Corrosion Prediction in Buildings Based on Simulation of Temporal Distribution of Humidity and Temperatures and the International Standard ISO-9223

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ABSTRACT

Energy efficiency and durability are two goals that have recently gained higher priority among building envelope specialists and architects. Often, these two goals have negative impact on each other. When steel is exposed to humidity corrosion prevention and control are unquestionable requirements. At design time and/or when planning for maintenance and durability simulation tools are needed to assess the potential for corrosion and its impact.

Recently, a number of hygrothermal simulation tools have been created that provide good predictions of the local temperature, relative humidity, and moisture contents in building envelope systems. While this information is invaluable, there is a need to include corrosion prediction in the cost, benefit, and risk analyses of particular envelope systems.

In this paper, we describe the development of a multivariate corrosion model derived from the ISO-9223 standard amenable to be incorporated or interfaced to existing hygrothermal simulation codes. We also describe the approach followed to generate time-dependent corrosion estimates from the yearly-averaged values and to account for temperature effects. For illustration, we present results obtained by simulating the time-dependent hygrothermal conditions and predict corrosion build-up of a building structure subject to typical interior and exterior conditions.

INTRODUCTION

Corrosion processes are complex, random, and highly dependent on the geometry, the environment, the materials involved, and their workmanship (Baboin; Maurenbrecher and Brousseau 1993). Nevertheless, engineering applications demand quantitative estimates for which the use of correlations is practical. Seldom exists, though, a correlation derived for the in-service conditions of interest. Even when a correlation for the exact conditions is found, a measure of the associated statistical distribution is often missing.

The ISO 9223 standard (Townsend 2002) provides guidelines to estimate yearly averaged corrosion rates of carbon steel, zinc, copper, and aluminum exposed to atmospheric environments. The standard defines corrosion rate categories from categorized levels of exposure to wetness, chloride, and sulfur contaminants. Since categorization implies ranging, once a corrosion category is determined, the uncertainty exists of how to choose consistently the most representative numeric value for the yearly-averaged corrosion rate estimate within the range. One approach is that of the ISOCORRAG3 (ISO 9233) which models the yearly average corrosion as a material-dependent linear combination of time-of-wetness, chloride deposition rate, and sulfur concentration derived from the original data that germinated the ISO 9223 standard. In addition, the use of yearly-averaged corrosion rates appears to relegate the computation of corrosion to a post-processing step or to be delayed for an undetermined time period.

Below, the approaches followed to allow hygrothermal simulations codes to predict the growth of corrosion in real-time (not as a post-processing step) are described. This opens the possibility to model the complex interactions between humidity, temperature, and corrosion at each simulation time-step in a manner akin to feedback algorithms.

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Description of ORNL's Corrosion Model

Average Annual Corrosion Rate. Using fuzzy-set interpolation of the ISO-9223 data, a third order multivariate correlation for the yearly-averaged corrosion rate as a function of the natural logarithms of time-of-wetness and chloride and sulfur exposures has been developed. The resulting formula has the following form:

$$\text{ISO9223\_CorrosionRate}[\text{g/m}^2/\text{a}] = a_0 + a_1 \cdot t + a_2 \cdot s + a_3 \cdot p + a_{11} \cdot t_2 + a_{12} \cdot s \cdot t + a_{13} \cdot p \cdot t + a_{22} \cdot s_2 + a_{23} \cdot p \cdot s + a_{33} \cdot p_2 + a_{111} \cdot t_3 + a_{112} \cdot s \cdot t_2 + a_{113} \cdot p \cdot t_2 + a_{122} \cdot t \cdot s_2 + a_{123} \cdot p \cdot s \cdot t + a_{133} \cdot t \cdot p_2 + a_{222} \cdot s_3 + a_{223} \cdot p \cdot s_2 + a_{233} \cdot s \cdot p_2 + a_{333} \cdot p_3 \quad (1)$$

where:

$t = \text{Ln}(T_{wetness}[\text{h/a}])$

$s = \text{Ln}(SaltDepRate[\text{mg/m}^2/\text{d}])$

$p = \text{Ln}(SO_2 Conc[\text{mg/m}^3]$

The subdindex a stands for annum, and the values of the coefficients *a*, *i*, *j*, and *k* are shown in Table 1.

For illustration, Figure 1 depicts the average annual corrosion rate of carbon steel computed with Equation 1 as a function of time-of-wetness and SO_2 pollution for a constant exposure to chloride salt deposition rate.

