Monitoring of Historic Structures for Whole-Building Improvements

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ABSTRACT

A long-term monitoring program was implemented at a historical structure to characterize exterior wall assembly performance and interior operating conditions prior to complete renovation. The purpose of the monitoring system was to analyze the effect interior operating conditions have on historic building enclosure components, which include sandstone veneer walls, exposed concrete walls, skylights, and art deco aluminum-frame glazing systems.

The monitoring system consists of specifically positioned temperature, relative humidity (RH), surrogate moisture content, pressure, and condensation sensors. The sensors are embedded in select wall assemblies, wired to a remote central data acquisition system, and uploaded online for review and analysis in real time.

The first year of data revealed several interesting facts about building enclosure performance and building operation: past renovations negatively affect the hygrothermal performance of the sandstone clad wall assemblies, condensation occurs frequently on glazing assemblies, interior wall surface temperatures are conducive to condensation formation behind displays, the mechanical system creates large pressure differences of >±100 Pa under normal operation, and tight control of temperature and RH is a constant challenge.

The measured data were used to calibrate hygrothermal modeling software (WUFI 4.2), and analysis was performed to determine the potential hygrothermal effects of adding insulation to the existing wall in order to develop appropriate design solutions for the upcoming renovation.

Suggestions for implementing large building monitoring programs are provided, as are uses of monitored data in historical building renovation design.

INTRODUCTION

A major building renovation is proposed for a historic museum structure located Seattle, Washington. As part of the proposed renovation, the exterior walls will be renovated to be more thermally efficient and the building mechanical systems will be upgraded to better control the indoor conditions. Due to the historical significance of the museum, scope of the potential repairs, and sensitivity of the existing wall assemblies, a long-term monitoring system was installed in the summer of 2008. Its purpose is to understand the in-situ building operating conditions and the resulting performance of the building enclosure components, including the exterior sandstone walls, concrete walls, basement walls, skylights, and glazing systems. The results of the monitoring study are used to assist with the design of appropriate enclosure assemblies for the proposed renovation. The focus of this paper is the historic sandstone veneer wall assembly.

PROJECT BACKGROUND

Construction of the subject building was completed in 1933, with several additions over the decades. Due to the historical designation of the original building areas, the sandstone veneer walls and front entry glazing system will be retained as part of the renovation. Many of the building

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enclosure assemblies are original, with the exception of the roof. The sandstone wall assembly at the west elevation was upgraded and restored in 1994. During the 1994 renovation, a self-adhered membrane was added to the interior of the wall assembly behind the drywall, intended to function as a vapor barrier.

Previous reports (Leavengood 1993; Twilley 1997) specified that the particular sandstone used at the building has a history of deterioration from surface spalling caused by salt subflorescence and expansion of iron-oxide elements naturally occurring within the sandstone.

A previous long-term monitoring program established methods and protocols implemented in the present program (Finch et al. 2006; Finch 2007).

MONITORING PROGRAM

A long-term monitoring program was designed to monitor the in-situ performance of the exterior wall assemblies and interior operating conditions. The building was monitored using a combination of specifically positioned temperature, relative humidity (RH), surrogate moisture content (wood-based moisture content sensor placed within stone), pressure, and condensation sensors, depending on the desired assembly and purpose. The sensors were embedded in selected wall assemblies or placed at strategic positions within the museum to measure the desired conditions. The sensors were wired to data loggers placed nearby, which were in turn wired to a central computer for upload to an Internet-based server and software review system.

The monitored data collected from the sensors were used to assess the performance of the building enclosure components, and assist with the renovation design. The sensors are intended to be left in place after renovation to monitor the new assemblies and interior climate as part of a post-construction quality assurance and commissioning program.

The following building areas or assemblies were monitored:

- North and south exhibit/gallery spaces (temperature and RH sensors)
    - N1, N2, S1, and S2 within sandstone veneer wall assemblies of the original structure; S2 sensor located in wall area behind fountain,
    - N7 and S7 within concrete and concrete masonry unit wall assemblies of later additions to the original structure
- Attic spaces (temperature and RH sensors)
- The building enclosure's pressure difference (differential pressure sensor)
- Sandstone wall assembly (moisture level, temperature, and RH sensors)
- Exposed concrete and concrete block wall assemblies (moisture levels, temperature, and RH sensors)
- Attic skylight assembly (glazing and frame surface temperatures and condensation sensors)
- Main entry aluminum glazing assembly (glazing and frame surface temperatures and condensation sensors)
- Below-grade foundation wall at storage stacks (surface temperature and RH sensors)
- Auditorium exposed concrete wall assembly (surface temperature and RH sensors)

HYGROTHERMAL AND THERMAL MODELING

Thermal Modeling

To assist with the design recommendations for the proposed new wall assemblies, hygrothermal and thermal modeling computer software was used. Thermal modeling is used to determine R-values of simple and complex building components and calculate surface temperatures and condensation risk when subject to static design conditions. The two-dimensional thermal modeling software THERM 5.2 (LBNL 2003) was used for this project to determine interior wall surface temperatures and assess the risk for condensation, particularly behind artwork in the galleries.

Hygrothermal Modeling

Hygrothermal modeling analyzes both heat and moisture flow through a building enclosure assembly, and is used to understand the long-term behavior of assemblies under real climatic conditions and to assist with the design of durable assemblies. This project is unique in that the hygrothermal modeling software can be calibrated with the measured data to improve the accuracy of future performance predictions. The WUFI Pro 4.2 computer model (IBP 2008) was used for this project in the design of the renovated exterior wall assemblies to ensure durable long-term wall performance under substantially different interior environmental conditions than the building had experienced to date.

WUFI can account for rain absorption and different water absorption/redistribution for arbitrary physical property data and boundary conditions. Given the appropriate physical property data, WUFI calculates heat and moisture flow every hour under the influence of sun, rain, temperature, and humidity. The analysis is, however, only as accurate as the assembly data, the material properties, and the interior and exterior conditions provided. The accuracy of this analysis is improved by direct input of measured weather conditions collected at the roof of the subject building.

