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Assessing the Freeze-Thaw Resistance of Clay Brick for Interior Insulation Retrofit Projects

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Designers have used 2D heat flow and 1D dynamic hygrothermal models to predict the temperature and moisture conditions in these retrofitted wall assemblies. Unfortunately, there are few guidelines for assessing the susceptibility of clay brick to freeze-thaw problems. Two pass/fail tests have been used in the past to assess the freeze-thaw resistance of bricks: the cold water/boiling water absorption ratio (c/b ratio), and the 50-cycle freeze-thaw test. These approaches do not adequately represent the freezing mechanisms or conditions that bricks experience in the field.

An alternative approach is suggested here: frost dilatometry can be used to determine the critical degree of saturation at which freeze-thaw damage is likely to occur. Informed design decisions can be made by *comparing moisture predicted loads during freezing from hygrothermal models to the freeze-thaw resistance of the clay brick defined by the critical degree of saturation.*

This paper summarizes some of the limitations of the various approaches to assessing the freeze-thaw resistance of brick masonry units and presents a detailed methodology for using frost dilatometry to determine the critical degree of saturation of brick material. Test results are presented for bricks from several historical load-bearing masonry. Recommendations are made for applying this approach together with hygrothermal model in the design of retrofit insulation projects.

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ABSTRACT

Older load-bearing brick masonry buildings are common throughout North America and are considered good candidates for renovation and conversion. Insulation retrofits are typically implemented as part of this work. The addition of insulation can change the thermal and moisture balance in the wall assembly and, in some cases, initiate moisture problems such as freeze-thaw damage in masonry units.

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This paper summarizes some of the limitations of the various approaches to assessing the freeze-thaw resistance of brick masonry units and presents a detailed methodology for using frost dilatometry to determine the critical degree of saturation of brick material. Test results are presented for bricks from several historical load-bearing masonry. Recommendations are made for applying this approach together with hygrothermal model in the design of retrofit insulation projects.

INTRODUCTION

Older load-bearing clay brick masonry buildings are common throughout North America and are considered good candidates for renovation and conversion: they are often in desirable urban location, have strong structures, are often aesthetically pleasing with architectural significance, and have useful window areas and floor plans. Given the current and expected future energy costs and demands for carbon emission reductions, insulation retrofits are a highly desirable as part of any modern retrofit of this type of building stock.

Adding insulation to the exterior of any existing building is always the preferred approach for retrofits. This practically eliminates thermal bridging while simultaneously protecting the load-bearing structure from all exterior climatic elements. However, for aesthetic and historical reasons, the exterior of many load-bearing clay brick buildings must remain exposed, and interior retrofits must be considered. Unfortunately, the addition of insulation will change the thermal and moisture balance of any wall assembly and, in some cases, can initiate moisture problems such as freeze-thaw damage (Straube and Schumacher 2007) in masonry units by decreasing the drying capacity while simultaneously reducing the temperature of the inner wythes (note: the number and severity of freeze-thaw cycling of the exterior wythe is rarely changed significantly by an interior insulation retrofit, as the exterior face was always exposed to severe temperatures and rain wetting).

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Table 1. Exterior Grade/Severe Weathering Acceptance Criteria from CSA and ASTM Standards

	Compressive Strength		Max. Boiling Absorption 5-Hour, %	Max. Saturation Coefficient	Max. 24-Hour Cold Absorption
	MPa	psi			
CSA individual brick	17.2	—	17.0	0.78	8.0
Five-brick average	20.7	—	—	—	—
ASTM individual brick	17.2	2500	20.0	0.80	8.0
Five-brick average	20.7	3000	17.0	0.78	—

The very real increased risk of freeze-thaw damage has caused many designers and owners to avoid the addition of interior insulation. This is a major loss of energy saving potential and often renders a building less comfortable and usable than it would be if insulated. A rational method of assessing the risk of freeze-thaw damage due to various insulation strategies is required to guide owners in decision making.