The basic time-of-wetness is defined in ISO 9223 as the amount of time per year that the material of interest experiences a relative humidity above 80% at temperatures above 0°C. Application of any ISO 9223-based correlation to estimate corrosion rates may require the use of time-of-wetness modifiers to accommodate for significant differences in geometry and corrosion mode from those on which ISO 9223 was based.

Equation 1 was applied to test the model as affected by the conditions for masonry-ties at the four Canadian cities described in "Comparison of theoretical and empirically determined service lives for wall ties in brick veneer steel stud wall systems" (Hagel et al. 2007), specifically in Tables 2 and 6, i.e.,

Adjusted_TOW(% year) = [0.85, 0.70, 0.86. 0.15]

SO_2(mg/m^2/d) = [11, 36, 11, 11]] (converted to [14.85, 48.6, 14.85, 14.85]μg/m^3)

Chloride(mg/m^2/d) = [300, 180, 180, 180]

and obtained the following values for the average annual corrosion rates for Zinc specimens:

CR_{zinc} = [47.3, 42.4, 42.5, 18.8] g/m^2/a.

Table 1. Material Dependent Coefficients for Equation 1: The Average Annual Corrosion Rate

Coefficient	Carbon Steel	Zinc	Copper	Aluminum
a_0	3.94E+2	2.57E+1	2.11E+1	5.16E+0
a_1	3.83E+2	1.33E+1	1.07E+1	3.21E+0
a_2	5.24E+1	2.64E+0	2.22E+0	2.78E-1
a_3	–2.96E+0	–2.82E+0	–2.45E+0	–7.28E-1
a_{11}	7.69E+1	4.85E+0	4.07E+0	1.02E+0
a_{12}	2.49E+1	1.40E+0	1.21E+0	5.84E-2
a_{13}	–1.05E+1	7.65E-1	7.03E-1	1.59E-1
a_{22}	6.75E+0	2.93E-1	2.47E-1	3.84E-2
a_{23}	5.65E-1	–1.00E-1	–8.15E-2	–8.11E-3
a_{33}	1.48E+1	6.49E-1	5.55E-1	1.27E-1
a_{111}	6.63E+0	4.36E-1	3.68E-1	1.02E-1
a_{112}	3.40E+0	1.84E-1	1.62E-1	1.21E-2
a_{113}	–1.09E+0	2.83E-2	2.48E-2	1.72E-2
a_{122}	1.18E+0	7.31E-2	6.21E-2	–5.59E-4
a_{123}	–8.61E-2	–9.20E-3	–9.40E-3	–3.04E-3
a_{133}	–1.29E+0	6.37E-2	5.88E-2	9.89E-3
a_{222}	2.34E-1	1.09E-2	9.16E-3	1.83E-3
a_{223}	–1.66E-3	–3.40E-3	–2.61E-3	–1.57E-4
a_{233}	4.60E-2	–7.58E-3	–6.25E-3	–4.20E-4
a_{333}	1.17E+0	7.12E-2	6.10E-2	1.50E-2

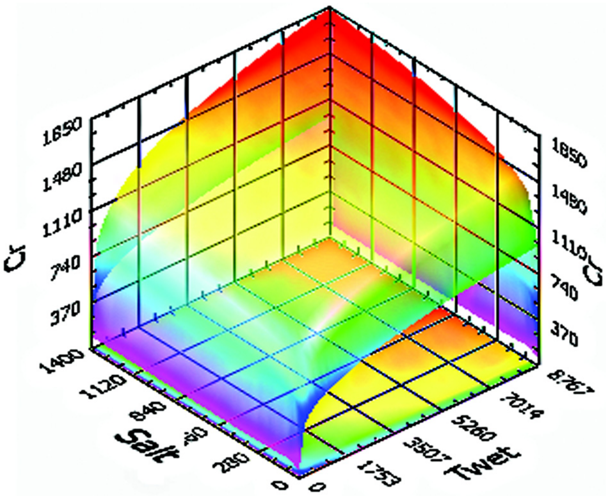


Figure 1 *Average annual carbon steel corrosion rate as a function of time-of-wetness and chloride salt deposition rate for a constant exposure to 250 mg/m^3 SO_2 pollution.*

