Measuring the Impact of Interior Insulation on Solid Masonry Walls in a Cold Climate

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BUILDING OWNERS AND designers are increasingly considering upgrading the exterior enclosure's thermal performance in existing buildings. Our aging building stock provides tremendous opportunities to reduce our overall environmental footprint through upgrades to the exterior enclosure.

Given the embodied energy inherent in existing buildings, it is often preferable to modify existing assemblies instead of tearing them out and sending waste to the landfill. Buildings with solid or load-bearing masonry walls typically employ interior insulation retrofit strategies as these buildings often have heritage or historical significance that preclude work from the exterior. This may result in accelerated masonry freeze-thaw deterioration, embedded steel (lateral ties and supporting angles) corrosion, interior plaster finish deterioration and/or mould growth.

This paper describes a fully instrumented large-scale mock-up completed in a southern Ontario private school to allow direct comparisons between insulated and non-insulated walls with a focus on the evaluation of freeze-thaw and corrosion risks. Climate conditions and wall temperature, relative humidity and moisture content are compared and discussed. Climate conditions (wetting and temperature) over the monitoring period were less severe than average. As a result, measured values were used to refine computer models to simulate wall performance under more severe climate conditions.

Findings show low freeze-thaw risk to the insulated brick, but an increased risk for embedded steel corrosion. Further study is recommended to evaluate sensor response, confirm selected freeze-thaw thresholds and monitor walls under more severe climate conditions.

INTRODUCTION

The objective of this study was to evaluate the risks associated with insulating exterior masonry walls from the interior. The building reviewed is a three-storey school constructed in Toronto, Ontario in the late 1950s. The exterior walls are load-bearing masonry measuring three wythes thick. The wall interior is finished with hollow clay tile and painted plaster.

A literature review on insulating masonry walls revealed case studies demonstrating adequate performance, recommended practices to minimize risks and preferred insulating methods. Specifically, two case studies of insulated masonry walls in a cold climate were reviewed; Dumont (2001), shows walls performing as designed up to 14 years after retrofitted. General practices to minimize risks as outlined by Goncalves (2003) are: minimize exterior rain penetration into the wall, minimize penetration of interior humidity into the wall (from vapor diffusion and/or air flow), limit the thickness of the insulation, and minimize air pressure difference across the wall. Some risks associated with fiberglass batt insulation have also been highlighted by Straube (2007); in particular, convective loops promote condensation where the insulation is not applied tightly against the masonry wall.

There are numerous methods to insulate masonry walls from the interior, each with specific risks and benefits in particular situations. Common materials used to insulate masonry from the interior are:

1. Fiberglass insulation (with independent air flow and/or vapor control layer(s);
2. Open-cell spray-foam insulation; and
3. Closed-cell spray-foam insulation.

Mechanical system interventions can also be employed to supply warm/dry air to wall cavities inboard or outboard of the retrofit insulation to promote wall drying and reduce deterioration risks.

Our study is focused on the use of interior closed-cell spray foam insulation at a building in Toronto without supplying conditioned air to any of the wall cavities. For this specific case study, several deterioration risks were identified in a feasibility study and examined through computer modeling, including: freeze-thaw deterioration, embedded steel corrosion, organic growth, plaster deterioration and differential thermal expansion. These risks were further evaluated through field measurements of insulated and un-insulated mock-up walls, and simulated further under more severe climate conditions. This paper focuses on the more significant risks raised in the field study:

1. Freeze-thaw deterioration: Applying insulation to the building interior can increase the risk of freeze-thaw deterioration in the exterior brick and mortar since the drying potential is reduced and materials outboard of the insulation are colder during winter conditions.
2. Embedded metal component corrosion: Insulating the masonry from the interior can increase the embedded metal corrosion risk, since relative humidity increases as temperatures and drying potential decreases. However, lower temperatures may also reduce corrosion risk, since corrosion rates slow down as temperatures decrease.