The interior climate is modeled in WUFI based on the measured conditions observed by the monitoring program. More stringent and tightly controlled operating conditions for a modern museum space are also modeled.

Since it is often not convenient (or even possible) to determine the many material properties necessary for hygrothermal simulations, WUFI 4.2 Pro includes a database of several hundred common materials. However, hygrothermal computer models are only as reliable as their input data, and it is often desirable to test a few key material properties and use the results to modify the materials in the database. For the

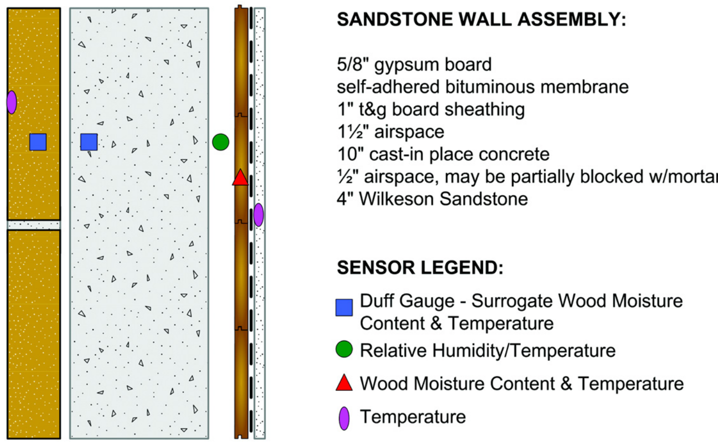

Figure 1 *Existing sandstone wall assembly and installed sensors.*

purpose of the museum hygrothermal simulations, samples of the sandstone veneer were collected from spare pieces at the site and tested to determine the necessary hygrothermal properties to calibrate the WUFI material properties for a similar sandstone material.

SANDSTONE WALL HYGROTHERMAL PERFORMANCE

The sandstone wall assemblies were monitored to determine the performance of the assembly under the as-built conditions and apply that knowledge to the development and calibration of a hygrothermal model to simulate a proposed thermally upgraded wall assembly.

The sandstone wall assembly was monitored at four locations: three at the west elevation and one at the south. At one west-facing location, the wall sensors were located close to an exterior fountain where the sandstone is exposed to significant wetting from water splashing when the fountain is in operation from spring through fall.

The existing sandstone wall assembly and location of the installed sensors is shown in Figure 1. Installed sensors include the following:

- Relative humidity/temperature sensors to measure the RH within the air-cavity behind the board sheathing.
- Wood moisture content/temperature sensors to measure the moisture content of the >80-year-old fir board sheathing.
- Surrogate wood moisture content/temperature "duff gages" (i.e., surrogate gages) to measure moisture level in the sandstone and concrete, which can be determined by using the sorption isotherm (relationship between moisture content and equilibrium RH) for the calibrated wood sensor.
- Exterior and interior wall surface temperature in addition to the temperatures measured at the RH and MC sensors. The temperature at the RH/MC sensor locations are also used to temperature correct the RH and MC sensor outputs.

Sensors were installed from the interior of the exhibit spaces, and were typically located within a 1 ft^2 section of wall. Surrogate moisture sensors were drilled in to the wall from the interior and located 2.5 in. from the exterior sandstone surface. During sensor installation, it was noted that the 1 in. tongue-and-groove board sheathing consists of old-growth fir, installed some 80 years previously. Core samples were taken for calibration of the moisture content pins.

Sensor Calibration and Accuracy

Point Moisture Measurement (PMM) Sensor. The PMM sensors were installed within the building wall system behind the gypsum wall board, probing into the old-growth fir tongue-and-grove sheathing. The PMM sensor provides a surface temperature for the correction factors to moisture content calculations. The 80-plus-year-old wood was lab-tested to obtain the difference in moisture content from the electrical resistance readings of the material via gravimetric sampling over a range from 5% to 35%. The average gravimetric moisture content was calculated to be 9.3% less than the moisture content from the resistance measurement. The moisture content of the aged fir sheathing was reduced by this factor in the results.

Embedded Moisture Sensor (EMS). The EMSes (duff gages) used for this project were manufactured using hemlock wood as the surrogate moisture material. The moisture content percentage of the hemlock was calculated by

$$MC = \left[\frac{M + (0.567 - 0.0260x + 0.00051x^2)}{0.88(1.0056^x)} - b\right] \div a \qquad (1)$$

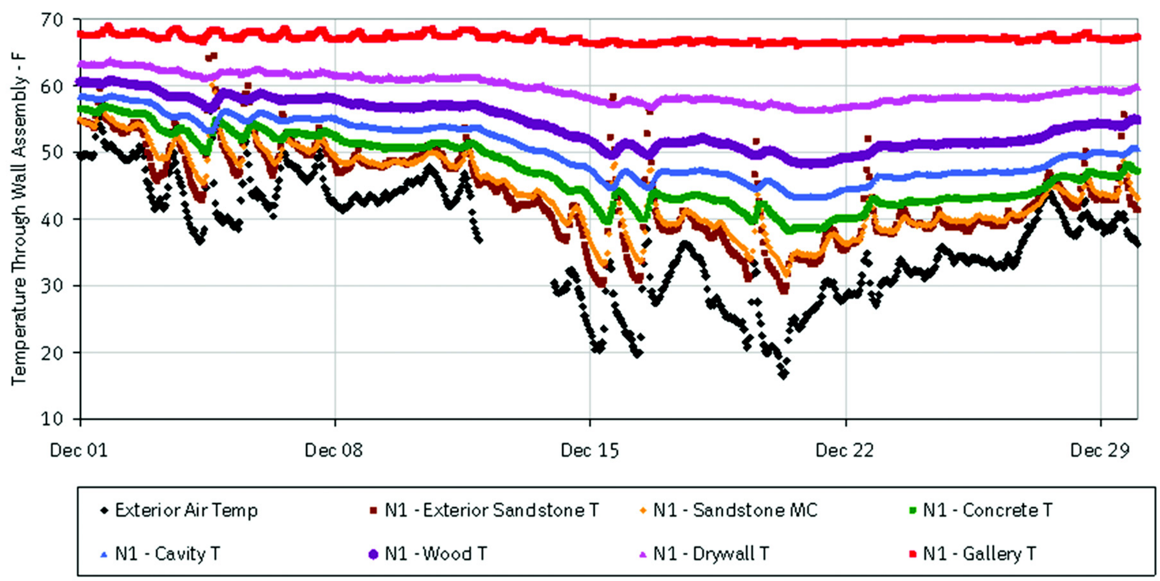

Figure 2 *Temperature profile through west-facing sandstone wall at north gallery, December 2008.*

where

M = moisture content at 23°C

x = temperature of the wood, °C

a, b = species correction regression coefficients (Garrahan 1989)

The correction regression coefficients for eastern hemlock (Pfaff 1974) were used to estimate the moisture content of the material around the embedded moisture sensor; $a = 0.904$, $b = -0.051$.