All but one compare reasonably with the values shown in Table 7 of "Comparison of theoretical and empirically determined service lives for wall ties in brick veneer steel stud wall systems" (Hagel et al. 2007) for ISOCORRAG:

$$[45, 45, 45, 10] \text{ g/m}^2\text{/a}$$

And for the city-averaged field measured corrosion rates:

$$[41, 38.6, 10, 21.3] \text{ g/m}^2\text{/a}$$

The discrepancy in the corrosion rate estimated for the third city is large enough to warrant speculating about the validity of the adjusted time of wetness, the sulfur, and the chloride values reported assuming that the corrosion rate average is accurate. In this case, Equation 1 changes the corrosion rate estimate from 42.5 to (1) 22.7 if the chloride value is taken as zero, (2) 34.1 when the SO_2 pollution is taken as zero, and (3) 13.1 when both, the chloride and SO_2 are taken as zero.

Instantaneous Corrosion Rate. The approach taken by this study to compute the growth of corrosion with time using average annual corrosion rate data is as follows.

Let C_i represent the corrosion present after a certain exposure time, T_i, shorter than a year, and assume that during the next time interval, of length, dT_i, i.e., at time $T_{i+1} = T_i + dT_i$, there is a new value for the time-of-wetness TOW_{i+1} and that, according to Equation 1, the corresponding value of the average annual corrosion rate is CR_{i+1}. Then, to compute the value of C_{i+1}, we need to consider what happens if from T_{i+1} to the end of the year it is dry enough so that there is no change in the time-of-wetness. One possibility is to assume that the corrosion rate is zero during dry periods. Then, at T_{i+1} the corrosion value would need to be equal to the one expected at the end of the year, i.e., $C_{i+1} = C_{ai} = 1\text{a} \cdot CR_{i+1}$ and, as shown in Figure 2, a plot of corrosion versus time show horizontal plateaus in periods of dryness.

A more flexible approach is to define a corrosion rate for dry periods that could be larger or equal to zero. This dry corrosion rate could be chosen to be of constant value or could be derived at each wet interval from the average annual corrosion rate corresponding to the time-of-wetness observed up to that time. In all cases, the dry corrosion rate is constrained to yield the proper corrosion value at the end-of-year if for the remainder of the year happens to be dry.

Let us use the subindices d and w to indicate that the time interval is dry or wet, respectively, and assume that K_{w2d} is the value chosen for the ratio of the wet and dry corrosion rates. Then:

$$K_{w2d} = CR_i / CR_{di} \tag{2}$$

$$C_{i+1} = C_i + CR_i \cdot dT_i \tag{3}$$

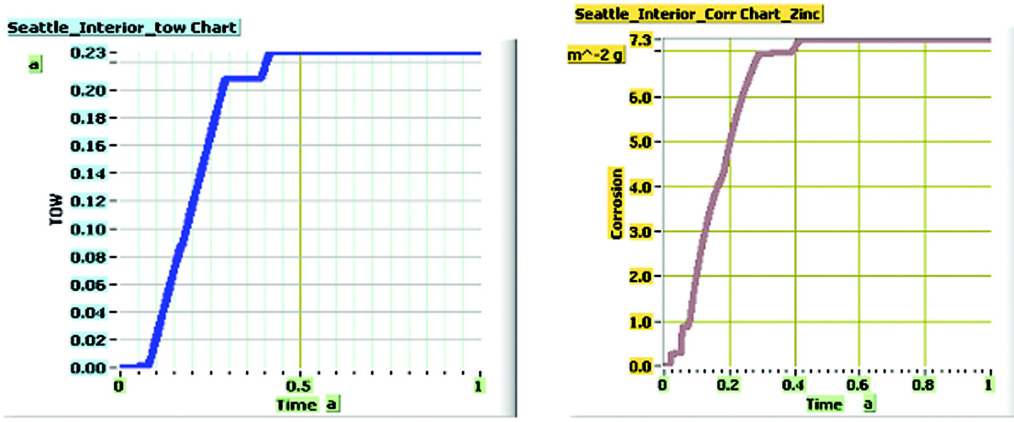
$$CR_{di} = CR_i / K_{w2d} = (C_{ai} - C_{i+1}) / (1a - T_{i+1}) \tag{4}$$

Solving Equations 2, 3, and 4 yields the corrosion at time T_{i+1}:

$$C_{i+1} = C_i + dT_i / (1\text{a} - T_{i+1}) \cdot (C_{ai} - C_i) \cdot K_{w2d.} \tag{5}$$

