TOWARDS A LIMIT STATES APPROACH TO INSULATING SOLID MASONRY WALLS IN A COLD CLIMATE

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ABSTRACT

Our aging building stock provides tremendous opportunities to reduce our overall environmental footprint through upgrades to the exterior enclosure. Buildings with solid or load-bearing masonry walls typically employ interior insulation retrofit strategies as these buildings often have heritage significance that preclude work from the exterior. Insulating from the interior may result in accelerated masonry freeze-thaw deterioration, embedded metal corrosion and/or embedded wood joist rot.

A limit states design approach is used extensively when designing structures but is still in its infancy for designing building enclosures. This approach compares factored loads to factored material resistance to assess resulting safety factors against reaching a limit state or failure threshold.

Loads that are considered when insulating solid masonry walls include external/internal moisture and temperature. These can be measured through weather stations and sensors or predicted through models that incorporate weather files. Pertinent material resistance limits/thresholds include the Critical Degree of Saturation (S_{crit}) and the Temperature/Relative Humidity levels where metal corrosion or wood rot progress. S_{crit} is obtained through frost dilatometry testing where brick or stone samples are subjected to freeze-thaw cycles at various moisture saturation levels to determine the limit/threshold where internal damage may occur.

This paper describes applying a Limit States Design Approach for two case studies: an institutional facility in southwestern Ontario and a museum in northeastern Ontario. Expected climate conditions from numerical models are compared to S_{crit} values (obtained from testing site specific brick/stone samples) and to typical corrosion/rot thresholds.

Findings show low freeze-thaw risk to the insulated brick and stone for these specific facilities but increased risk for embedded steel corrosion and wood rot. Strategies to control metal corrosion and wood rot are presented.

INTRODUCTION

Buildings with solid or load-bearing masonry walls typically employ interior insulation retrofit strategies as these buildings often have heritage significance that preclude work from the exterior. Adding insulation on the interior side of solid masonry walls may result in accelerated masonry freeze-thaw deterioration in addition to embedded metal (lateral ties and supporting angles/structure) corrosion, or embedded wood joist rot.

Currently, there are few tools available to determine if an interior insulation retrofit would increase the risk for deterioration. This paper proposes initial steps to moving towards a limit states approach to determining if a building is at increased risk for deterioration. This approach consists of identifying thresholds at which deterioration commences and then designing a retrofit that minimizes the risk of reaching these thresholds. This paper will explain how this approach can be applied to addressing freeze-thaw damage, embedded metal corrosion and wood rot, followed by two case studies that illustrate how it has been applied in practice.

LIMIT STATES APPROACH

Limit states approaches are commonly used in engineering. In general terms, it involves identifying "various types of failure and unserviceability that are to be avoided" and then keeping "the probability of reaching a limit state below a certain value previously established for a given type of structure" or material [1]. For example, when designing a structural element, a design professional may calculate a combination of factored, expected loads that a structural element may need to support. Candidate structural members are then selected based on their resistance. Material resistance is often factored down depending on the expected variability for that material type. Overall, the factored resistance must be greater than the factored load to avoid reaching a limit state (with an inherent safety factor).

Similarly, a limit states approach can be applied to assess material durability, where the threshold at which a deterioration process is initiated is compared to actual or expected conditions. When considering risks associated with insulating solid masonry walls, the most common failure types in a cold climate include freeze-thaw damage, embedded metal corrosion, or embedded wood rot.

FREEZE-THAW DAMAGE

Past research has demonstrated brittle porous materials including clay brick, concrete and stone (limestone, granite, sandstone) expand when experiencing frost damage [2-4]. Furthermore, expansion will only occur if the material is wetted above a certain threshold, termed the Critical Degree of Saturation (S_{crit}) [5,6]. If a brittle, porous material is wetted beyond S_{crit} every damaging freeze-thaw cycle will cause irreversible, cumulative expansion. S_{crit} can be identified by frost dilatometry, a technique that measures strain induced by frost damage at various degrees of material saturation [7,8].

