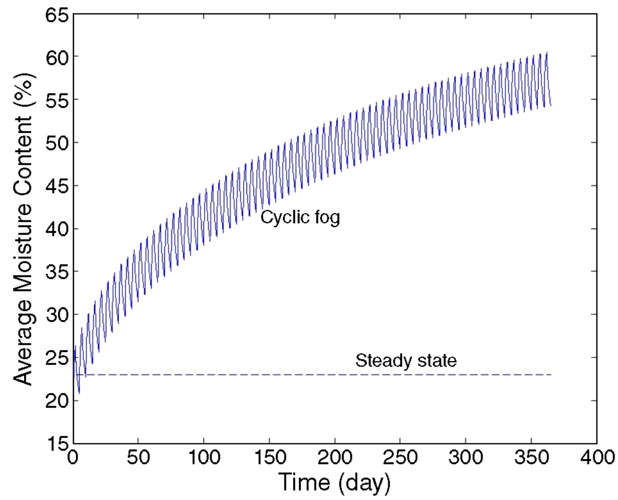

FIGURE 5. *Average moisture content of the wood specimen with the default simulation parameters after 1 year of testing. The specimen continues to accumulate moisture.*

is 23%, and Equation (1) predicts a corrosion rate for a hot-dip galvanized steel fastener of 15.8 μm y^{-1}. This is equivalent to 5.2 μm occurring during the 120 day test. The results of the steady-state test can be compared to the results of the cyclic fog test in Figure 8, which shows the cumulative amount of corrosion as a function of time for the default cyclic fog simulation with spruce material properties (Table 1). The resulting average corrosion rate is 17.2 μm y^{-1}, while the average amount of corrosion is 5.6 μm. Importantly, although the average amount of corrosion is 5.6 μm, the corrosion is not distributed evenly and has a maximum corrosion penetration of 17.1 μm.

Table 1 shows the results of the sensitivity analysis. The results are summarized by the average amount of corrosion after the 120 day test. The RH and rainfall intensity had little effect on the result-

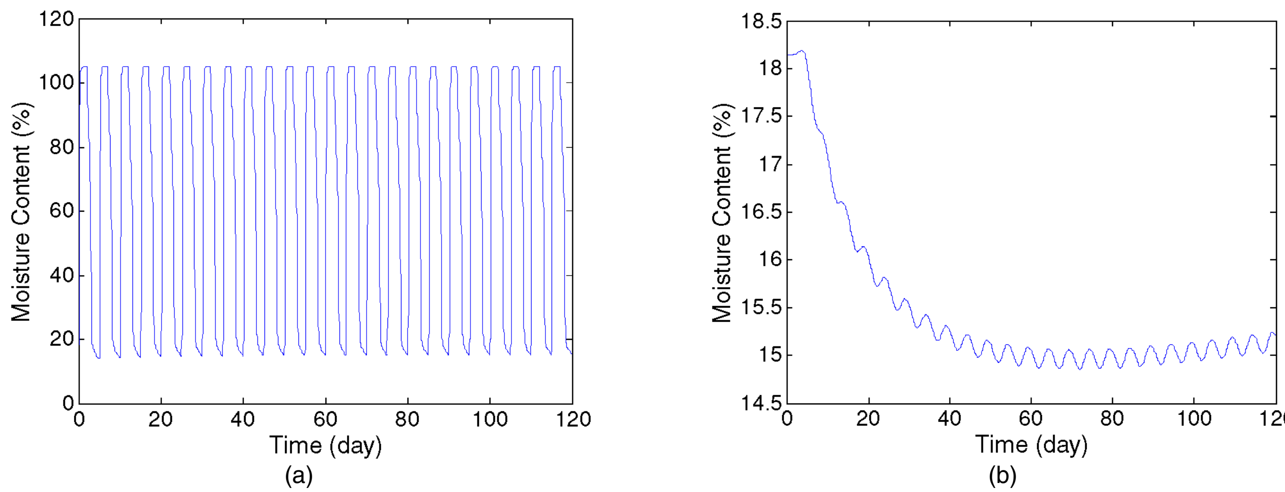

FIGURE 6. *Moisture content 1 mm below the surface receiving precipitation (a) and 70 mm below the surface, which corresponds to the bottom of the nail (b) for the default simulation.*

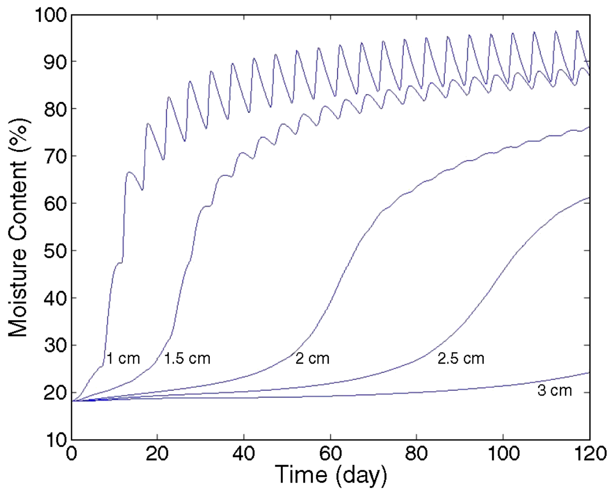

FIGURE 7. *Moisture content along the length of the fastener as a function of time in the cyclic fog test.*