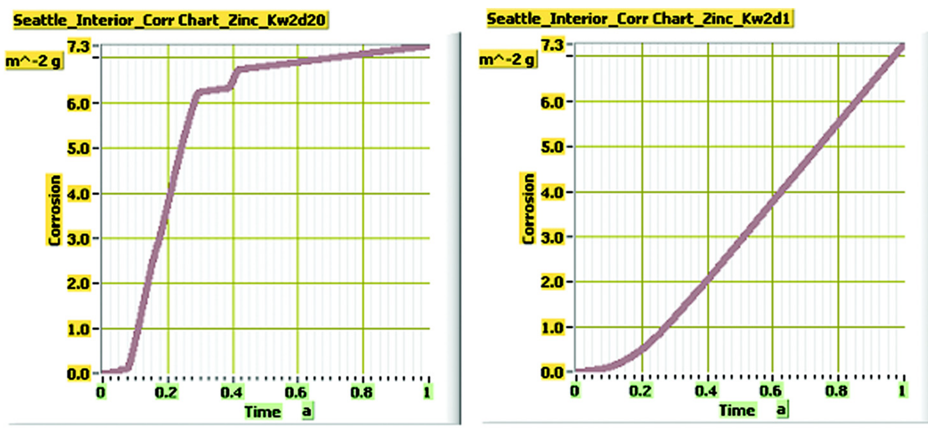
Figure 3 shows the buildup of corrosion predicted for the time-of-wetness of Figure 2a for two non-zero values of the wet-to-dry corrosion ratio.

Temperature. The effect of temperature on corrosion is not simple as it varies with the material, its geometry and the environmental conditions. One approach is to define an effective-time-of-wetness dependent on humidity and temperature (Mikhailov et al. 2004; Corvo et al. 2008; Tidblad et al. 2000).



(a) (b)

Figure 2 *Results for zinc at the inside surface of the stucco in Seattle's simulation where (a) depicts time-of-wetness vs. time computed with hygrothermal simulation and (b) depicts corrosion vs. time for zinc for the conditions in Figure 2a assuming wet-to-dry corrosion rates of (a) 20 and (b) one.*



(a) (b)

Figure 3 *Effect of the wet-to-dry corrosion factor on the estimation of corrosion of zinc at the conditions computed for the inside surface of the stucco in Seattle's simulation where (a) depicts wet-to-dry corrosion rate = 20 and (b) depicts wet-to-dry corrosion rate = 1.*

For the purposes of this experiment, temperature effects on chloride corrosion rates are modeled by means of the Arrhenius multiplication factor:

$$TemperatureCorrosionRateFactor[T,S] = e^{k_{ar}[S] \cdot (1/T - 1/Tref)} \quad (6)$$

where:

$k_{ar}[S] = m_1 + m_2 \cdot \mathrm{Ln}(S)$, S = SaltDepRate[mg/m^2/d], T = Temperature[K], T_{ref} is the reference temperature for the base corrosion rates, and m_1, m_2 are fit coefficients.

The rate factor is affected significantly by the presence of chloride in the air.

We extracted a set of chloride-dependent m_1, m_2 coefficients from data in Pacheco and Ferreira's "An Investigation of the Dependence of Atmospheric Corrosion Rate on Temper-