A brick or stone unit is at low risk of freeze-thaw damage if its critical degree of saturation is greater than its free water saturation (w_f). Free water saturation is the amount of water a material absorbs when fully immersed in water for 24 hours (i.e. maximum saturation coefficient as defined in ASTM C-62 [9]). Free water saturation, w_f, is less than the total amount of water that can be held in a brick's pore space. As liquid water enters a dry material most of the air in the pore space is expelled, however a portion of it will be trapped in dead-end pores, illustrated in Figure 1. In order to accurately measure a material's total pore space, trapped gas must be removed by a vacuum (S_{total}). It can be assumed that an in-situ brick or stone unit will almost never be exposed to wetting above w_f, therefore if S_{crit} is greater than w_f, the risk of freeze-thaw damage is low and adding interior insulation is not expected to compromise brick or stone durability.

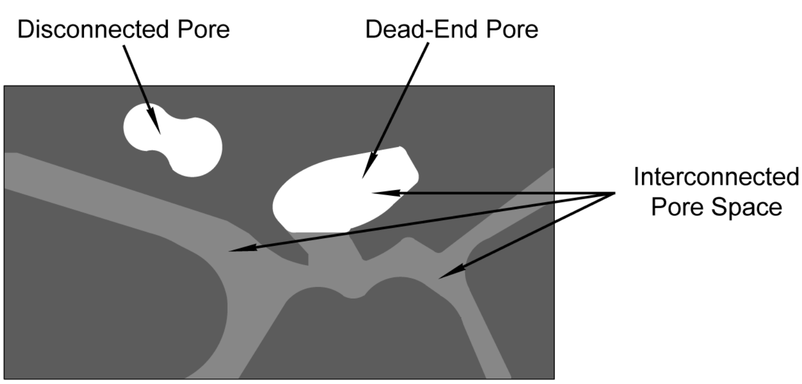

FIGURE 1: IDEALIZATION OF A LIQUID-SATURATED PORE SPACE [7]

There have been some cases with historic brick where measurements by the authors demonstrated S_{crit} value less than w_f. Assessing freeze-thaw damage risk in masonry units with an S_{crit} value less than w_f is more difficult since one must estimate or predict whether the S_{crit} threshold is expected to be exceeded in service. In this case, hygrothermal modeling can be used to assess *the change* in risk of freeze-thaw damage between an existing and insulated wall assembly. The hygrothermal model employed for freeze-thaw risk assessment should use project-specific material properties, such as porosity and A-value, determined during the frost dilatometry test, and be capable of predicting the effects of wind-driven rain, solar-heating, thermal mass, condensation, evaporation, capillary flow, and diffusion. A hygrothermal simulation should be completed of the existing and proposed insulated wall assembly for a reasonable duration, such as three to five years, using location-specific climate records and the past and proposed interior conditions. The resulting data sets should be analysed for the number of hours and freeze cycles where any element of the masonry has a moisture content above S_{crit} and is subject to freezing below -5ºC (the lower temperature threshold is used to account for the lowered freezing point in small capillaries and pores).

The number of freezing cycles and their duration during which the moisture content is greater than S_{crit} in the existing and proposed retrofit wall assembly should be compared as significant changes in either parameter increases freeze-thaw damage risk. The number of cycles is important as the more cycles the brick experiences, the more rapidly it will deteriorate. Furthermore, the amount of expansion caused by a freeze-thaw cycle increases as moisture contents greater than S_{crit} are experienced. An experienced design professional can review both parameters and exercise judgment as to whether the increase in either the length of time, severity of freezing, or both, presents an unacceptably high risk of frost damage. If so, alternate approaches to insulating the assembly including decreasing insulation thickness, material selection or whether to insulate at all should be considered.

The proposed method has not been used to assess freeze-thaw risks for the mortar between brick or stone units. The mortar is often considered sacrificial and is expected to require ongoing maintenance.