Individual embedded sensor calibration was completed by comparing gravimetric and resistance-based moisture content readings over the range of moisture content interest from 15% to 35%. The 14 calibrated sensors used in the project were selected to have the closest moisture characteristics to each other, with a corresponding standard deviation ranging from 0.04 to 0.07 from the average of 27 sensors.

Relative Humidity Sensor. HTM2500 is factory calibrated to within to ±2% at 55% RH. Over the range from 10% to 95% RH, typical sensor accuracy is ±3%. Temperature correction was performed on every measurement.

Pressure Sensor. Setra Model 265-0R5WB has a range of ±0.5 in. of water (±124.5 Pa). The sensor has a accuracy of ±1% of full scale or 0.005 in. of water (1.2 Pa). Zero offsets were site calibrated, and expected zero-shift sensor drift was ±0.033%, or 0.5 in. of water, which equals 0.0165 in. of water (4.1 Pa). Periodic maintenance to zero-shift the sensors was performed and correction factors applied to the data.

Data Acquisition System. The data acquisition system was hybrid wired/wireless, enabling densely located sensors to be wired together and powered, while the sparse or difficult-to-wire sensors communicated wirelessly and were powered by batteries. The raw resistance and voltage values from the analog-to-digital conversion process in the WiDAQ were maintained separately throughout the system from processed data, so correction factors could be applied to the processed data at any time.

Analysis of the sandstone assembly is discussed in the following section.

SANDSTONE VENEER WALLS

Interior Surface Temperatures

Temperatures were compared to understand the thermal performance of the sandstone and concrete wall assemblies, particularly the interior surface temperature and risk for condensation at the interior wall, and exterior surface temperature for risk of freeze-thaw damage of the sandstone veneer.

Measured temperatures throughout the west-facing sandstone wall assembly at the north exhibit space are plotted in Figure 2. The measured temperatures at the N1 exhibit are representative of typical conditions for the sandstone wall assemblies.

The sandstone wall is an uninsulated but thermally massive wall assembly; therefore, the assembly's thermal response is slow. The exterior surface is strongly affected by solar heating over all seasons, with large daily fluctuation in temperature. Temperatures throughout the wall's mass remain more consistent, only slightly affected by daily temperature swings. At the coldest time of the year (<20°F exterior temperatures), the surface of the sandstone drops down to only slightly below freezing, 29°F to 30°F. Depending on the saturation level of the sandstone's surface, it could be susceptible to freeze-thaw damage. Based on a review of the sandstone

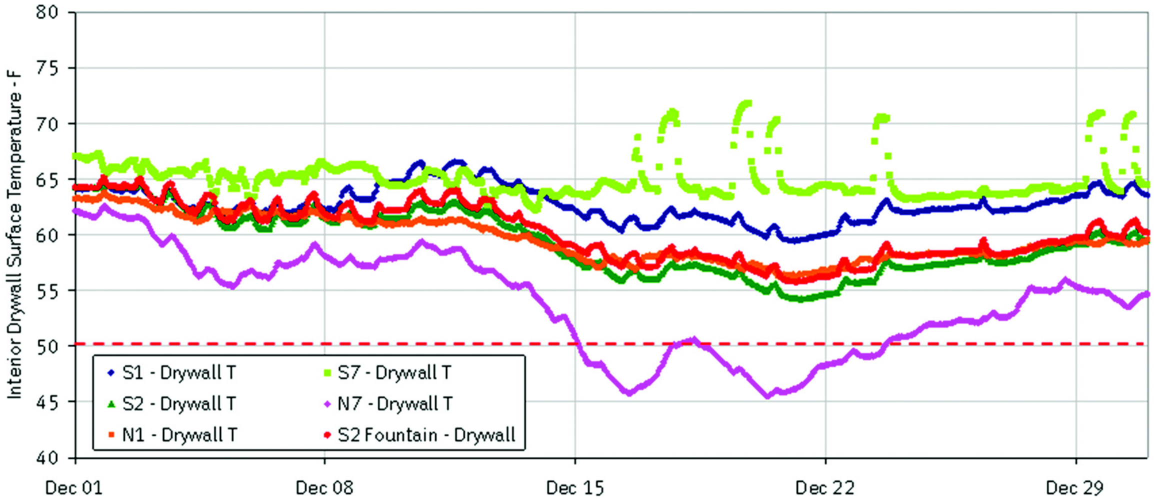

Figure 3 *Interior wall surface temperature of monitored exterior walls; worst-case December 2008 conditions.*

façade, freeze-thaw damage does not appear to be an issue, as typical in Seattle's temperate climate.

Interior wall surface temperatures are much lower than interior air temperatures, with a maximum wintertime difference of approximately 10°F. As a result of the lower temperatures, the RH level at the wall surface will be higher than the exhibit space, and conditions behind artwork may be conducive to organic growth (>80% RH [moderate risk] to >95% [high risk]). If the wall surface temperature drops below the exhibit space air dew-point temperature of approximately 50°F, then condensation is likely to occur. Interior wall surface temperatures are compared for four sandstone wall locations monitored at the south and north exhibition spaces and are plotted in Figure 3 for the coldest period in December.

