ABSTRACT

Load-bearing mass-masonry buildings are prevalent on the Canadian landscape, many of them carry a heritage designation. With Canada's commitment to net-zero emissions by 2050 and the ambitious climate target of 40-45% emissions reductions to below 2005 levels by 2030 (Environment and Climate Change Canada, 2022), the drive for building envelope improvements is urgent.

Retrofitting these buildings to today's standards, however, is challenging. The heritage fabric of the building must be maintained without altering the outward appearance or compromising long-term durability. Insulating exterior masonry walls reduces the drying potential to the interior, leading to higher moisture contents within the masonry. In our cold Canadian climate, wetter conditions present higher potential for corrosion risk of embedded steel, decay of embedded timbers, and freeze thaw deterioration of mortar and masonry.

So, how do we assess whether a mass masonry building is a good candidate for thermal upgrades? One key piece is understanding the hygrothermal performance of the building; the dynamic movement of heat, air, and moisture within the assembly. How does the existing building behave and what are the impacts of the proposed changes?

Hygrothermal modelling software is an excellent and widely used tool for assessing this, however, it can offer incomplete and inaccurate information if it is not used in conjunction with other evaluation tools. There are several preliminary steps that should be taken to confirm the existing building performance, composition, and material properties. These steps will provide information necessary for calibrating the hygrothermal models and help predict the impact of proposed changes.

This paper will explore the preliminary investigations that should occur as part of the hygrothermal analysis prior to any modelling; visual reviews, exploratory openings, material testing, and monitoring. Combined, information from these investigations can improve the modelling accuracy and help predict impacts of thermal upgrades on long-term performance.

ASSESSING THE IMPACTS OF THERMAL UPGRADES ON MASS MASONRY WALLS: A TOOL KIT FOR THE HYGROTHERMAL ANALYST

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INTRODUCTION

Load-bearing mass-masonry buildings are prevalent on the Canadian landscape, many of them carrying a heritage designation. With Canada's commitment to net-zero emissions by 2050 and the ambitious climate target of 40-45% emissions reductions to below 2005 levels by 2030 (Environment and Climate Change Canada, 2022), the drive for building envelope improvements is urgent.

Retrofitting these buildings to today's standards, however, is challenging. The heritage fabric of the building must be maintained without altering the outward appearance or compromising long-term durability. Many buildings such as nationally historic and locally important buildings can be prime candidates for emission reduction retrofits (Images 1 and 2). Insulating exterior masonry walls reduces the drying potential to the interior, leading to higher moisture contents within the masonry. In our cold Canadian climate, wetter conditions present higher potential for corrosion risk of embedded steel, decay of embedded timber, and freeze thaw deterioration of mortar and masonry.

Image 1: Parliament of Canada, Centre Block, currently undergoing a large emission reduction retrofit strategy (WSP – Harnessing Built Heritage for Climate Action, 2022)

Image 2: Rendering of repurposing a mass masonry building including interior thermal upgrades (WSP – Harnessing Built Heritage for Climate Action, 2022)

Image So how do we assess whether a mass masonry building is a good candidate for thermal upgrades? One key component is understanding the hygrothermal performance of the building: the dynamic movement of heat, air, and moisture within the assembly. How does the existing building behave and what are the impacts of the proposed changes?

Hygrothermal modelling software is an excellent and widely used tool for helping to answering this question, however, to accurately predict the impacts of proposed upgrades, the hygrothermal model must be well calibrated. As with any modelling exercise, assumptions must be made to some extent. There are several key preliminary investigations that building off one another, providing site and building specific information that can help reduce the number of assumptions in the model. These include background document reviews, visual reviews, exploratory openings, material testing, and potentially, hygrothermal monitoring. Without site-specific information, the uncalibrated hygrothermal model will offer incomplete and inaccurate information, resulting in misinformed design decisions that could be detrimental to the long-term durability of the building.

The process should start with a thorough review of any background documentation available, including building age, construction and material types, historical and present-day occupancy, operating conditions, past repairs, and performance issues. This basic information about the building and lay the knowledge foundation for the rest of the investigations help focus the next investigation: visual reviews.