METHODOLOGY

Work completed for this evaluation included:

1. Mock-up wall monitoring: Four exterior wall areas were instrumented

in one room. Hourly measurements were taken on existing (un-insulated) and upgraded (insulated) wall assemblies on the east and south elevations. Details of this installation are outlined below.
2. Brick testing: Nine brick samples were removed from the exterior wall and tested to determine their water absorption properties (A-value, Straube 2005). These bricks were also used to calibrate the moisture content sensors (wood wafers) with the corresponding brick moisture content.
3. Climate analysis: The exterior climate during the monitoring period was evaluated by comparing local temperature and rain data to climatic normals (tipping rain buckets were also set-up to directly measure driving rain at the mock-up locations).
4. Computer model extrapolations: Our previous computer models were refined using measured brick properties and verified against measured data. Models were then completed with more severe climatic conditions than those measured (due to less than normal wetting conditions during the initial monitoring period), to further evaluate wall performance. This work was completed using a computer based analytical program (WUFI® Pro 4.1, Fraunhofer Institute for Building Physics 2006).

Mock-up wall monitoring set-up

Four mock-up walls were constructed. A room was selected on the top floor and at an outside corner facing south and east since this was expected to be the most severe climate exposure for this building. **FIGURE 1** contains the wall sections and sensor locations. **PICTURE 1** shows the mock-up wall locations from the exterior. A description of the tested wall assemblies is as follows:

1. Zone A: Existing (un-insulated) wall assembly, east elevation: Three wythes brick; 50 mm (1.9 inches) hollow clay tile; 20 mm (0.78 inches) plaster; 2 coats paint (likely oil);
2. Zone B: Modified (insulated) wall assembly, east elevation: Three wythes brick; 50 mm (1.9 inches) SPF insulation; 25 mm (0.98 inches) air space; 12 mm (0.47 inches) drywall; 1 coat primer; 2 coats latex paint;
3. Zone C: Modified (insulated) wall assembly, south elevation: Three wythes brick; 50 mm (1.9 inches) SPF insulation; 25 mm (0.98 inches) air space; 12 mm (0.47 inches) drywall; 1 coat primer; 2 coats latex paint; and
4. Zone D: Existing (un-insulated) wall assembly, south elevation: Three wythes brick; 50 mm (1.9 inches) hollow clay tile; 20 mm (0.78 inches) plaster; 2 coats paint (likely oil).

Nine sensors were installed in each wall to measure temperature, relative humidity and moisture content at various locations across the wall (see **FIGURE 1**). Exterior temperature and relative humidity were measured directly outside the test walls. Driving rain was measured on the exterior of the walls, at the bottom of Zones B and C (south and east). Interior temperature and relative humidity were also measured at two locations within the test room.

The temperature sensors are 10K Ohm NTC thermistors, and the relative humidity sensors are capacitance based sensing elements housed in vapor permeable covers to protect them from liquid water. The moisture content in the brick and mortar was measured using surrogate wood resistance sensors. These sensors are a plug of eastern white pine with the resistance measured across the material by a pin on one end and a ring around the other. These sensors are similar to those examined by Carll & TenWolde (1996) and Ueno & Straube (2008).

All wall sensors were installed from the interior, through 13 mm (0.51 inches) diameter holes drilled to the depth of interest. The temperature and relative humidity sensors had a prefabricated

Picture 1. Exterior south-east corner. All wall mock-up zones shown, zones A/B (east elevation), zones C/D (south Elevation).

plastic plug matching the diameter of the hole attached to the back of the sensor. Once in place, the back of the plugs were sealed in place with epoxy. The balance of the drilled hole was then filled with spray foam insulation.

The moisture content sensors were also installed through drilled holes, but were encapsulated with bentonite clay to provide full contact between each sensor and the parent material. The balance of these holes was also filled with spray foam insulation. The wood