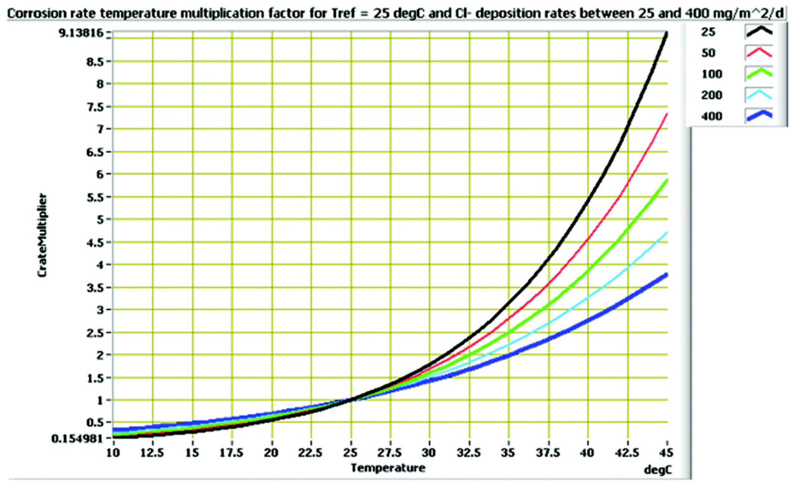
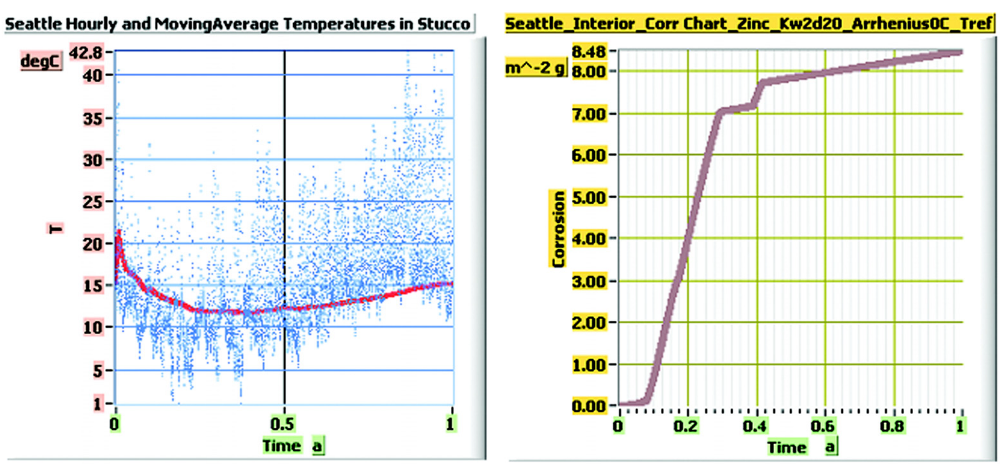


Figure 4 *Corrosion rate factor vs. temperature and chloride deposition rate for T_{ref} = 25°C.*



(a) (b)

Figure 5 *Effect of temperature on zinc corrosion vs. time for Seattle's simulation where (a) depicts temperature inside stucco and (b) depicts corrosion for zinc, T_{ref} = 0°C and Kw2d = 20.*

ature Using Printed-Circuit Iron Cells" and applied it to a hypothetical case with reference temperature of 25°C. The temperature dependence of the corrosion rate factor predicted by Equation 6 is shown in Figure 4.

Applying Equation 6 to the moving average temperature at the exterior surface of the Seattle stucco the prediction of corrosion of zinc is shown in Figure 5b, which can be compared to the prediction without direct temperature effects previously shown in Figure 3a.

Results of Combined Hygrothermal and Corrosion Computations

The WUFI10 code was used to compute the humidity and temperatures across the building wall structure shown in Figure 6, subject to two years of interior and exterior conditions characteristic of three USA cities: Seattle, Boston, and Houston. The computed humidity and temperature at several points of interest were stored by WUFI in a spreadsheet file and the corrosion estimator picked the data of interest one step at a time in order to emulate real-time analysis. Note that for these analyses we have assumed that there is no corrosion

(a)

(b)