Most historic brick we have tested cannot meet modern brick freeze-thaw standards. Hence, designers cannot rely on modern brick standards. As will be shown below, current brick freeze-thaw brick standards are not reliable indicators of field performance (even for modern brick) and will incorrectly reject many historic bricks even though they may be durable before and after insulating. The fundamental problem with existing brick standards is that they assume there is such a thing as a “freeze-thaw–resistant brick.” There is no such thing. Any brick can be made to fail with severe enough freeze-thaw cycling and a high enough moisture content.

Fagerlund (1977a, 1977b) many years ago showed that, below a certain degree of saturation S_{crit} (the degree of saturation S, defined as the ratio of the moisture content over the moisture content when all accessible pores are filled with water), a brick can be cycled hundreds and thousands of times above and below freezing without any measurable damage. He defined the degree of saturation above which freeze-thaw might occur as S_{crit}.

It is proposed in this paper that one approach to assessing the risk of frost damage to brick in a insulation retrofit is to have a test that could quickly and easily determine the critical degree of saturation S_{crit} of the brick and compare this to the maximum degree of saturation it will experience during freezing events in field service. This is approach analogous to designing a structural member by ensuring that it possesses the strength to resist anticipated loads. There is no such thing as an inherently load-resistant beam or column. So, when planning a retrofit strategy, an engineer or architect can pursue a strategy in which the predicted in-service moisture load will be less than the critical degree of saturation of the material. The brick properties cannot be changed in a retrofit, but the temperature and moisture conditions experienced by each wythe can be by a combination of insulation strategy (quantity, vapor permeance) and exterior surface rain control details (e.g., rain shedding at parapets, window sills, base splash-back). Obviously this strategy should be customized for each climate zone, exposure of building, and brick (including the differences between face brick, core brick, and interior brick).

EXISTING METHODS FOR ASSESSING FREEZE-THAW RESISTANCE OF MODERN BRICKS

In most new building projects, manufactured clay brick must meet criteria established by ASTM International in the United States and the Canadian Standards Association (CSA) in Canada. *ASTM Standard C62-05, Standard Specification for Building Brick (Solid Masonry Units Made from Clay or Shale)*, and *ASTM Standard C216-07a, Standard Specification for Facing Brick (Solid Masonry Units Made from Clay or Shale)*, grade brick based on its resistance to frost damage as severe weathering (SW), moderate weathering (MW), or negligible weathering (NW) and *CSA Standard A82-06, Fired Masonry Brick Made from Clay or Shale*, grades brick as either exterior grade (EG) or interior grade (IG). Due to Canada’s cool climate, all brick used in exterior applications must be exterior grade (ASTM grade SW).

ASTM and CSA have adopted very similar criteria for SW and EG bricks. In order for brick to be accepted as exterior grade or severe weathering, it must meet the criteria listed in Table 1. The compressive strength criteria are identical in both standards. The absorption and saturation criteria of CSA are equal to the more stringent criteria for a 5-brick average of the ASTM standard, while the ASTM standard slightly relaxes the maximum allowable boiling absorption and saturation coefficient required of an individual brick. ASTM and CSA also specify that a brick needs only to pass either the maximum saturation coefficient or maximum cold-water absorption criteria; it does not need to meet both. It should be noted that the procedures used in calculating the values of acceptance criteria are contained in a separate standard, *ASTM Standard C67-07a, Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile*.

The acceptance criteria used by ASTM and the CSA were selected under the assumption that adequate open-pore space should be provided to accommodate expansion of water as it freezes (Crawford 1984). The boiling absorption value is assumed to be an estimate of the open-pore space available to store water. The 24-hour cold-water absorption is an approximation of the likely moisture content after a severe wetting event. The saturation coefficient, calculated as the ratio of cold-water absorption to boiling absorption, is a measure of the amount of open-pore space available to accommodate freezing expansion. The 8% maximum limit for water absorption after 24 hours is intended to ensure the brick does not too readily absorb water, but has limited basis in research.