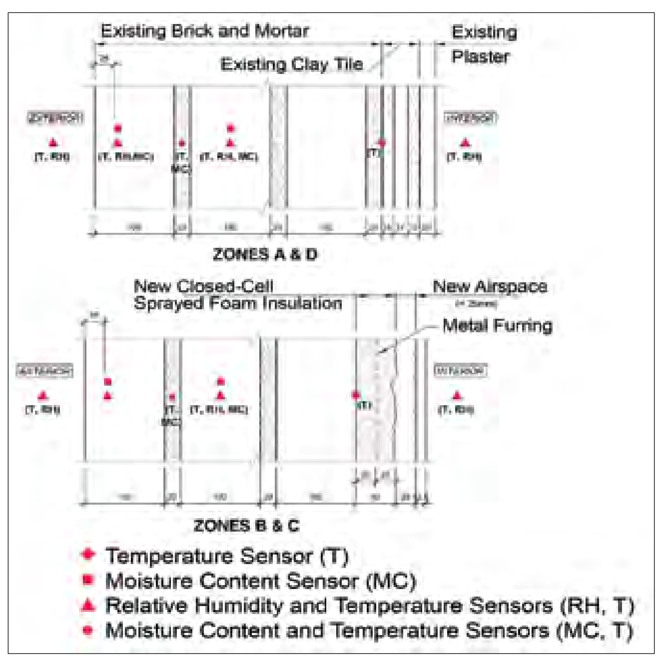

Figure 1. Mock-up wall sections. Zones A&D: existing un-insulated wall assembly. Zones B&C: modified insulated wall.

resistance sensors were tested in a lab to calibrate the wood moisture content readings with the moisture content of the parent brick and mortar. Further details about similar sensors used are described in Straube et.al. (2002).

The driving rain gauge uses a standard tipping bucket to measure water volume, mounted in a custom housing. The housing mounts flush to the wall, covering an area about 300 mm x 300 mm (11.8 inches), and is delineated at its perimeter by 75 mm (2.9 inches) long returns, perpendicular to the wall.

The monitoring system was commissioned on September 18, 2007. This paper reviews data collected over the first winter, from September 19, 2007 to June 1, 2008.

KEY FINDINGS

Our key findings from the work performed are as follows:

Below-average climate conditions during monitoring period

The climatic conditions at the site over the monitored period were less severe than average for Toronto. The key climatic variables for this evaluation are rain wetting and exterior temperatures as they dictate the number of expected freeze-thaw cycles and conditions for embedded metal corrosion.

Below-average wall wetting: Expected driving rain at the site was calculated using publicly available vertical rainfall, wind direction and wind speed data from nearby Queens Park (calculated per procedures described in Straube and Burnett (2005)). A rain deposition factor of 0.5 was used, as determined by comparing calculated wind driven rain from the data noted above against measured wind driven rain on site. Based on this evaluation, the monitored walls were only exposed to about half the driving rain that occurs in an average year, as shown in **FIGURE 2**.

While there was less-than-average driving rain on the south and east elevations over the period under review, there was significant vertical rainfall over this period. Unfortunately, most of this rain was driven onto the N, W and SW elevations. In fact, these elevations experienced 2.5 times the average rainfall. In short, this was an uncharacteristic year for driving rain, with less driving rain from typical directions and more from atypical directions. As the conditions on the monitored walls provide below-average conditions for evaluating freeze-thaw or corrosion risks, the monitoring results were used in combination with computer modeling to further evaluate deterioration risks.

Below-average number of zero degree-crossings: The monitored walls were exposed to 70 percent of the zero degree-crossings that would result during the third coldest year in thirty (10th percentile) from the computer model database. The number of zero-crossings is comparable to the amount seen in the third warmest year in thirty (10th percentile) from the computer model database.

As these are also below-average conditions for evaluating freeze-thaw risks, the monitoring results were used in combination with computer modeling to further evaluate deterioration risks.

Bricks tested may not meet modern freeze-thaw performance standards

The water absorption properties of the tested brick show that they are highly absorptive. **TABLE 1** contains a summary of measured brick properties.

When brick properties are compared to modern CSA standards, the bricks may not meet the specified freeze-thaw resistance performance. While this testing is not designed for existing or aged brick, it could give insight into expected brick freeze-thaw resistance.