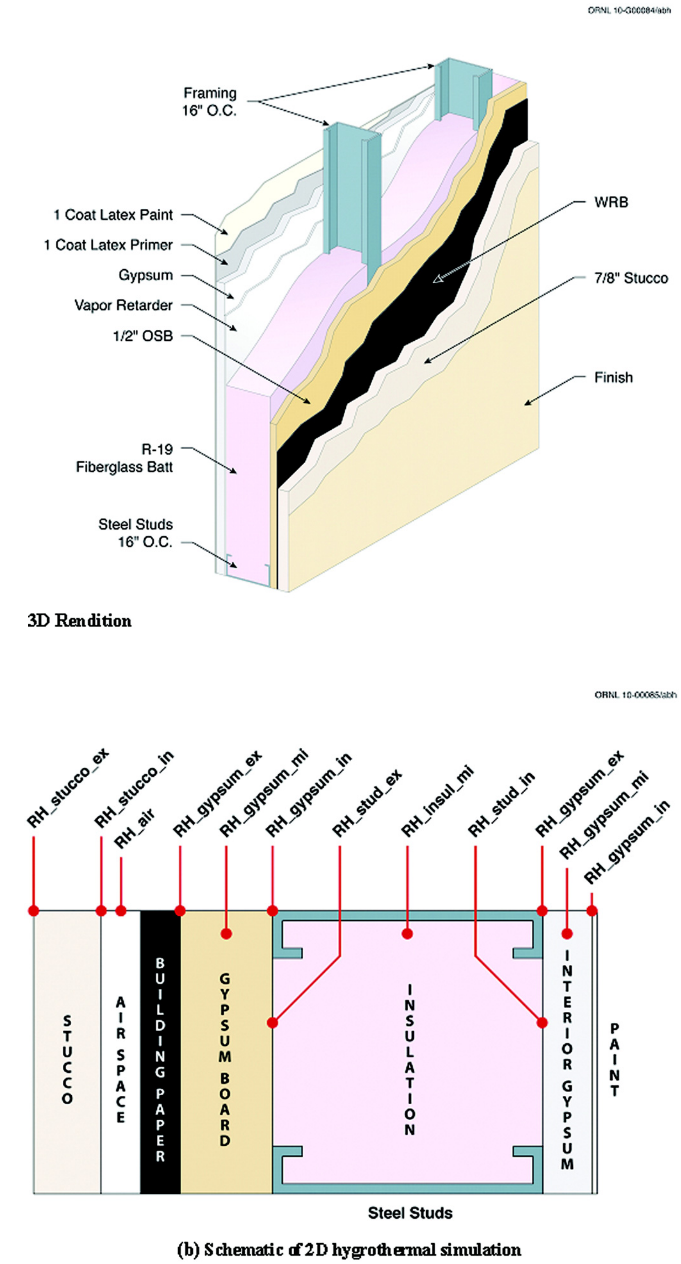
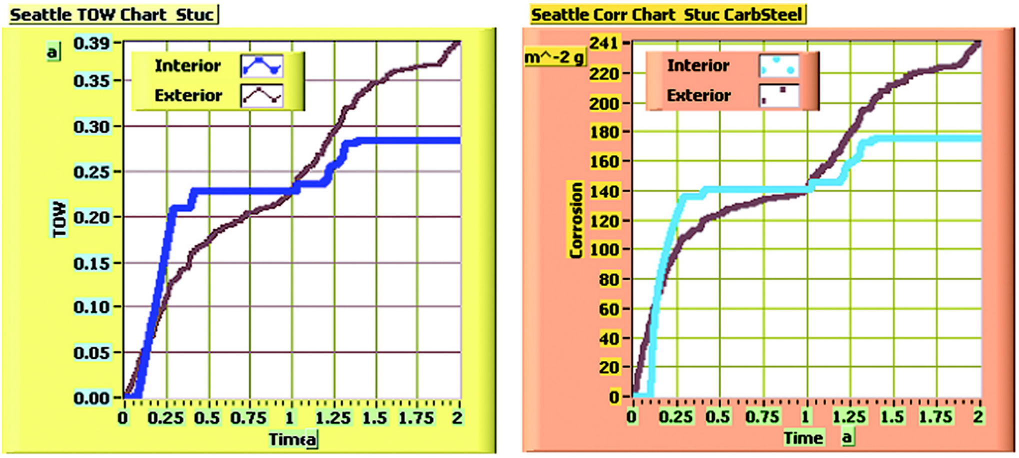


Figure 6 *Building wall analyzed with WUFI1 in which (a) depicts a three-dimensional rendition of building wall structure and (b) depicts a schematic of the two-dimensional hygrothermal simulation.*

during dry periods, by choosing a large number for the ratio of wet-to-dry corrosion rates.

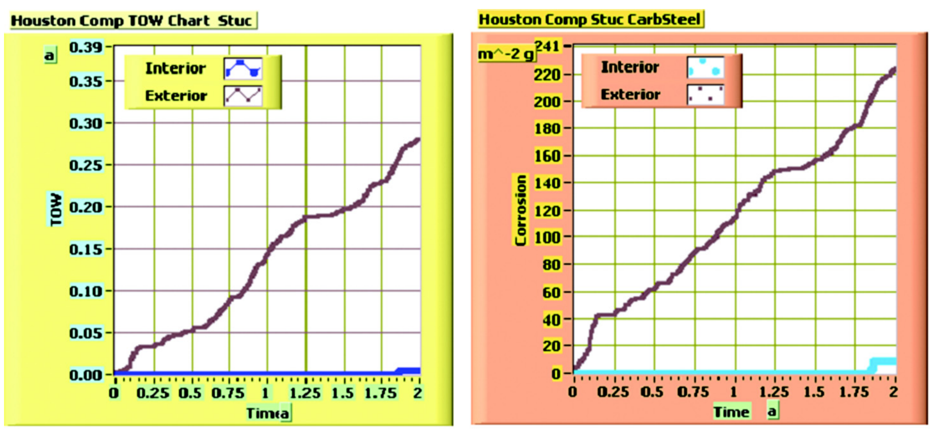
Seattle, WA. Time-of-wetness events with relativity humidity larger than 80% at temperatures above 0°C were only found at the stucco surfaces and in the air space. The time-of-wetness and Carbon Steel corrosion estimates obtained as a function of time are shown in Figure 7 for the hygrothermal conditions at the interior and exterior surfaces of the stucco.