It is has been well documented that a significant fraction of bricks that pass the ASTM/CSA standard subsequently fail in service, while other bricks that fail the standard have been proven durable in practice (Butterworth and Baldwin 1964; Litvan 1975). Some highly absorbent bricks (well over the 8% maximum limit) have shown very good durability in the face wythe of buildings in cold climates (i.e., they are exposed to freeze-thaw cycling). Despite this, no improved standard has been developed and adopted.

A brick that does not meet the acceptance criteria can still be passed by the ASTM/CSA standards provided it passes an omni-directional pass/fail freeze-thaw test specified by *CSA Standard A82-06*, clause 14, and *ASTM Standard C67-07a*, clause 9. The freeze-thaw test specified by the CSA is essentially identical to the ASTM test. The test procedure can be summarized as follows. Half-brick samples, after being oven-dried and cooled to room temperature, are soaked for approximately 4 hours in a thawing tank. They are then removed from the tank and the head face is laid in 12 mm (1/2 in.) of standing water and placed in a cold chamber for approximately 20 hours. This constitutes one freeze-thaw cycle, and should be approximately 24 hours in duration. The samples are subjected to 50 cycles (taking 10 weeks to complete if cycles are only carried out on standard business days) or until disintegration, which the CSA defines as 5% mass loss (ASTM defines it as 3% mass loss) or the development of cracks in excess of the specimen's least dimension as determined by visual inspection. If, after 50 cycles, the specimens do not have a mass loss greater "than that permitted by the referenced unit specification for the appropriate classification" and has not developed cracks with a length greater "than that permitted by the reference unit specification for the appropriate classification" (*ASTM Standard C67-07a*, clause 9.4.3), it is considered to have passed the test. This test is meant to replicate extreme field conditions of multiple freezing cycles while the brick is in a saturated condition.

The primary shortcoming of predicting durability of a material based on the ASTM and CSA acceptance criteria is that they are based on an incomplete understanding of the physics of freeze-thaw damage, an oversimplification of field exposure conditions, and testing that focus on unit, not material, response to freeze-thaw cycling. The c/b ratio is based on the expectation that frost damage is principally due to the volumetric expansion of water as it freezes. However, this is not the sole mechanism of freeze-thaw damage, although it may be the most important (Litvan 1988). Therefore, the inference between the saturation coefficient and durability that forms the basis of the ASTM/CSA acceptance criteria is at best a rough guide to in-service clay unit durability; it is not a reliable measure of the frost resistance of the clay brick unit, or the clay brick material.

The 50-cycle freeze-thaw test has additional shortcomings. In the field, the mode of freezing is unidirectional; that is, a freezing front advances inwardly from the outer face of the brick. The 50-cycle test is omnidirectional: multiple freezing fronts advance from all exterior faces of the brick towards the center. This may build up hydraulic pressures in the centre of the brick that would not occur under the unidirectional mode of freezing experienced in service by most brick.

The 50-cycle test also does not attempt to determine the moisture content of brick specimens as they are subjected to freeze-thaw cycles. This is worrisome, because the degree of saturation of the brick during the test S_{test} may not closely approximate the degree of saturation of the brick when in service $S_{service}$. Not controlling the degree of saturation of the brick while testing leads to two types of incorrect test results. Bricks that will reach a degree of saturation greater than S_{crit} in service, but absorbed less moisture than S_{crit} during the test, will eventually fail in service despite passing the test. Alternatively, if the moisture content of a brick never surpasses S_{crit} in service, but surpassed S_{crit} during the test, then the brick will be incorrectly rejected despite having the ability to be durable in service.

Relying solely on acceptance criteria or the 50-cycle test does not provide an adequate basis for determining market eligibility of a product and can expose building owners to hefty maintenance or replacement costs in the case of incorrect approvals. Furthermore, in existing buildings, pass-fail criteria are not always very useful, as the masonry already exists and cannot be modified in situ. A designer may be able to reduce the moisture load on a masonry façade, and thereby reduce the risk of freeze-thaw damage, by changes in the building façade.