Through exterior and interior visual reviews are undertaken to confirm current building condition and performance by identifying types and locations of deterioration, building performance issues related deterioration, and the mechanisms driving that deterioration. Visual reviews will also help target locations for exploratory masonry openings. Exploratory masonry openings can confirm wall composition, moisture ingress (if any), and condition of existing embedded steel or timber. Masonry samples from these openings can be harvested for material testing.

Material testing for hygrothermal properties is an import piece of the preliminary process. Material test results, in conjunction with the visual review findings, can help draw conclusions on the durability of masonry. At this stage in the evaluation, there should be enough information to generally predict the impacts of thermal upgrades and start building the hygrothermal model to support these predictions.

In cases where time and budget allow, a pre-construction monitoring program could be implemented, strategically targeting several locations. Ideally, a program such as this should span a minimum one-year period and could include several locations. Embedded moisture sensors, installed at various depths of the masonry, will record hourly temperature and moisture content data, providing insight into the annual wetting and drying patterns of the assembly. This data can be used to corroborate findings from visual reviews and further calibrate the baseline model, ensuring a higher level of confidence in the modelled results of the proposed upgrades.

With information compiled from these preliminary investigations a well calibrated hygrothermal model of the existing building can be constructed with a relative confidence in its accuracy. This accuracy will inform design decisions and aid in the development of appropriate long-term maintenance strategies.

BACKGROUND DOCUMENT REVIEW & VISUAL REVIEW

Starting with a review of any available background documents will set a foundation of knowledge that can help focus subsequent investigations. Background review can include formal documents such as existing and/or current drawings, building maintenance programs, or other written documents. It should also involve interviews with building operations staff, owners, or occupants. This process should seek to answer some basic information such as building age, construction and material types, historical and present-day occupancy, operating conditions, past repairs, and performance issues.

Image 3: Mortar deterioration and loss below decorative banding.

Image 4: Evidence of efflorescence at window stone surround

Building on information gained from the background review, exterior and interior visual reviews will be necessary to understand the current building condition and performance. The reviews should focus on the building but also include focused attention on issues identified in the background review, including past repairs and zones identified as having performance issues. Observations should be well documented to include deterioration types and location, such as masonry or mortar cracks and spalls, masonry movement or displacement, organic staining, efflorescence, and evidence of air or moisture ingress (deterioration examples in Images 3 and 4, above). Observations made during the interior and exterior visual reviews can help target locations for future exploratory openings and material testing and support the development of pre-construction monitoring programs.

EXPLORATORY OPENINGS

Exploratory openings provide valuable information on the current wall condition by allowing the observation of concealed conditions (Image 5). They can help confirm assembly composition and dimensions, identify the extent of moisture ingress, and observe the condition of embedded masonry or timbers. Key findings from the exploratory opening can later be used to support the baseline hygrothermal results to confirm the model's accuracy.

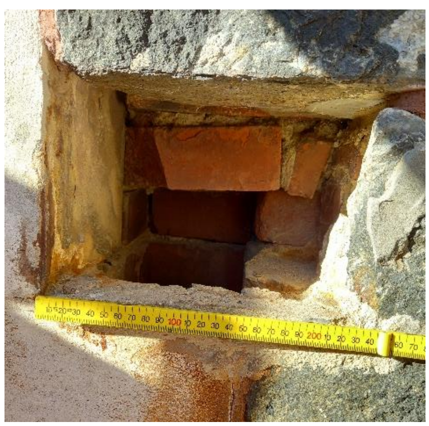

Image 5: Exterior masonry exploratory opening revealing double wythe brick back-up wall. (WSP Applied Sciences Building, University of Otago, NZ, 2021).

MATERIAL TESTING

Material properties of natural stone masonry can vary greatly depending on geographical location and even harvesting location the quarry. Physical material testing of masonry samples collected from site provide immense value when evaluating the existing wall performance and impacts of proposed thermal upgrades (Image 6, below). Test results can help predict durability and susceptibility to deterioration, such as freeze-thaw damage, and identify key locations of concern. Material properties from test results can also be used to develop and calibrate the hygrothermal models by accurately representing site masonry as opposed to a generic material from a database.

Image 6: Masonry samples collected from exploratory openings to be tested to obtain physical properties (Building Enclosure Labs Inc., 2021).