The bricks tested did not pass the first two of three CSA test thresholds. These first two tests evaluate the amount of water absorbed into the brick relative to the amount of air remaining in the brick pores (i.e. the room remaining for freezing water to expand). A brick can still have reasonable freeze-thaw resistance

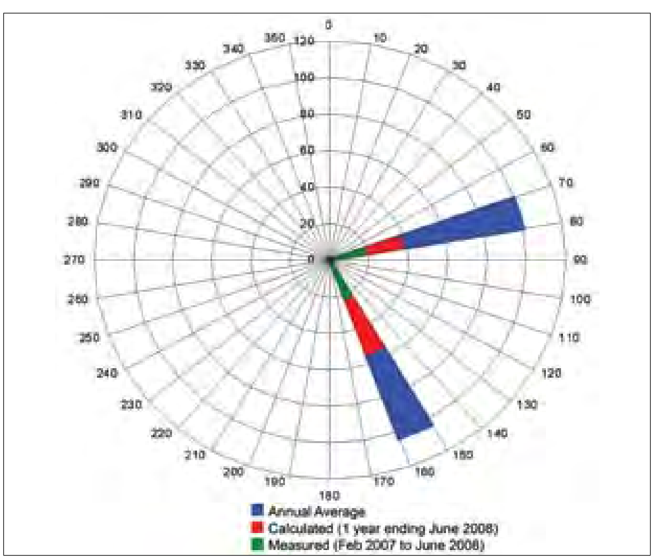

Figure 2. Wind-driven rainfall on test walls. Wind-driven rain shown is for various periods using Toronto Pearson Airport and Queen's Park Weather Stations. A rain deposition factor of 0.5 is used, as determined by on site wind-driven rain measurement.

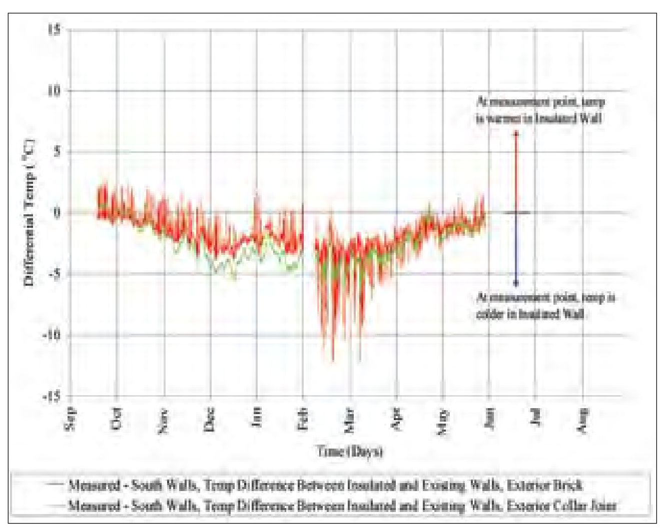

Figure 3. Measured temperature difference between insulated and existing walls. Temperature difference between east mock-up walls at critical locations for freeze-thaw evaluation (exterior brick and exterior collar joint). Generally the insulated wall is up to 12°C cooler than the existing wall.

if it fails these two thresholds, but must pass the third test to prove this under the CSA standard. This third test, (a freeze-thaw test, which cycles partially saturated brick through 50 freeze-thaw cycles) is costly and its reliability is controversial in the industry (Robinson 1995, Vickers 1993). An alternative freeze-thaw test could be performed to evaluate the critical degree of saturation.

Walls demonstrated low freeze-thaw deterioration risk

The measured and modeled insulated walls demonstrated low freeze-thaw deterioration risk.

The measured insulated walls were cooler than the measured un-insulated walls throughout the winter. At wall locations critical for freeze-thaw damage (exterior brick and exterior collar joint), the insulated walls were up to 12°C (53.6°F) cooler than the un-insulated walls (see **FIGURE 3**). This resulted in up to five times as many zero crossings in the insulated walls. The increase in zero crossings was most pronounced on the south exposure, where cooler walls were subject to increased daily heating from the sun (see **FIGURE 4**).

The moisture content in the measured walls was low throughout the monitoring period and, as a result, there were no hours where freeze-thaw damage was likely to occur (see **FIGURES 5** and **FIGURE 6**). The maximum monitored moisture content was 4 percent in the brick and mortar, which is below the estimated 12 percent threshold where freeze-thaw damage is expected to occur (this 12 percent threshold corresponds to 85 percent of the free water saturation). This threshold is expected to be conservative since there should be sufficient room remaining in the pores to alleviate pressures from freezing water.