EMBEDDED METAL CORROSION AND WOOD ROT

The approach used by the authors to assess the risk of embedded metal corrosion or wood rot starts by selecting a threshold for relative humidity and temperature at which corrosion or wood rot is expected to initiate. The corrosion threshold is termed the Time of Wetness (time where metal is exposed to conditions greater than 0ºC and 80% relative humidity) [10]. Wood rot typically occurs at 28% moisture by weight or around equilibrium with 95% relative humidity [10]. Hygrothermal modeling (e.g., with WUFI) of the existing and retrofitted wall assembly is then completed to compare the expected environmental conditions within the wall assemblies. The authors have had the most success using the WUFI model [13], as it has repeatedly been validated against field measurements of solid masonry buildings [11, 12]. The length of time over a year that the location within the wall assembly at which the embedded metal or wood is located above the selected threshold is compared between the existing and retrofitted wall. To facilitate the analysis, a combined threshold is typically used (i.e. time greater than 5ºC and 85% relative humidity) as this is more conservative for the wood rot (i.e. similar to a material resistance factor) and since corrosion rates are expected to be very slow closer to freezing conditions.

CASE STUDY 1: MUSEUM REPURPOSING

A three-story historic stone masonry building located in northeastern Ontario is being renovated into museum/cultural space. The building was built in two stages, the original wing was constructed between

1904 and 1906 and an addition was constructed between 1924 and 1926. The exterior facade of both the original building and addition consists of squared, rough-faced Nepean Sandstone laid in a random, uncoursed pattern. Decorative elements on the original building include window and door surrounds, lintels, quoins and copings, as well as the exposed foundation and plinth course, of Gloucester limestone while the balustrade and decorative crests and carvings at the roof level are Wallace sandstone. Similar decorative elements on the addition are a mix of Berea (Ohio) and Wallace sandstone, which are nearly indistinguishable in appearance. The building was to be renovated prior to the new owner's occupancy, and interior insulation of the exterior walls was under consideration, expected to consist of applying 75mm of medium density closed cell spray foam insulation, an air space, drywall and interior finishes.

The structural system in the original building consists of arched terra cotta floors with a concrete topping supported by steel framing members which bear on the exterior masonry walls. The ends of these beams and girders are embedded within the wall assembly. (There are no structural wood members in this facility.) The structural system in the addition consists of concrete floor slabs spanning between concrete-encased steel beams and girders which are supported by steel columns embedded within the exterior masonry walls, see Figure 2. The masonry walls in the addition are not gravity load-bearing.

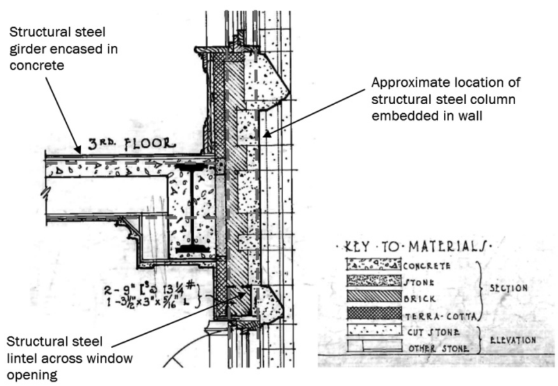

FIGURE 2: EMBEDDED STEEL IN THE ADDITION'S WALL ASSEMBLY

TEST RESULTS

Frost dilatometry was used to determine if the proposed retrofit would increase the risk of freeze-thaw in the stone units, and hygrothermal modeling was used to assess the risk of embedded metal corrosion.

The test values for the free water saturation (w_f) and critical degree of saturation (S_{crit}) for all types of stone used in the building facade demonstrated that w_f was considerably less than S_{crit}. Typical values of w_f for the brick were 15.5 kg/m^3 (30% degree of saturation) whereas S_{crit} was found at 40 kg/m^3 (80% degree of saturation); or 2.5 times greater than w_f. A typical plot of S_{crit} results for a stone unit is shown in Figure 3. The frost dilatometry test results indicated that the stone is at almost no risk of freeze-thaw deterioration. This was consistent with the generally good stone condition observed at both the original and addition portions of the building. Furthermore, hygrothermal modeling predicted that the moisture levels in the back-up materials in the wall assembly would not exceed the estimated critical degree of saturation (testing was not completed to establish the actual properties for the back-up materials).