There are several material properties that should be included in the hygrothermal testing to inform the models and evaluate for durability. Generally, testing should include density, porosity, water absorption, permeability, free water saturation, critical degree of saturation, and reference water content. It is always best to review the software inputs required for the hygrothermal models prior to testing to ensure that right properties are captured. When reviewing test results, it is prudent to compare these with other databases such as ASHRAE, WUFI, and past projects to determine if there are any outliers present.

Certain properties such as free-water saturation and critical degree of saturation can help determine the freeze-thaw durability of the material (Image 7, below). Critical degree of saturation (S_{crit}) is defined as the saturation level at which the material experiences expansion due to ice formation when exposed to freezing conditions. In other words, the saturation point at which freeze-thaw damage can occur. It determined using the frost dilatometry method, a process that puts thin slices of the masonry samples at increasing levels of water content through freeze-thaw cycles until damage occurs. S_{crit} is the measured water content of the material at the point of failure. *This value is not used directly in the model but is used as part of the post-processing when evaluating the results and deterioration criteria*. Free water saturation is the maximum water content a material can store in the field. If the masonry undergoes freeze-thaws cycling at moisture contents below S_{crit}, there is negligible risk for freeze-thaw damage.

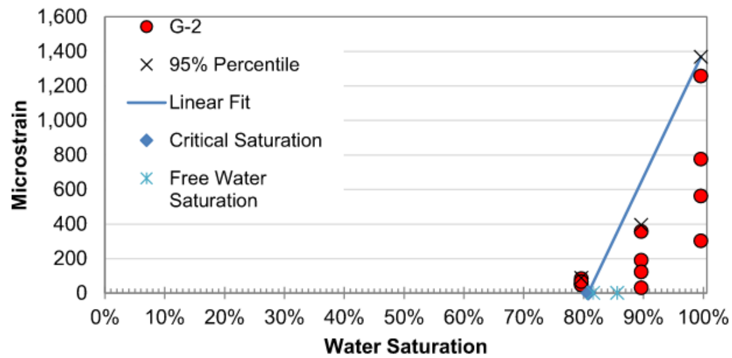

Image 7: Graph of water saturation level vs length change (in microstrain) for sandstone sample - determining critical degree of saturation. (RDH, 2019)

By comparing free water saturation to S_{crit}, conclusions can be made about the durability of the masonry. If free water saturation is less than S_{crit}, then the material is unlikely to reach critical saturation in the field; freeze-thaw damage cannot occur, and the material could be considered durable. However, if free water saturation is greater than S_{crit}, the material could reach critical saturation in the field and is, therefore, susceptible to freeze-thaw damage.

Material durability conclusions from the material testing should be supported by the visual review observations. For example, if material testing indicates that the S_{crit} is higher than the free water, concluding that the material is durable, the exterior visual review should support this by the absence of observed freeze-thaw deterioration of the material. In this example, there may be enough conclusive evidence to support the overall durability of the building and further hygrothermal modelling may not be required. Conversely, material testing may suggest that the masonry is not durable, and if this is backed up by the visual reviews, it may also be concluded that thermal upgrades are not appropriate and further modelling may not be required. There are many instances, however, where material properties vary greatly, and it becomes more difficult to define the durability level of the masonry. Using the hygrothermal models to support test results and visual observation can be valuable in these cases.

MONITORING PROGRAM

A pre-construction monitoring program can assist in calibrating the baseline hygrothermal models and refine its accuracy. Embedded moisture sensors are installed at various locations and depths within the existing wall to record hourly temperature and moisture content. The visual review and exploratory opening observations can help target strategic monitoring locations. A monitoring program could also include a weather station to record hourly temperature, relative humidity, rain deposition, radiation, etc. Measured weather data can be used to create a custom weather file to be used with modelling software. Using a custom weather file and comparing the measured hygrothermal performance of the assembly to the modelled performance can help calibrate and validate the models.

Embedded Moisture Sensors (EMSs), known also as a surrogate moisture sensors or duff sensors, use wood to measure indirect moisture content of the surrounding material using electrical resistance (Image 8, below). Higher resistance equates to lower moisture content. Some EMS manufactures have proprietary software and can configure each sensor individually, applying temperature-specific compensation calibrations to convert resistance to moisture content relative the wood species using known species regression coefficients for said species.