Given that the low moisture content in the measured walls (and no freeze-thaw risk) likely resulted from less than average wetting conditions discussed earlier, modeling was used to evaluate the freeze-thaw risk in these walls under more severe climate conditions.

The hygrothermal performance of the modeled and measured walls generally compared well (see **FIGURE 7**), particularly at locations sensitive to freeze-thaw (exterior brick and exterior collar joint). The thermal properties of the components are well understood. The relative humidity trends are also consistent between the measured and modeled results, but the modeled values are typically within 10 percent of the measured values.

These results seem reasonable given that a one-dimensional model is being used to represent two-dimensional moisture flow through the mortar and bricks.

The moisture contents are generally comparable between the calculated/modeled and measured results (see **FIGURE 8**). However, there are spikes in the modelled exterior brick moisture content soon after rain events, which do not appear as significantly in the measured walls. This discrepancy is discussed in more detail later in this article. The model was used to evaluate these peak moisture content values, as they are important to freeze-thaw performance.

In the modelled walls subjected to more severe weather conditions than those experienced in the field (using rain deposition factor of 0.5), there were no instances where freeze-thaw damage was likely to occur (see **FIGURE 9**). The maximum moisture content was 10.6 percent (peaking in the brick soon after rain events). The moisture content in the brick between rain events is typically near 0 percent. The mortar moisture content is fairly constant between 2 to 8 percent. These moisture contents are below the estimated threshold levels of 12 percent and 13 percent (brick and mortar respectively) where freeze-thaw damage is expected to occur.

Minor increase in risk for embedded metal component corrosion in insulated walls

There may be a minor increase in embedded metal component corrosion risks for the insulated walls compared to the existing un-insulated walls.

Brick	Brick Type	24 h cold water absorption (kg) / Brick dry mass (kg)	Saturation Coefficient	Meet Freeze-thaw thresholds for Exterior Brick (Y/N)
		CSA: Not greater than 8.0%	CSA: Not greater than 0.78	
1	Interior	9.8%	0.97	N
2	Interior	9.6%	0.99	N
3	Interior	9.9%	0.96	N
4	Interior	10.0%	0.95	N
6	Exterior	10.0%	0.83	N
7	Exterior	9.2%	0.83	N
8	Exterior	13.6%	0.86	N
9	Exterior	13.9%	0.89	N
10	Exterior	11.8%	0.87	N

Table 1. Comparison of brick test results to CSA Standard. The water absorption properties were evaluated for 9 bricks taken from walls near the mock-up location (4 bricks from the interior and 5 from the exterior). These results are compared to the CSA Standard A82-06 "Fired masonry brick made from clay or shale" (see Section 6 - Freeze-thaw durability/ 6.2.2 -Absorption testing).

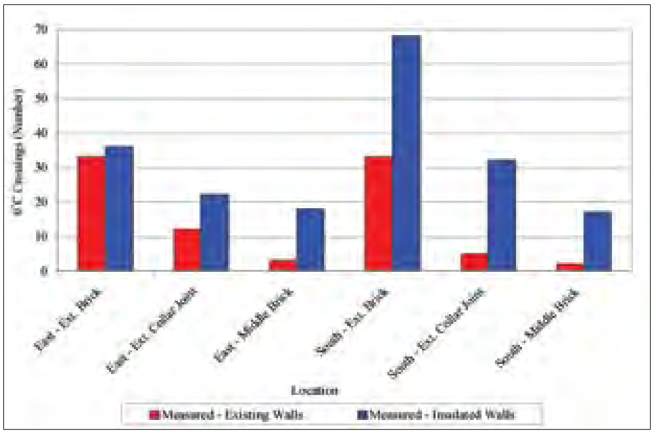

Figure 4. This figure illustrates climate conditions relevant to freeze-thaw cycles. All insulated walls have an increase in the number of zero crossings, particularly the south elevation due to impacts from solar radiation. There were no hours when freeze thaw cycles were observed (when a zero crossing occurred and moisture contents were also above 85 percent of free water saturation).

FIGURE 10 shows the time above corrosion thresholds. Corrosion threshold is Time of Wetness (i.e. hours above 0°C and 80 percent relative humidity) as defined in ISO (1992).