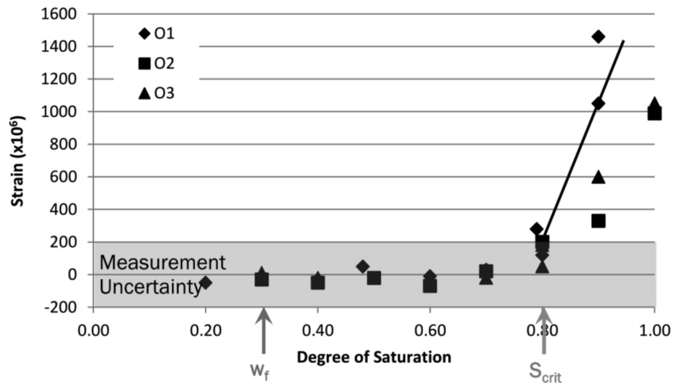

FIGURE 3: EXAMPLE OF FROST DILATOMETRY TEST RESULTS ON THREE STONE UNITS FROM THE OTTAWA MUSEUM

As a result of being located within the masonry walls that are exposed to rain wetting, structural steel elements have risk for corroding. In addition to weakening of the steel elements, expansion from corrosion risks may cause damage to stone masonry units. Embedded metal in the wall assembly consisted of steel lintels and beams bearing on the walls in the original building while the addition has lintels and columns embedded within the walls.

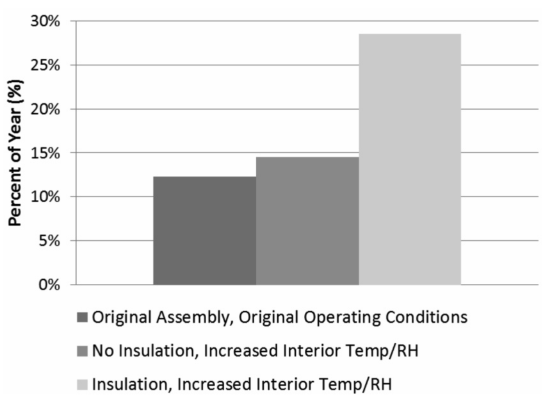

FIGURE 4: HYGROTHERMAL MODELING RESULTS: TIME THAT INNERMOST EMBEDDED METAL IS ABOVE CORROSION THRESHOLD (5ºC AND 85% RELATIVE HUMIDITY).

Hygrothermal modeling was employed to estimate the increased risk for embedded metal corrosion from insulating the walls. The model predicted no change to the risk of corrosion for the outermost embedded metal in both the original building and the addition. However, the model indicated that insulating the walls would result in the innermost portion of the steel elements being above the corrosion threshold about 10% of the year at the original building, and 30% of the year at the addition, (see Figure 4 for summary of Addition results).

Although insulating the walls is expected to increase corrosion risk at the innermost steel, all beams, columns and lintels exposed for review were found to be in good condition with only surface corrosion observed, see Photo 1. A doubling of a slow corrosion rate would still result in a slow corrosion rate.

PHOTO 1: INNER EMBEDDED STEEL COLUMN AT ADDITION WING OF MUSEUM

IMPACT OF LIMIT STATES ANALYSIS ON RETROFIT DESIGN

Using a limit states analysis confirmed that this building was a good candidate for an interior insulation retrofit. The limestone units and back-up wall material were at essentially no risk of experiencing freeze-thaw damage and the low rate of corrosion in the outermost embedded metal was not expected to change. The corrosion rate of the inner embedded metal was expected to more than double, however, given the low rate of corrosion, this was not expected to be problematic for some time. We recommended that the client look into the feasibility of installing a cathodic protection system for embedded metal elements for increased certainty against corrosion given the client's low threshold for deterioration.

CASE STUDY 2: INSTITUTIONAL BUILDING RENEWAL

This case study focuses on the renovation of an institutional building in southwestern Ontario. The building is a 2-storey historic masonry structure, shown in Photo 2, and was to be renovated into educational space that would house equipment in some areas, such as pianos, that are sensitive to large swings in relative humidity and temperature. The new owner wanted to increase and maintain the interior temperature and relative humidity for the musical instruments and was considering insulating the east exterior wall to maintain desired interior humidity and temperature conditions, improve occupant comfort, and to improve energy efficiency.

PHOTO 2: INSTITUTIONAL BUILDING RENEWAL

The exterior walls consist of load bearing brick masonry with an air cavity between three outer wythes and an inner wythe of masonry. The proposed retrofit was to consist of applying 50mm of medium density closed-cell spray foam insulation covered by drywall and interior finishes.