The fundamental problem with grading frost resistance of brick, as enshrined in the CSA/ASTM standards, is that no such thing exists. ASTM recognizes this in Appendix X4 of *Standard C216-07a*, which includes the disclaimer that "in severe exposures, even Grade SW brick may spall under certain conditions of moisture infiltration, chemical actions, or salt crystallization." This is just another way of saying that all materials will fail when subjected to harsh enough conditions. Thus, "freeze-thaw resistance" is a misleading concept because it implies that a material can be capable of withstanding all possible damage mechanisms imposed by frost action under all conceivable circumstances.

PROPOSED FROST DILATOMETRY APPROACH

The approach taken to analysis was to separate the freeze-thaw load on an assembly from the material response. Hygrothermal modeling to predict the temperature and moisture fields in masonry walls, and hence the freeze-thaw loading, are well developed. The goals in developing the laboratory test method described below were to provide a repeatable and quantitative measure of the clay brick material's response. Ideally, this would be an estimate of the critical moisture content of a brick material at which it begins to experience freeze-thaw damage (defined as S_{crit} when reported in terms of a saturation coefficient). A material-specific freeze-thaw threshold moisture content can be assumed based on the extensive work by Fagerlund (1977a, 1977b, 1996), Litvan (1973, 1975, 1988), and others (e.g., Maage [1984], Prick [1997]). This approach explicitly does not attempt to assess the distribution of temperature and moisture in a brick unit (as unidirectional and omnidirectional tests do) using laboratory testing, but focuses on the material level response.

After a review of possible methodologies for identifying freeze-thaw damage, including destructive compressive strength tests, visual observation, and dynamic modulus, frost dilatometry was chosen. It has long been known and is regularly observed that clay bricks exhibit irreversible expansion as they experience frost damage (Ritchie 1968). Frost dilatometry has the advantages of being a quantitative measure; nondestructive; requires only commonly available, relatively inexpensive equipment; and can be used in a short-duration test. What follows is an overview of the test methodology developed and used in a pilot study of this proposed method.

Sample Preparation

The bricks selected for testing should be sliced into as many 10 mm thick specimens as possible by sawing parallel to the header face (ie., the brick should be sliced like a loaf of bread). For a standard solid brick 8 in. (200 mm) in length, this will result in approximately 12 specimens, depending on the saw blade thickness. Many modern bricks have cores, which will reduce the number of specimens that can be cut from a single brick. The 10 mm thickness was decided upon as it allows a significant number of samples to be taken from a brick and results in samples with a high surface-area-to-volume ratio, which allows rapid heat transfer and uniform moisture levels during freeze-thaw cycling.

Proposed Methodology

For each brick sample, the following material properties are determined prior to any testing: dry mass, saturated mass, water absorption coefficient (A-value), and initial distance between targets (if determining strain mechanically).

Specimens are dried in an oven at 105°C and measurements of the mass taken every hour thereafter. When the change in mass over 2 hours is less than 0.05%, the specimen is considered to have reached a dry state.

The saturated mass of a specimen can be determined using one of two methods: boil saturation or vacuum saturation. It may be helpful to take one specimen and determine its saturation moisture content using both the boil and the vacuum methods. If the difference in saturation moisture content between the two methods is not great, perhaps less than 5%, boiling may be preferable because it is the more expedient method to saturate the specimens. We have found that vacuum saturation can provide much higher values for some bricks than the 5 hour boil saturation test method.

The capillary water uptake or absorption coefficient (i.e., the A-value) of each brick sample should be determined by a water uptake test. Supports for the brick specimens are placed in a tray and water is poured into the tray until the supports are covered to a depth of 1 to 2 mm. The mass of each dry brick specimen is recorded and then each specimen is placed on the supports with the largest face in contact with the water. At regular intervals, the specimens are removed from the water and the mass is recorded.