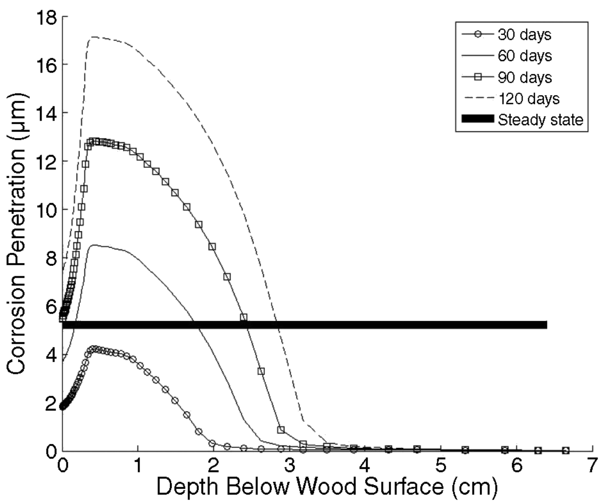

FIGURE 8. *Simulation results of the amount of corrosion along the length of the fastener; the simulation assumes a hot-dip galvanized fastener embedded in ACQ-treated wood.*

ing corrosion rate. Values ranged from 5.52 μm for both the low RH and low rainfall intensity to 5.78 μm for the high RH during the dry cycle. These represent about a 2% difference from the default case (5.65 μm). It appears that the test is more sensitive to the RH during the drying cycle than it is to the rainfall intensity. This is a result of the surface of the wood quickly saturating during the fog cycle so additional liquid water does not greatly increase the driving force for water uptake.

As expected, the amount of corrosion is sensitive to the number and duration of the dry cycles. Having a single extended dry cycle lowered the amount of corrosion by 3% to 5.45 μm. If the first 10 cycles have a longer drying time, the average corrosion drops nearly 20% to 4.54 μm. However, in the case where the dry cycles alternate between 72 h and 120 h, it is closer to the default case (4.9 μm, a 13% decrease). Finally, if the 120 h drying time was used for all of the cycles, the amount of corrosion drops by 25% to 4.24 μm.

This sensitivity analysis gives a preliminary picture of how different experimental variables affect the corrosion. The average amount of corrosion is not particularly sensitive in absolute value to any of the variables because corrosion is confined to the first 3 cm of the fastener (Figure 8). It may be that maximum corrosion penetration or amount of the fastener experiencing non-zero corrosion may further separate these experimental differences. From a practical standpoint, the remaining structural capacity of the nailed joint is not a linear function of the amount of corrosion but depends upon the joint geometry, dowel-bearing stress of the wood, and the fastener-bending yield strength. Zelinka and Rammer have examined the loss of structural capacity caused by corrosion for various geometries and corrosion rates but had assumed a uniform fastener diameter.[20] Further analysis may be needed to determine how the corrosion profile predicted in Figure 8 affects the structural capacity of nailed connections.

Results of these studies are useful in examining the sensitivities of variables in the ASTM test. There are uncertainties in both the wood material properties and the function that relates the wood moisture content to the corrosion rate. While a full correlation between the model and field tests is currently being conducted by the author, the simulations predict a key result seen in field exposures; the maximum amount of corrosion occurred a short distance below the head of the fastener.[21] Despite the uncertainties in the model, the relative differences between the scenarios presented in this paper are less sensitive than the absolute value of predicted corrosion in any given scenario.

CONCLUSIONS

This paper has presented preliminary modeling results on the corrosion in the ASTM G198 test and several conclusions can be drawn from these results.

❖ The wood moisture content in the cyclic fog test never dips below the starting moisture content (equilibrated at 95% RH). The wood continues to accumulate moisture throughout the test. While the surface of the fastener may dry during the dry cycle, the wood surrounding the fastener remains relatively wet throughout the test.

❖ Combining the corrosion model with the hygrothermal model shows that the cyclic fog test is more aggressive to embedded fasteners than the steady-state moisture test.

❖ The combined hygrothermal-corrosion model used has uncertainties in both the material properties and corrosion model and has not been compared against the results of ASTM G198 tests. However, relative differences between simulations should track with testing. Of the variables examined, the cyclic fog test is most sensitive to the length of the dry cycle. When the longest specified dry cycle is used, the simulated corrosion of a hot-dip galvanized steel fastener in ACQ-treated wood is 25% lower than if only short cycles are used. It may make sense to set a maximum number of long dry cycles in the standard.

❖ In spite of the above conclusions, future modeling is still needed to better understand the ASTM G198 test. Specifically, the present work was limited by the lack of hygrothermal material property data for southern pine. Additionally, the simulations were simplified by ignoring "cuts" in the wood between fasteners, which may change the dimensionality of the simulation needed. Further sensitivity analyses could also yield additional insight to variations that may be observed in the tests.

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