Sandstone Moisture Levels

Because no sensor exists to accurately measure the in-situ moisture content of sandstone or concrete for prolonged periods, moisture levels within the sandstone panels and concrete wall were measured using surrogate moisture content sensors made of wood. Wood sensors embedded in the sandstone or concrete reach equilibrium with the moisture level within the stone; based on the known relationship between wood sensor moisture content and RH level, an equivalent RH (referred to in the figures as "eRH") within the sandstone/concrete can be determined. Thus, it was determined that RH levels within stone and concrete materials exposed to exterior environments are high (greater than 80% year-round), with levels typically slightly higher than the average exterior RH level, based on the amount of wetting from rainfall and other sources.

By using surrogate moisture content sensors, the RH level was measured within the sandstone near mid-depth, 2 to 2.5 in. from the exterior of the 4 in. thick panel. The measured wood moisture content and calculated RH levels in the sandstone from July 2008 through June 2009 are provided in Figure 4. The calculated RH levels within the concrete behind the sandstone veneer are shown in Figure 5. Figure 6 presents the calculated driving rain on the west façade, correlating with the moisture content of the sandstone.

The RH and subsequent moisture levels in the sandstone and concrete remained fairly consistent throughout the monitored period and were at normal levels. As expected, the sandstone and concrete at the S2 exhibit fountain remained the highest as a result of continuous wetting from fountain water splash-back against the wall (Figure 5). When the fountain was shut off in October, the sandstone dried slowly over the winter, until the fountain was turned back on again in May. The moisture levels in the stone and concrete near the fountain are indicative of worst-case conditions for the sandstone façade.

Moisture levels in the exposed west-facing sandstone veneer remained fairly consistent, although after large driving rains in November and January (as shown in Figure 6), the monitored locations at S1 and N1 (exposed at west elevations) were both wetted significantly, resulting in an increase in the overall sandstone moisture content, up to similar levels caused by the fountain.

The monitoring data show that driving rain has an influence on the moisture levels of the sandstone, and that winter rains can keep the sandstone wet for the entire winter. Drying is slow and occurs in the spring, but springtime driving rain also has a significant effect on wall moisture levels. Figures 4, 5, and 6 clearly demonstrate that moisture from a driving rain at the end of April was driven into the wall by solar radiation, wetting both the sandstone and later the concrete.

Board Sheathing Moisture Levels

The moisture content of the board sheathing was measured at each of the monitored wall locations. The condition of the old-growth fir was generally good, although minor evidence of moisture staining and organic growth was

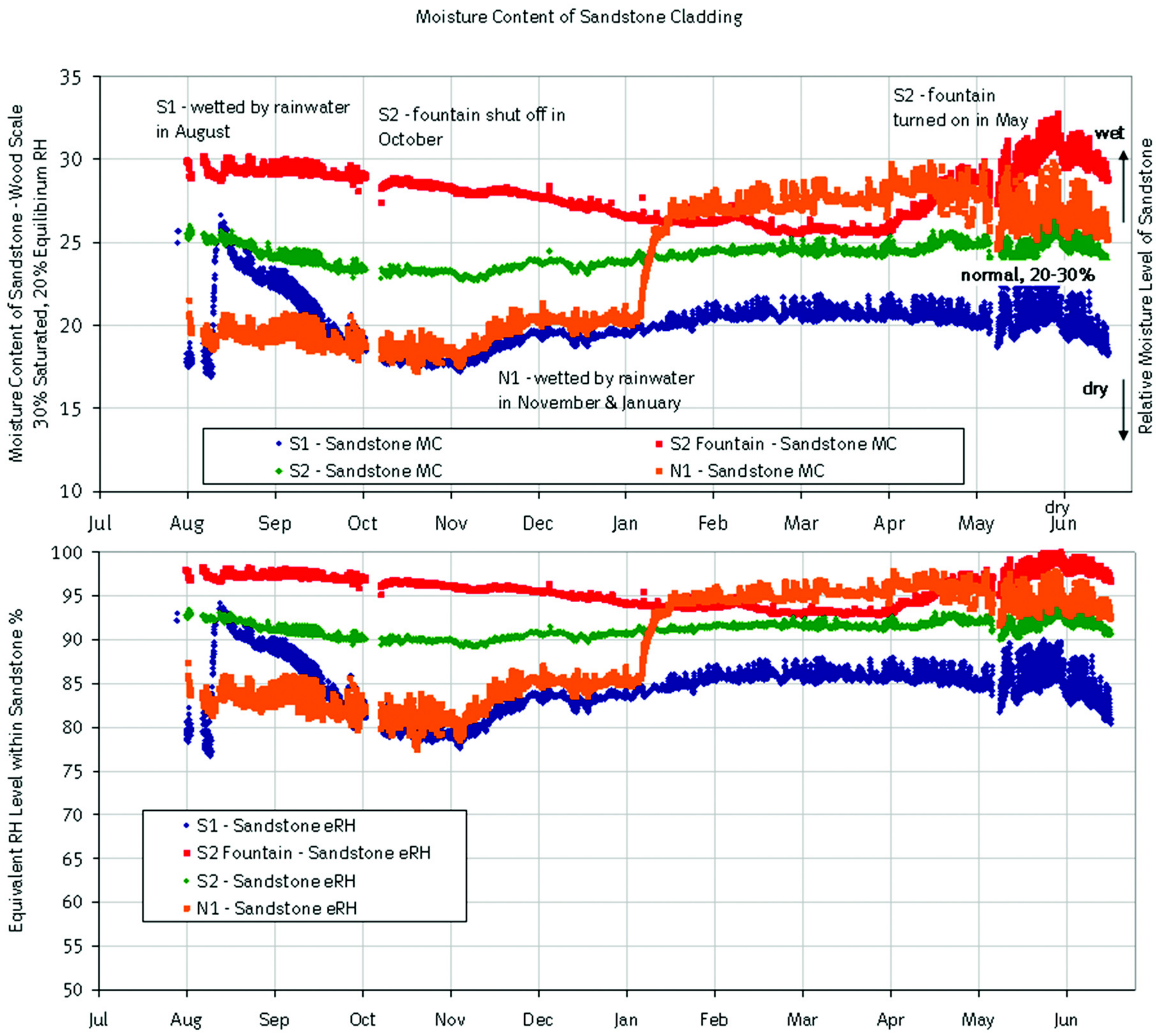

Figure 4 *Measured RH within sandstone veneer at mid-depth: July 2008 through June 2009.*