Each specimen's change in mass is plotted against the square root of time that the specimen has been absorbing water. Initially, the brick sample will rapidly absorb water until its capillaries are saturated, at which point the brick will continue to slowly absorb water as trapped gases dissolve and escape to the exterior. Highly absorbent bricks may require additional measurements early in the test (e.g., at 1 minute intervals) to determine the initial slope of the curve, and low-absorptivity bricks may need to be in contact with water for as many as 12 hours for the pore system to become mostly saturated.

The length of each sample must be measured precisely and accurately: in our work, a ratchet-tightened outside micrometer, accurate to ±0.001 mm, was used to measure length by placing it in contact with pins mechanically inserted in the end of each sample. A ratchet is necessary to ensure that a consistent tightening pressure is applied with each measurement. The micrometer should be calibrated on a gage block prior to each use. The flat face of the anvil and spindle are placed in contact with the rounded targets that have been secured to the ends of a specimen and then tightened with the ratchet stop until the measured length on the digital gauge no longer decreases. A record of the sample length is taken, the specimen rotated 180°, and a second length measurement is made. The length is recorded to the nearest thousandth of a millimetre. The average of these two measurements is considered the sample length. The orientation of the brick sample when the first measurement is taken must be marked so that the sample is subsequently measured in the same orientation. These precautions are important to ensure consistency among measurements, as the samples occasionally seat differently depending on orientation when in contact with the micrometer; typically this ranges within ±0.005 mm. The instrument used in this study was a 3 in. to 4 in. digimatic outside micrometer manufactured by Asimeto. This micrometer allowed expansion measurements to be made with a precision of about 10 microstrain for the sample size used.

The test protocol to determine the critical degree of saturation S_{crit} (equal to the measured threshold moisture divided by the maximum or vacuum saturated moisture content) can only commence after initially establishing physical properties described above. This test may require multiple rounds of freeze-thaw cycling to establish S_{crit} to a useful degree of precision. It has been found most expedient to use the first round of freeze-thaw testing to determine S_{crit} within the nearest 20% degree of saturation, and then conduct a second round to more precisely (to about 5%) define the degree of saturation at which frost damage occurs.

In the first round, five specimens from a brick have water added equal to 0.20, 0.40, 0.60, 0.80, and 1.00 of the saturation moisture content based on boil or vacuum saturation, as determined earlier. When wetting to low degrees of saturation, water can be simply placed in contact with the face of the specimen to be absorbed into the brick. To reach higher degrees of saturation, a specimen may have to be saturated and then dried to the desired moisture content. Seal the specimens by tightly wrapping them in plastic or aluminum tape, taking care to minimize the air space between the surface of the specimen and the sealant material. The sealed specimens is then set aside for at least 24 hours, prior to freezing, to allow moisture to distribute evenly throughout the pore space. For specimens with low A-values, approximately 0.005 kg/($m^2 \cdot s^{1/2}$) or less, it may necessary to wait for up to 72 hours after wetting for redistribution to be mostly complete.

The wetted, wrapped samples should be subject to multiple freeze-thaw cycles; in this study, the number of cycles chosen was six, primarily based on the precedent of other work. Although damage should occur after only one cycle if the moisture content is above S_{crit}, dilation will increase with the number of cycles and hence be easier to measure reliably after numerous cycles. It is also unlikely that the specimen will actually disintegrate after only six cycles, but may after 20 or 30.

Freeze-thaw cycling can be imposed by transferring the samples from a room to a conventional freezer (with an air temperature of approximately –18°C), and then removing the sample to the room. This approach requires some labor, and takes some time to cool and thaw the specimens. We chose to place the specimens in an uninsulated, watertight pouch and submerse them in a stirred, chilled liquid bath programmed to cycle six times between temperatures of –15°C to 20°C: this allowed for automatic cycling, and, aided by the high heat transfer rate of the stirred, chilled liquid, samples reached the target temperatures within 3 hours for freezing and thawed with 6 hours. Hence, 6 cycles were completed in 54 hours.