There were a number of metal and wood elements that were supported by, and embedded in, the exterior masonry walls including metal trusses, wood purlins at sloped roof areas, and wood joists at flat roofs. This case study will focus on how a limit states approach was used to assess the deterioration risk for the embedded ends of the wood roof joists, since embedded metal elements were looked at in the first case study. The wood roof joists were supported on the two innermost wythes of masonry, as shown in Figure 5 below.

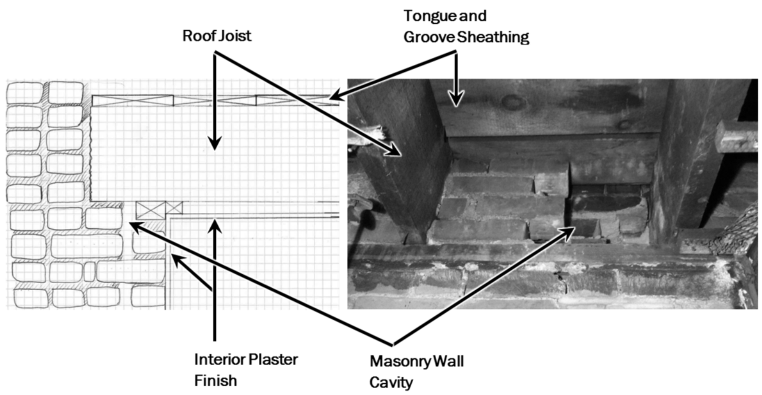

FIGURE 5: ORIGINAL ROOF JOIST SUPPORT DETAIL

TEST RESULTS

Frost dilatometry and hygrothermal modeling were used to determine if the proposed retrofit would increase the risk of freeze-thaw damage in clay brick and limestone units and rot in the embedded wood joists.

The test values for the free water saturation (w_f) and critical degree of saturation (S_{crit}) for the brick masonry units demonstrated that w_f was consistently less than S_{crit}. Typical values of w_f for the brick were 221 kg/m^3 (80% degree of saturation) whereas S_{crit} was found to be 240 kg/m^3 (88% degree of saturation), see Figure 6. These findings are consistent with site observations that exterior brick was in generally good condition at unheated locations of the building that had high exposure to rain (i.e. parapet and turret). Frost dilatometry testing on brick units confirmed that they are at low risk of freeze-thaw damage and are good candidates for interior insulation.

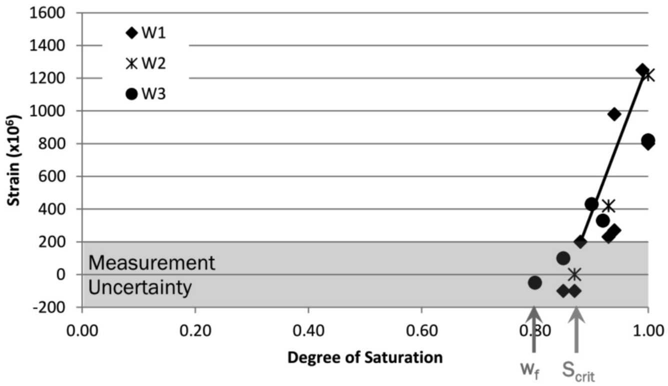

FIGURE 6: EXAMPLE OF FROST DILATOMETRY TEST RESULTS ON THREE MASONRY SAMPLES

Hygrothermal modeling of the wall assembly, under the three conditions listed below, was completed to assess the impact of proposed retrofit and interior operating conditions changes on embedded wood joists:

1. Original wall assembly at existing operating conditions;
2. Original wall assembly with increased interior temperature and relative humidity; and
3. Insulated wall assembly with increased interior temperature and relative humidity operating conditions.

The threshold at which wood rot was expected to commence was at temperatures above 5ºC and relative humidity (RH) greater than 85%.

The hygrothermal modeling results indicated that the amount of time in a typical year that the joists would be above the wood rot threshold was greatly increased under both the modified interior operating conditions and the proposed insulated wall assembly when compared to the original wall assembly and operating conditions, see Figure 7. In the existing assembly and under the traditional interior operating conditions, the temperature and humidity level in the wall rarely exceeded the deterioration threshold for the embedded wood. This was confirmed by the sound condition of the embedded wood joists exposed for visual review. Under increased interior relative humidity and temperature conditions, the conditions in the wall exceeded the deterioration threshold close to 40% of a typical year, and the retrofitted wall assembly was expected to produce conditions in the wall at which the deterioration threshold would be exceeded for 75% of a typical year.