The modelled walls show no increase in corrosion risk between un-insulated and insulated walls. However, the measured walls show an increased risk. We believe this discrepancy is, in part, due to the nature of the sensor installation, with a wood resistance sensor embedded in the parent material using bentonite clay. In addition, moisture transport in the model may occur by liquid transport, while moisture transfer to the sensors is predominantly by vapor diffusion (i.e. slower process). This may result in the sensors showing more time above thresholds after a rain event.

When conditions in the wall support corrosion, it does not necessarily mean corrosion is occurring. The high pH of mortar provides a passive oxidation layer that protects embedded metal from corroding. The pH drops over time as CO2 enters pores in the mortar or where CO2 has direct access to metal through cracks. When and if carbonation reaches the location of metal in the wall, corrosion could begin. Carbonation is, generally, a slow process.

DISCUSSION

The moisture content sensors used are not suitable to detect critical moisture content levels in this brick for a freeze-thaw analysis, since their time response was not fast enough to capture short-term moisture content spikes after rain events and their range of sensitivity is below that of critical levels of interest.

The measured and modeled moisture contents (both over a 25 mm slice at same location in wall) compare well outside of short-term peaks, where the measured values are less than the modeled values. The MC spikes are important to a freeze-thaw analysis, as this is the time when materials could be saturated enough to cause freeze-thaw damage when coincident with below 0°C temperatures. We speculate that the MC spikes are not

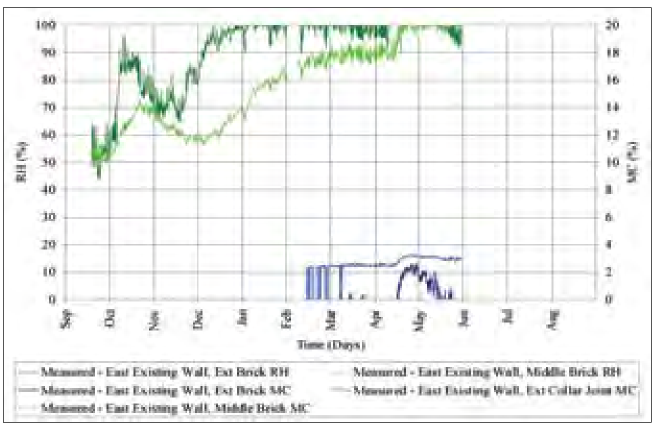

Figure 5. Measured RH and MC in east existing wall. Actual relative humidity and moisture content (wood wafer) measured in the existing east wall. The moisture content is well below thresholds for freeze-thaw. MC values shown are for the wood resistance sensors embedded in the brick, instead of the corresponding brick moisture content in order to increase measurement resolution.

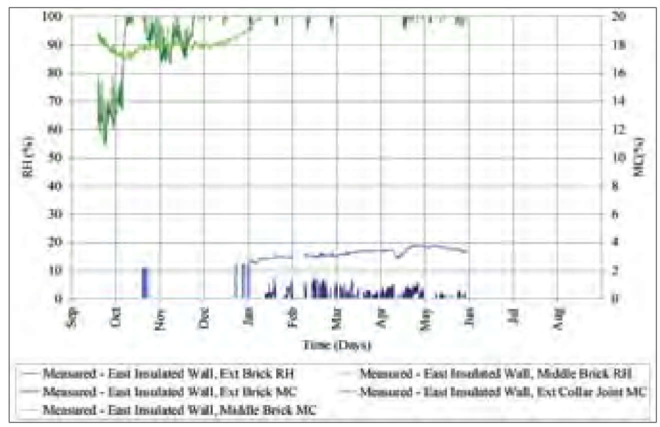

Figure 6. Measured RH and MC in east insulated wall. Actual relative humidity and moisture content (wood wafer) measured in the insulated east wall. The moisture content is well below thresholds for freeze-thaw. MC values shown are for the wood resistance sensors embedded in the brick, instead of the corresponding brick moisture content in order to increase measurement resolution.