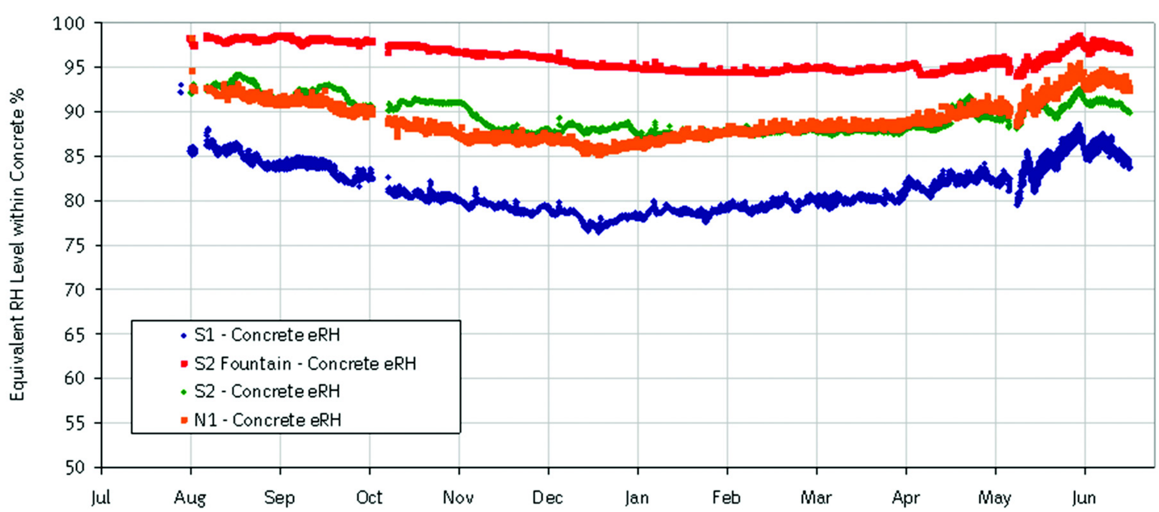

Figure 5 *Measured RH within concrete, directly behind sandstone veneer; July 2008 through June 2009.*

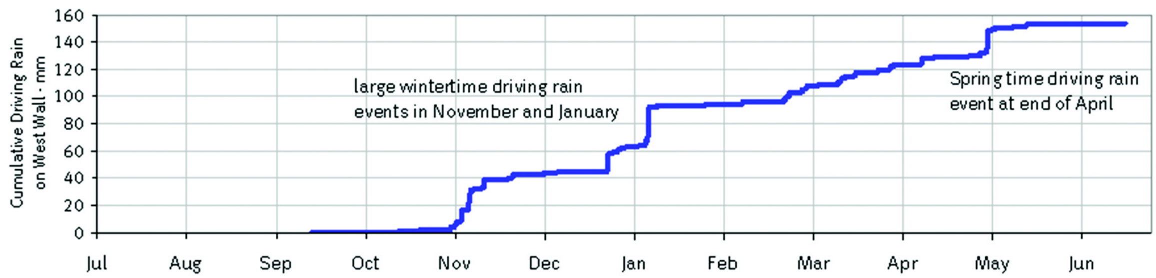

Figure 6 *Calculated driving rain on west-facing sandstone façade: September 2008 through June 2009.*

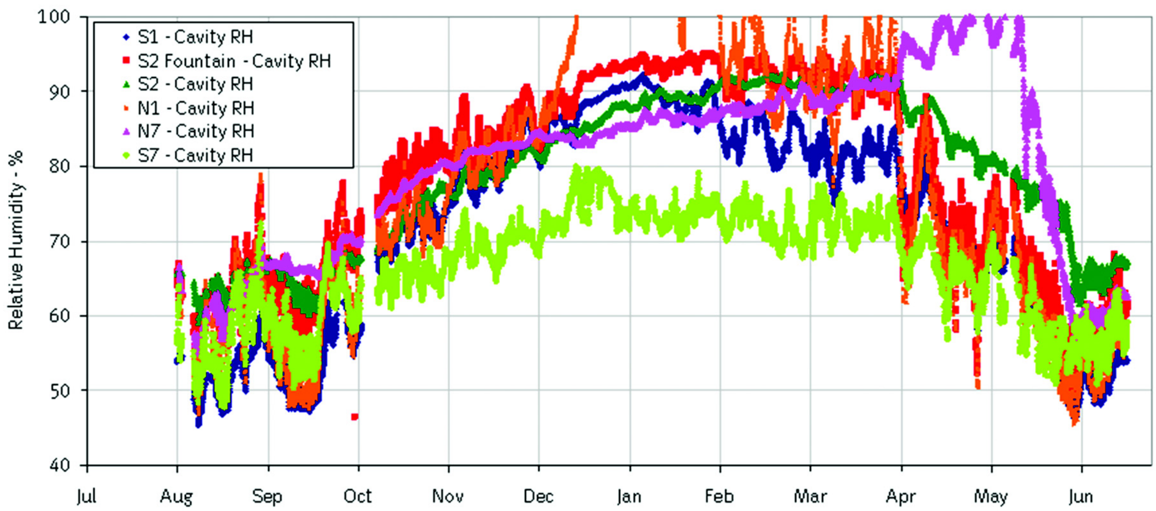

Figure 7 *Humidity within cavity between concrete and wood sheathing boards: July 2008 through June 2009.*

observed on the back-primed surface of the sheathing at each of the four monitored sandstone locations. Figure 7 shows the measured relative humidity within the air cavity space between the fir sheathing and concrete, and Figure 8 shows the moisture content of the fir sheathing. Moisture content sensors were installed on the backside of the sheathing boards.