After undergoing six freeze-thaw cycles, the wrapping around the specimens was removed and the mass weighed to verify that the moisture content had not appreciably decreased during the freeze-thaw test. Next, the length of the specimen should be measured in order to calculate expansion experienced by the specimen during freezing using the same procedure as before. The expansion of the sample in terms of strain is calculated by the following equation:

$$\varepsilon = \frac{l_6 - l_0}{l_0} \times 10^6$$

where

ε = expansion, microstrain

l_0 = initial specimen length, mm

l_6 = specimen length after six freeze-thaw cycles, mm

Given that the measurements by the micrometer are accurate to better than ±0.005 mm, expansion greater than 100 microstrain (equivalent to approximately 0.01 mm) was considered a reliable indicator of frost damage. Therefore, S_{crit} was taken as the lowest saturation level for which expansion exceeded 100 microstrain after six cycles of freezing and thawing.

In the second round, at least three specimens should be wet at increments of 0.05, 0.10, and 0.15 greater than the minimum saturation coefficient at which expansion did not occur, as determined earlier. For example, if in the previous round the brick was found to expand at saturation greater or equal to 0.6 of the saturated void space, then in the second round of testing, the brick specimens should be wet to 0.45, 0.50 and 0.55 of the saturated moisture content. Furthermore, brick specimens that were not damaged in the initial round of freeze-thaw testing were reused in later rounds; however, once a specimen experienced dilation, it was disqualified for use in any future testing as it had, by definition, been damaged.

This test protocol requires 6 to 12 days to complete, depending on the sample size and number of freeze-thaw cycles required to determine S_{crit}. Preparation of the specimens should be completed in 1 day. Determining material properties can take 2 to 4 days, depending on the number of bricks being tested and staffing. One day should be set aside to allow moisture redistribution, as explained earlier. Freeze-thaw cycling will take between 2 to 6 days, depending on the number of cycles required to determine S_{crit} to within 0.05 degrees of saturation.

EXAMPLE RESULTS AND DISCUSSION

The critical degree of saturation S_{crit} of a material is the lower limit of moisture content at which the material experiences dilation after being exposed to freeze-thaw conditions. In this study, dilation was measured in terms of microstrain expansion. S_{crit} is very clearly seen when dilation of samples is plotted against its moisture content during freeze-thaw cycling.

The critical degree of saturation was determined for several sets of sample bricks: "Canada brick," modern extruded clay brick from a Canadian manufacturer; "UCC," historical brick collected from Upper Canada College; and "Old Montreal," historical brick collected from a home in the old part of Montreal City. The dilation experienced by specimens at various degrees of saturation (found using vacuum saturation), is plotted for each set of brick in Figures 1 to 3.

All sets of brick appear to have a clearly defined critical degree of saturation below which frost dilation does not take place, confirming the pioneering work of Fagerlund. When subjected to freeze-thaw cycles above S_{crit}, frost dilation tends to increase as the saturation level rises. The tendency for frost dilation to increase as a function of saturation is far from linear, especially with the UCC and Old Montreal set of brick.

The value of S_{crit} varies widely between the three sets of bricks tested. The S_{crit} of Canada brick is approximately 0.87,