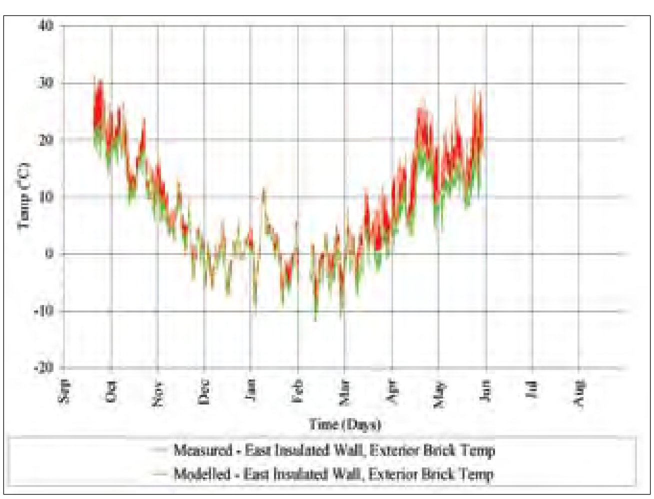

Figure 7. Temperatures shown are similar between modeled and measured walls. Other locations also compare well.

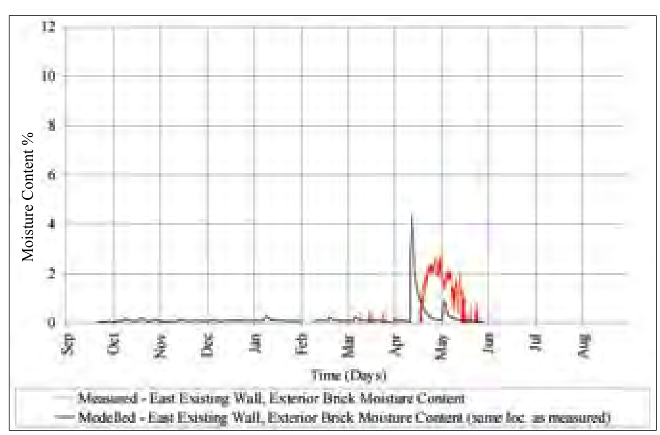

Figure 8. Moisture contents are generally similar, apart from severe spikes in modeled moisture content soon after rain events that are not observed in measured values. This discrepancy should be resolved with artificial wetting of the field sensors to test reaction time to wetting events.

as pronounced in the measured values due to slow sensor response, given sensor size and encasement in bentonite clay (which may impact capillary connectivity). After a rain event, the moisture may dry or be redistributed before the sensor can fully react.

The wood moisture content sensors used to evaluate the brick moisture content operate accurately in the 20 percent to 50 percent wood MC range (corresponding to 0 percent to 8 percent MC in this brick), as shown in **FIGURE 11 AND FIGURE 12**. The wood moisture content did not exceed 30 percent (4 percent in this brick) over the monitoring period due to a lack of wetting, so the upper range of the sensors was not an issue in this case **(SEE FIGURE 10)**. However, given that critical limits for freeze-thaw damage correspond to approximately 70 percent in wood (12 percent in this brick), these wood sensors would not adequately evaluate moisture content near the threshold in this brick.

In summary, the sensors used can indicate safe freeze-thaw performance, but have poor accuracy as one approaches critical moisture content levels in this brick. In addition, the size and capillary connectivity of the sensors should be further investigated and improved to provide a sensor that reacts more quickly.

CONCLUSIONS

Insulated walls

The walls evaluated may be insulated from the interior with a low increase in freeze-thaw risk, as the moisture levels in brick and mortar are not likely to reach freeze-thaw damage thresholds. Proactive measures should be taken to ensure excessive wetting of the wall is avoided (regular re-pointing, and effective water-shedding details, etc.).

Investigate condition of embedded steel prior to insulating walls

Inspection openings in the walls should be used to determine the function, extent and condition of the embedded metal components prior to insulating walls given the high number of hours above corrosion thresholds even for the existing walls. The depth of carbonation in the mortar (passive protection of metal by mortar) should also be checked. Metal components could be replaced with stainless steel components where embedded metal corrosion risk is expected to increase (e.g. stainless steel helical ties could be used to replace or supplement metal ties).

Further monitoring and testing

As climatic conditions experienced over the 2007/2008 winter were less severe than average, continued monitoring of the walls over another winter should be checked in the hopes of providing additional insight into the wall behavior under average or extreme conditions.