Relative humidity within the cavity between the concrete and board sheathing rises during the winter months. Consequently, the moisture content of the board sheathing elevates in most locations above fiber saturation. The four sandstone wall locations are noticeably much wetter than the exposed concrete or concrete block assemblies. The sandstone wall assembly contains a vapor barrier on the interior side of the board sheathing, which blocks vapor diffusion toward the interior and appears to prevent the wood from drying. The wall assemblies at exhibit N7 and S7 (exposed concrete and concrete block) do not have a vapor barrier.

Exterior leaks and vapor diffusion were ruled out as primary wetting mechanisms, leaving interior air-leakage into the cavity between the wood sheathing and concrete as the source of moisture wetting the sheathing. Measured temperatures through the sandstone wall assemblies indicate that concrete and wood surface temperatures within the cavity are between 10°F and 20°F colder in winter than the interior air (see Figure 2), because the wood sheathing and drywall are relatively insulating in comparison to the concrete and sandstone. Temperatures in the cavity are also at or below the dewpoint temperature of the exhibit spaces. As a result, when warm, moist air from the exhibit area enters the cavity, the RH level rises, contributing moisture to the porous concrete and wood surfaces via adsorption. When temperatures in the cavity warm up in the spring, the accumulated moisture evaporates and is removed by airflow through the cavity.

HYGROTHERMAL MODELING AND CALIBRATION

Performance of the existing wall assembly was modeled using WUFI 4.2 to improve our understanding of the walls performance and to calibrate the hygrothermal model with the measured data. The calibrated model was then modified and used to perform parametric simulations to predict the future performance of the proposed wall upgrades.

Measured weather data was also input into the WUFI model for simulation to allow for the comparison to the

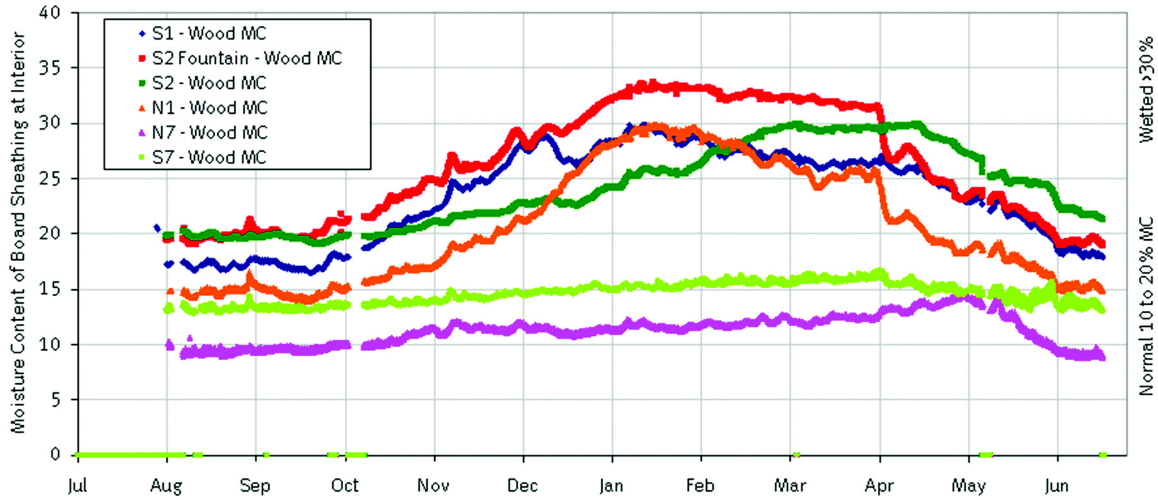

__Figure 8__ Moisture content of wood sheathing boards: July 2008 through June 2009.

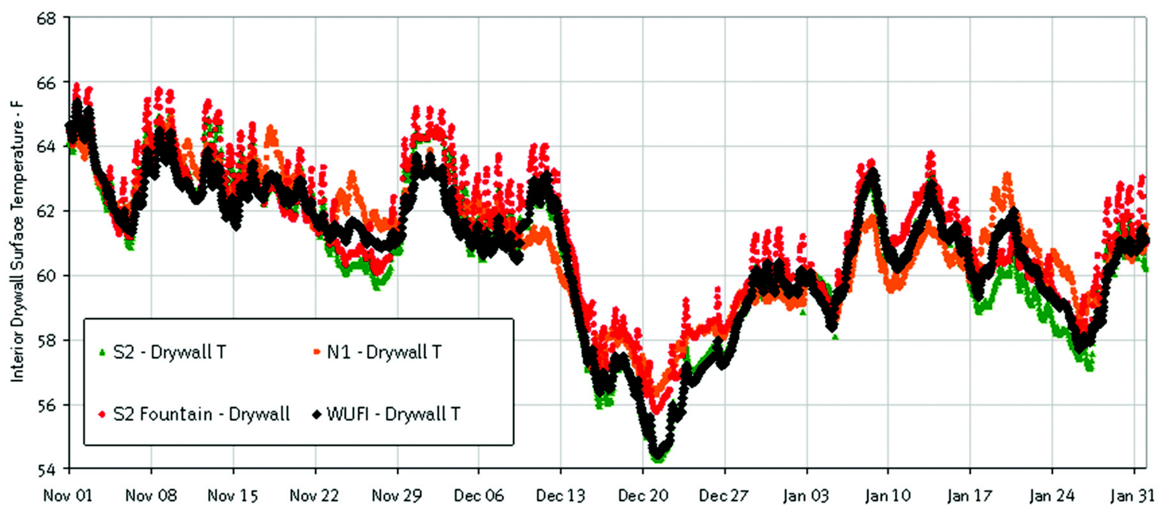

__Figure 9__ Measured versus WUFI modeled interior drywall surface temperature, November 1, 2008 through February 1, 2009.

measured data recorded at the various sensors. Measured climatic data from September through April (7 months) were used to calibrate the model and perform the simulations. Initial moisture levels within the materials were set based on the measured data.

The simulations showed that the WUFI model accurately approximated both the measured moisture and thermal performance of the sandstone wall assemblies. Of most concern for the analysis are the moisture levels and temperatures of the sandstone for freeze-thaw assessment, and interior wall surface temperatures, for wall surface condensation risk. Figure 9 compares the modeled and measured interior drywall surface temperature for a 2-month period during the winter. Small variations were observed between the model and measurements, but the hourly trends were well captured within ±2°F.