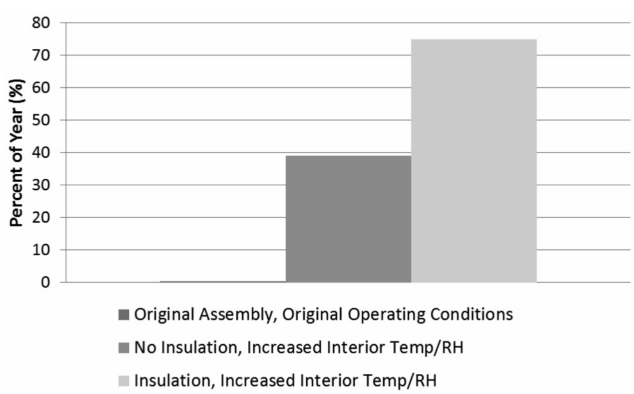

FIGURE 7: HYGROTHERMAL MODELING RESULTS: TIME THAT JOIST ENDS ARE ABOVE WOOD ROT THRESHOLD

IMPACT OF LIMIT STATES ANALYSIS ON RETROFIT DESIGN

The limit states analysis had a significant impact on the retrofit designs submitted for the client's consideration. It was predicted that interior insulation and the new interior environmental conditions would not increase the risk of freeze-thaw damage in either the clay brick or limestone masonry units. However, the increased risk of wood rot at the embedded joist ends was to be managed. We recommended providing supplemental gravity and lateral support of the existing wood roof joists inboard of the new insulation layer, shown in Figure 8 below. An alternate approach considered was to encapsulate the entire joist ends in spray foam insulation to minimize the risk of condensation and related wood rot (there were air gaps between the wood and masonry that could be filled with spray foam). Additionally, an air and vapour control layer was to be installed outboard of the roof decking during an upcoming roof replacement project to minimize the risk of condensation in the roof assembly.

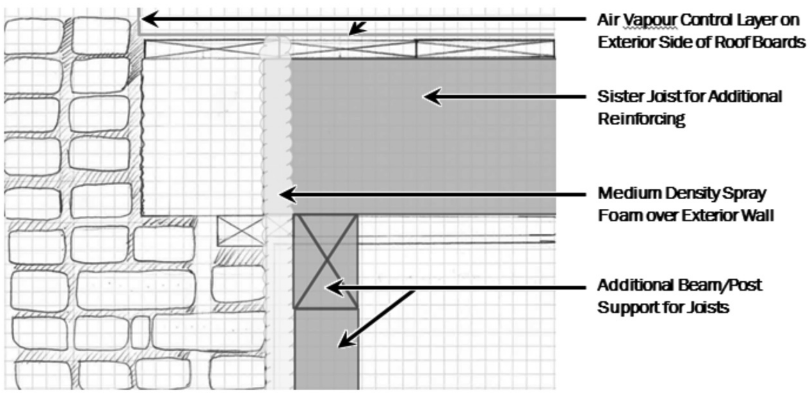

FIGURE 8: SUPPLEMENTARY SUPPORT FOR ROOF JOISTS (ROOF INSULATION NOT SHOWN)

CONCLUSIONS

Insulating our existing building stock provides an opportunity to reduce energy consumption while improving occupant comfort. This has introduced the risk for increased building envelope deterioration where retrofits are completed from the interior on solid masonry walls. A limit states approach can be used to asses these risks and provide guidance on whether a proposed retrofit should proceed or whether additional management strategies are required. Ideally this approach will be developed further and used with increasing frequency to allow owners to confidently improve our building stock. To improve and further develop the method, the repeatability of the Scrit test method should be verified between labs, comparisons between predicted and measured performance over the long-term should be conducted, guidelines for material sampling frequency and size and hygrothermal modeling should be developed. This is expected to result in increased occupant comfort and reduced energy consumption while preserving aesthetic value and limiting deterioration.

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