The moisture content sensors in the monitored walls should be checked to confirm their reaction time to rain events. This evaluation could be performed by applying water to the area in question, which would allow for a constant wetting condition with

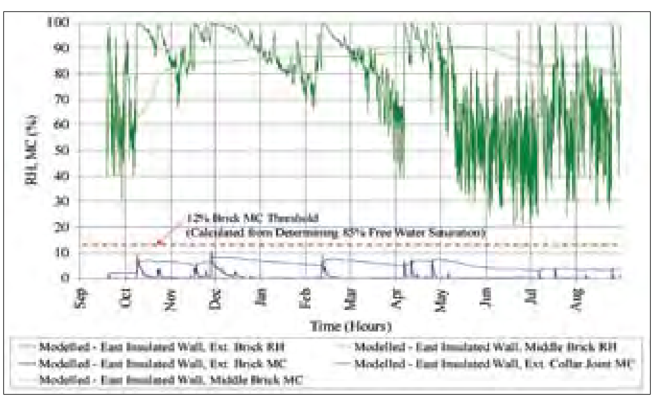

Figure 9. Brick moisture content in most severe modeled case is 10.6 percent, which is below the 12 percent MC freeze-thaw threshold.

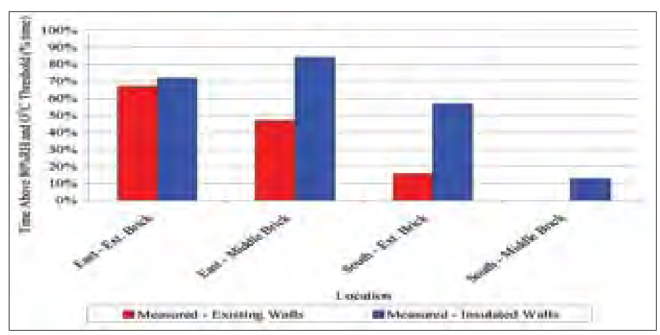

Figure 10. Insulated walls have significantly more time above corrosion thresholds than existing walls, increasing risks for embedded steel corrosion in insulated walls.

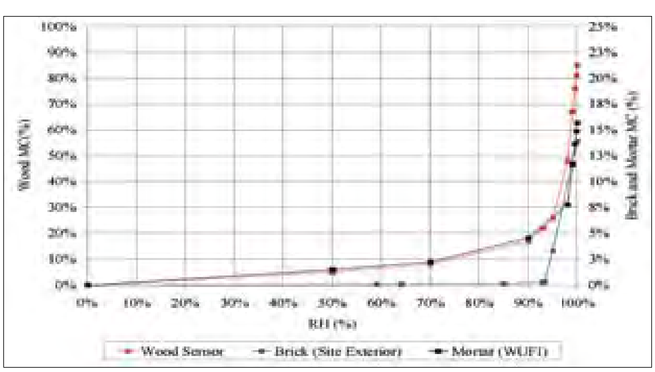

Figure 11. Measurements taken during lab testing of wood sensor installed in brick, as done in the field.

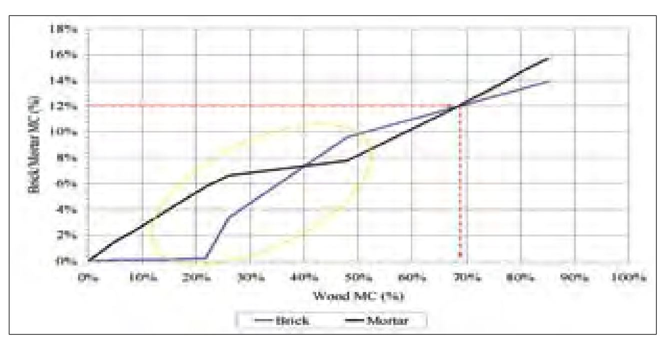

Figure 12. Corresponding brick MC for given wood MC reading. Wood sensors operate accurately in the range circled in yellow. Critical moisture content range for brick freeze-thaw analysis (and corresponding wood moisture content), shown with dotted red arrows.