WUFI is also able to approximate the moisture levels within the sandstone; however, small variations between the modeled and measured data were observed (Figure 10). These differences largely appear to be the result of variable driving rain rates on the sandstone surface, as well as external variables such as shading from nearby trees and vegetation, and unknown moisture redistribution characteristics of the sandstone. Both locations appear to receive less than the amount predicted by WUFI. Absorption of water into the sandstone also varies by location, as does absorption of water into the surrogate moisture content sensors embedded in the sandstone. Overall, the modeled RH within the sandstone provides a conservative estimate of its performance and is likely

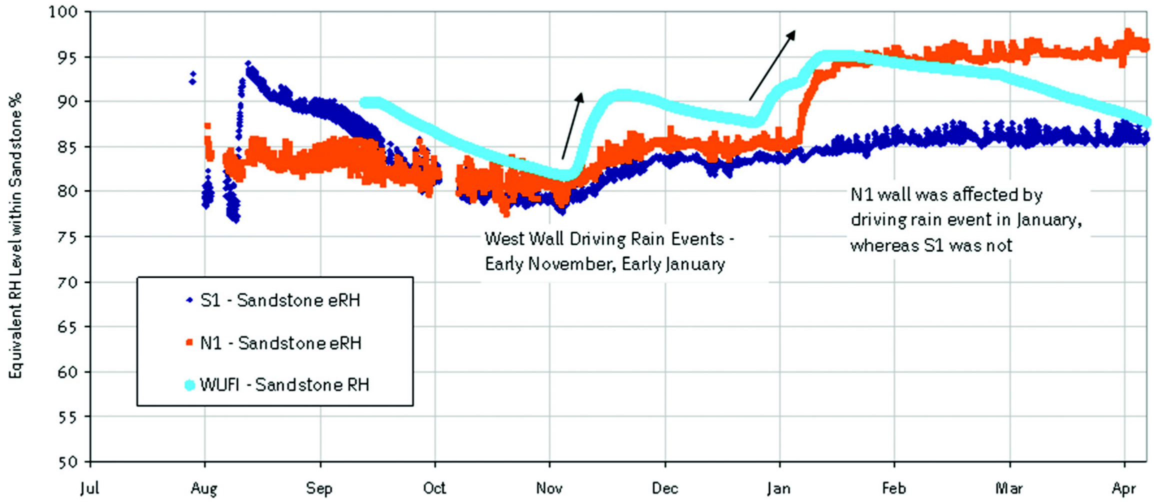

Figure 10 *Measured versus WUFI modeled RH level within sandstone at west-facing sandstone wall assembly.*

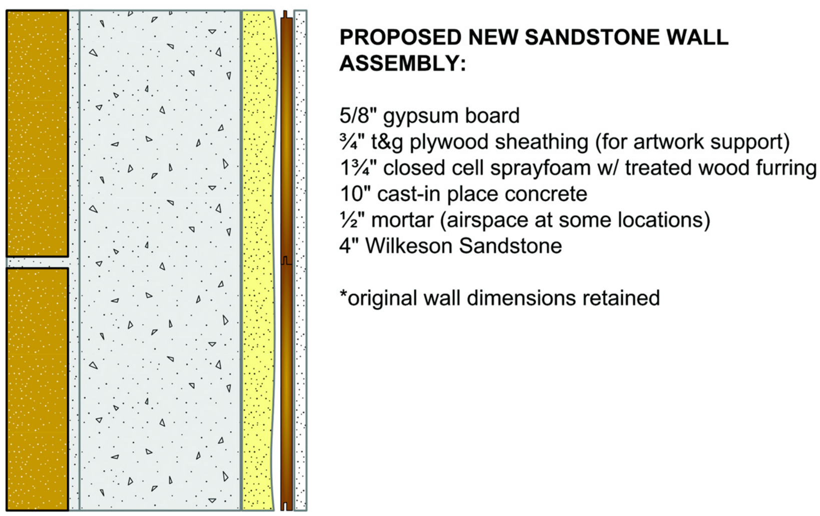

Figure 11 *Proposed sandstone wall assembly.*

representative of an exposed location near the top of the building, which receives more driving rain.

PROPOSED WALL UPGRADE

To improve the thermal performance of the sandstone wall assembly without removing the sandstone from the exterior, it was proposed that insulation be added to the interior of the wall assembly. The proposed wall sandstone wall assembly with the addition of 1 3/4 in. of closed-cell spray foam (R-10.5) is shown in Figure 11.

Insulating the sandstone wall assembly significantly improves thermal performance. In addition to reduced heat loss and energy savings, interior surface temperatures are improved. The measured data indicate that currently the interior wall surface temperature is low enough that condensation can occur behind artwork. Figure 12 compares the modeled temperature profiles for the existing and proposed wall assemblies visualized using THERM 5.2 and calibrated with the measured data and an exterior temperature of 20°F.

As shown, the interior surface of the insulated wall assembly is significantly warmer than the uninsulated wall, especially behind the artwork. Surface temperatures in the insulated wall are much higher than the air dew point temperature, reducing the potential for condensation.

One of the potential risks associated with insulating the interior of masonry or stone wall assembly is the possible increased chance of freeze-thaw-related damage to the sandstone surface. Although rare in Seattle's climate, the analysis