Houston, TX. Time-of-wetness events with relativity humidity larger than 80% at temperatures above 0°C were only found at the exterior stucco surface, the exterior steel-stud surface, and in the air space. The time-of-wetness and carbon steel corrosion estimates obtained as a function of time are shown in Figure 8 for the hygrothermal conditions at the interior and exterior surfaces of the stucco.



(a) (b)

Figure 7 *Seattle results for the stucco and the stucco interior and exterior surfaces where (a) depicts time-of-wetness vs. time and (b) depicts corrosion of carbon steel vs. time.*



(a) (b)

Figure 8 *Houston results for the stucco and the stucco interior and exterior surfaces where (a) depicts time-of-wetness vs. time and (b) depicts corrosion of carbon steel vs. time.*

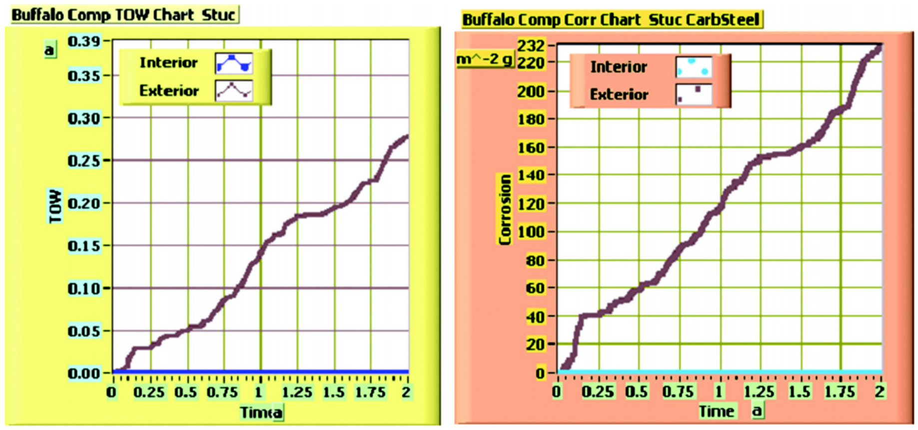
Buffalo, NY. The humidity conditions ended up being very similar to those for Houston as shown in Figure 9a. Since the effect of temperature on the corrosion rate is not being considered—except for it being above freezing—the computed corrosion estimates at the exterior surfaces of the stucco shown in Figure 9b are similar to those in Figure 8b for Houston.

CONCLUSION

A corrosion estimation methodology that facilitates the implementation of corrosion estimation in existing hygrothermal models has been presented. The methodology is based on a multivariate model of average annual corrosion rates, an algorithm for deriving instantaneous corrosion rates, and a model to account for temperature effects.

The average annual corrosion rate model was derived from the ISO 9233 standard data using a combination of fuzzy-set and multivariate regression techniques.

The algorithm to obtain instantaneous corrosion rates from yearly-averaged values could be applied to other phenomena. For corrosion, it tracks the time-of-wetness index and considers the possibility that dry conditions may occur the



(a) (b)

Figure 9 *Buffalo results for the stucco and the stucco interior and exterior surfaces in which (a) depicts time-of-wetness vs. time and (b) depicts corrosion vs. time.*

rest of the year. The algorithm also allows for corrosion to continue during subsequent dry time periods.

The approach used to model the effect of temperature in corrosion rates is based in the Arrhenius formulism and considers that the temperatures directly affecting the corrosion rates are those at the surface of interest, as computed by codes like WUFI-ORNL/IBP, not the ambient air temperature.

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