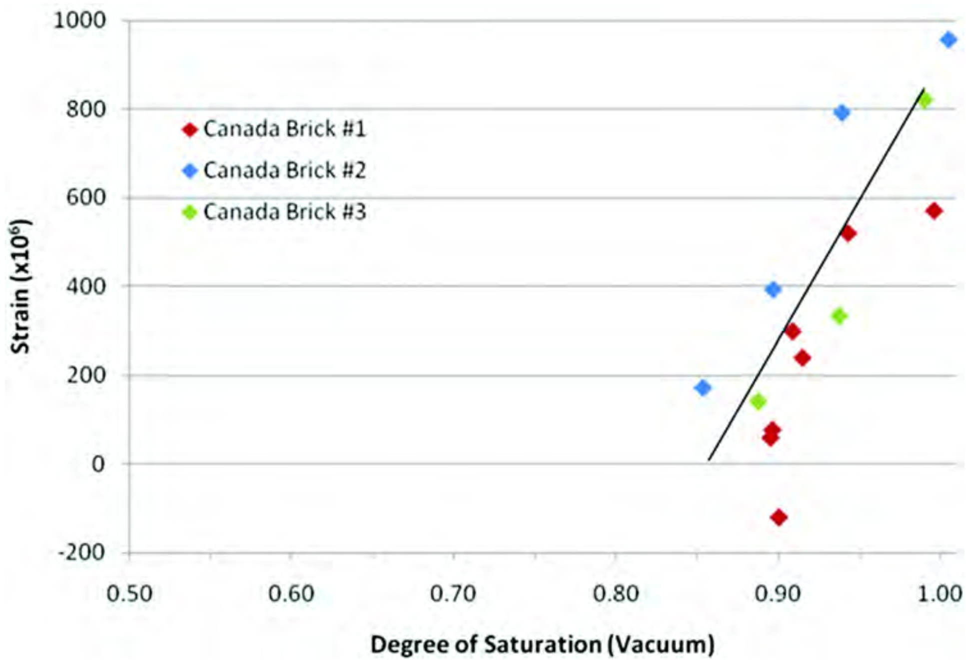

Figure 1 *Frost dilatometry: Canada brick.*

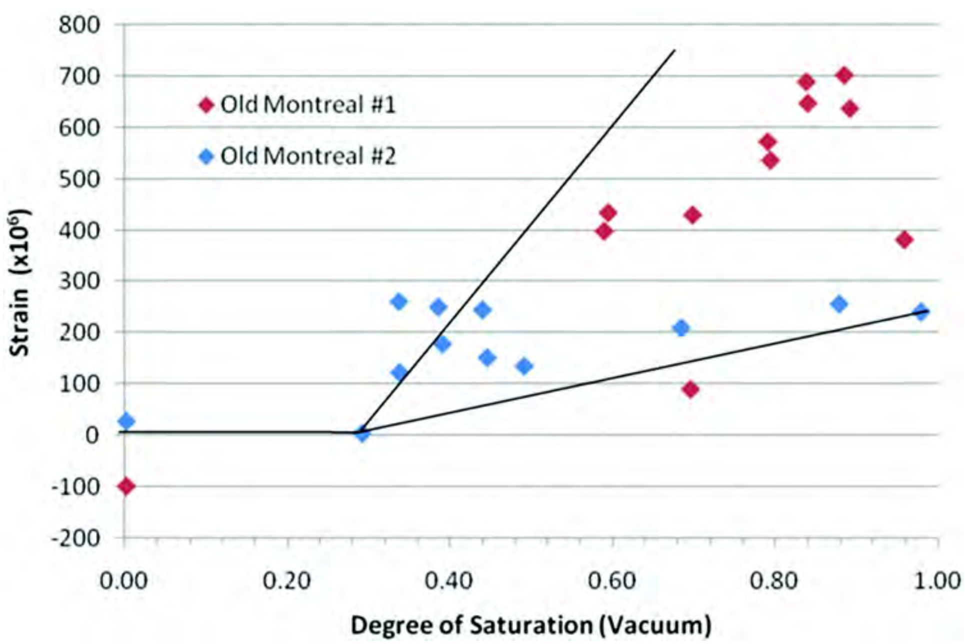

Figure 2 *Frost dilatometry: Old Montreal brick.*

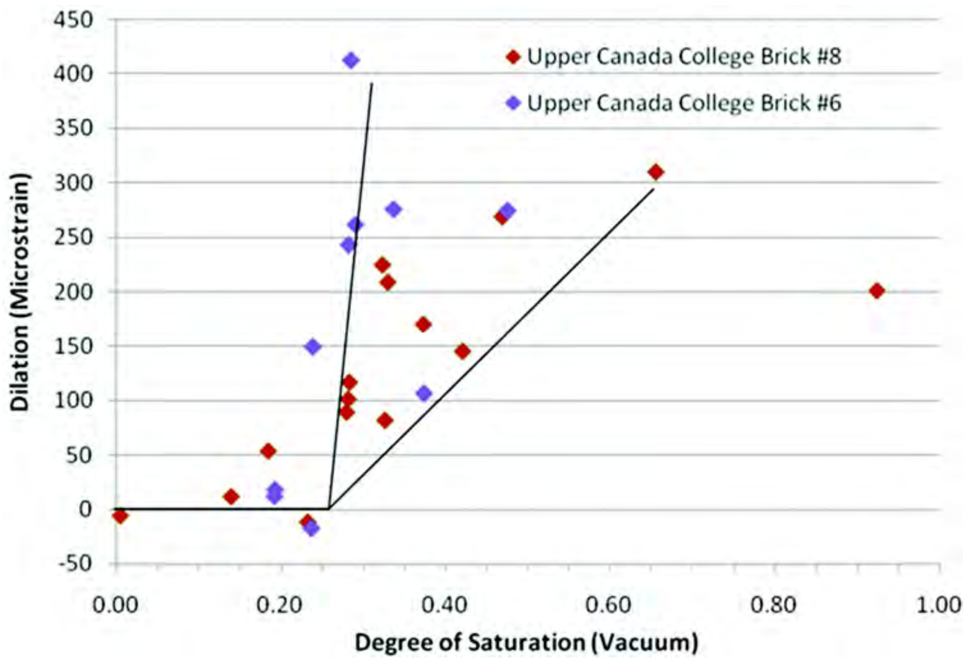

Figure 3 *Frost dilatometry: UCC.*

of Old Montreal brick is 0.30, and of UCC is 0.25. This wide difference between S_{crit} values ran counter to expectations and demonstrates how important it can be to assess the actual brick performance.

Given a "safe" moisture content (ie., the critical degree of saturation), rational engineering design can proceed. We have used detailed computer models (e.g., WUFI; see Straube and Schumacher [2006] and Wilkinson et al. [2009]) to compare the moisture contents of the brick masonry in a proposed building retrofit both before and after insulating. If the moisture contents predicted in service before and after retrofit are both below the critical degree of saturation of the brick in each wythe during freezing events, the design can be considered safe, even if the brick does not meet the modern ASTM/CSA pass/fail standards.

Modeling of loads and measurement of material response allows the designer to much more confidently assess the impact of different climates, insulation strategy, rain control approaches, building orientations, water-repellent coatings, vapor-permeable or capillary active insulations, and many other common questions that arise during interior insulation retrofits.

The challenge remains to ensure that the computer model has correct boundary conditions. The loading of primary importance is that of driving rain, and this is often complex to predict in realistic surroundings. Computational fluid dynamics (CFD) models are expensive and still unreliable. For very significant buildings, field monitoring can be considered, as even less than 1 year of driving rain measurements can provide very good information at modest cost.

CONCLUSIONS

Solid masonry buildings are increasingly being considered for interior insulation retrofits. The addition of insulation can change the thermal and moisture balance in the wall assembly and, in some cases, initiate moisture problems such as freeze-thaw damage in masonry units.

Designers have used 2D heat flow and 1D dynamic hygrothermal models to predict the temperature and moisture conditions in these retrofitted wall assemblies. Unfortunately, there are few guidelines for assessing the susceptibility of existing bricks to freeze-thaw problems. Two pass/fail tests are currently used to assess the freeze-thaw resistance of modern clay bricks: the c/b ratio and the 50-cycle freeze-thaw test. These approaches do not adequately represent the freezing mechanisms or conditions that bricks experience in the field and do not provide a performance threshold for comparison to computer models.

An alternative approach and laboratory methodology has been suggested: frost dilatometry can be used to determine the critical degree of saturation at which freeze-thaw damage is likely to occur. The testing methodology described has shown that a relatively fast and simple test protocol can provide the critical degree of saturation for clay brick materials. Informed design decisions can be made by comparing moisture predicted loads during freezing from hygrothermal models to the freeze-thaw resistance of the clay brick defined by the critical degree of saturation.

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