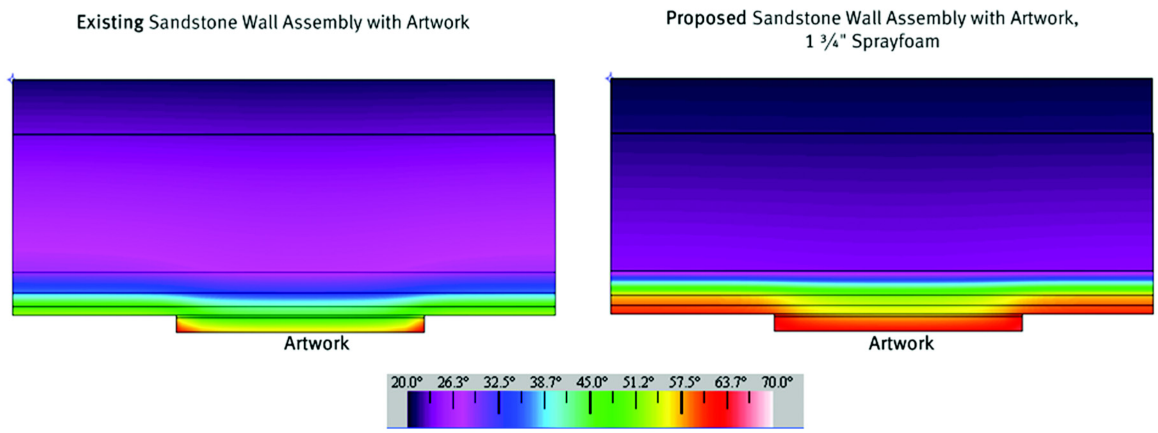

Figure 12 Plan view of existing and proposed wall section showing temperature profile of wall assembly.

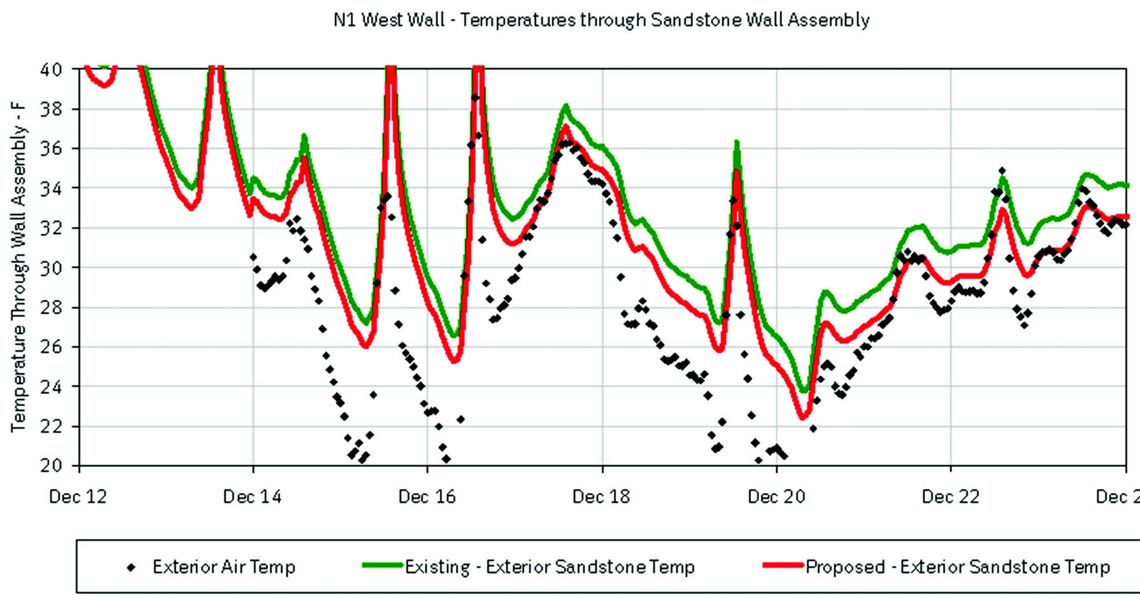

Figure 13 Temperature profile through west sandstone wall at gallery N1.

was performed as a precaution. Freeze-thaw damage can occur when the surface of the sandstone is near saturation (typically 80% of saturation) and drops below freezing and thaws. Depending on the properties of the stone, spalling may occur. No evidence of spalling caused by freeze-thaw damage was observed on the sandstone façade during our review. Using WUFI, it was confirmed that the number of freeze-thaw cycles the sandstone surface sees in a typical year when saturated is zero (Figure 13). The number of hours that the wall assembly spends below freezing was increased from 123 to 155 hours when simulating 2008 winter data, but no freeze-thaw cycles at critical saturation levels were observed. Therefore, an interior-insulated sandstone wall assembly does not appreciably increase the already low risk for freeze-thaw damage to the sandstone. Other previously discussed factors with the sandstone material itself are more likely to cause spalling than freeze-thaw damage.

DISCUSSION

The computer models WUFI 4.2 and Therm 5.2 can be invaluable tools when planning renovations of historic facilities to improve energy efficiency and airtightness. These modeling tools, coupled with a comprehensive building enclosure monitoring system, are necessary to understand the hygrothermal performance characteristics of existing assemblies and predict future post-renovation performance of potential renovation options. To that end, a long-term monitoring system was designed to measure key interior operating conditions and hygrothermal performance variables of wall assembly components. Data gathered over the course of one year provided the necessary information to analyze the effect interior and exterior conditions have on the subject building's exterior wall performance.

For the subject building, the monitoring system consisted of specifically positioned temperature, relative humidity (RH), surrogate moisture content, air pressure difference, and condensation sensors. The sensors were embedded in select wall assemblies, wired to a remote central data acquisition system, and uploaded online for review and analysis in real time.

The measured data were used to calibrate hygrothermal modeling software WUFI 4.2 and thermal modeling software Therm 5.2. To develop appropriate design solutions for the proposed exterior wall renovations, analysis was performed on a proposed wall assembly to determine the potential changes that adding insulation may have on the existing wall assembly materials, especially moisture-sensitive components. Access to monitored data makes it possible to compare material properties of the subject building to materials in the libraries of WUFI and Therm. If materials of the subject building are not available in the model libraries, similar materials can be chosen and their characteristics modified or calibrated for modeling purposes.

CONCLUSION

Though small variations between the modeled and measured data were observed, the close correlation between measured and modeled moisture data is sufficient for confidently predicting wall assembly performance. It was determined that, for the historic sandstone veneer portions of the building, adding 1 3/4 in. of closed-cell, 2 lb/ft^3 density spray polyurethane foam to the interior side of the wall is expected to improve interior surface conditions and have little effect on the historic sandstone veneer. Renovations have yet to be undertaken to the subject building, but post-renovation monitoring of assemblies is planned to compare with the computer models.

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