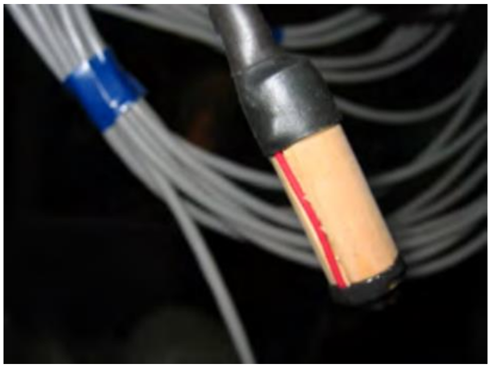

Image 8: Embedded moisture sensor with wood plug (SMT).

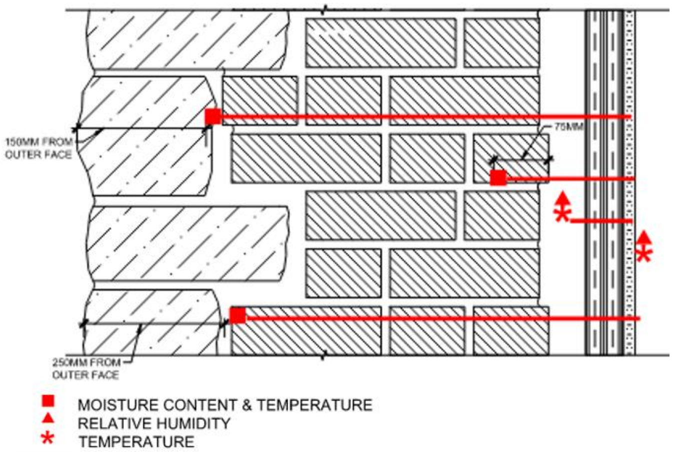

Image 9: Example of targeted sensor locations within a typical mass masonry wall.

It is important to understand that an EMS time response can be slow and asymmetrical. There tends to be a slower response to adsorption (increasing RH) and a fast response to desorption (decreasing RH). These sensors are best used for tracking seasonal trends rather than short-term diurnal activity (Ueno et al., 2008). Ueno et al. also conducted laboratory calibration and testing and found the accuracy of their surrogate moisture sensors to be in the +/- 10% range for high moisture-content ranges.

The location of sensors is crucial when using them to calibrate the baseline hygrothermal models. The sensors should be placed in critical locations where deterioration is most likely to occur like corrosion or rot of embedded beam ends (Image 9, below), which can be determined through the visual review and exploratory openings. In addition, sensors should be installed near the exterior surfaces of the exterior façade stone, mortar collar joint and brick backup wall to measure temperature and moisture contents to determine if freeze thaw conditions are present. Lastly, sensors should be installed within air cavities and at interior finishes to measure the risk for surface condensation and mould growth. The building material that the sensor is installed in can be difficult to determine when drilling a small hole from the interior. Visual reviews and exploratory openings can assist in determining depth of the assembly components and estimated depth the sensors are to be installed.

A minimum one-year period is recommended for a monitoring program, after which, the baseline hygrothermal model can be further refined to align with measured data. Initial conditions such as rain deposition factor, moisture sources, and long and short-wave radiation balances can be adjusted to improve accuracy. For example, if the sensors record a higher relative humidity and moisture content in the masonry due to precipitation than the models, an increase in moisture load is typically required. This can be achieved by increasing the rain deposition factor which determines how much moisture from a rain event is absorbed into the wall and how much is deflected off.

HYGROTHERMAL MODELLING

Hygrothermal modelling is the last tool used when evaluating the potential impacts of proposed thermal upgrades. Hygrothermal models are completed for the baseline existing assembly and the new proposed assembly to evaluate the risk of material deterioration and moisture risks due to the proposed thermal upgrades. Hygrothermal modelling software, such as WUFI, is widely used by professionals as an assessment tool and can simulate the moisture regime within a complex 1-D wall assembly (Image 10, below). However, a significant amount of background information, such as material properties, geographic location, climate, exposure, and operating conditions, is required to refine the model's accuracy and reduce the number of assumptions. The model outputs hourly results which can be used to evaluate the risk for deterioration such as freeze thaw, corrosion, rot, and organic growth. The accuracy of the model is ultimately determined by the accuracy of the inputs and thus it is imperative reduce the number of assumptions as much as possible and ensure appropriate inputs for other assumptions are used. Many assumptions can be eliminated by carrying out thorough preliminary investigations as described above.

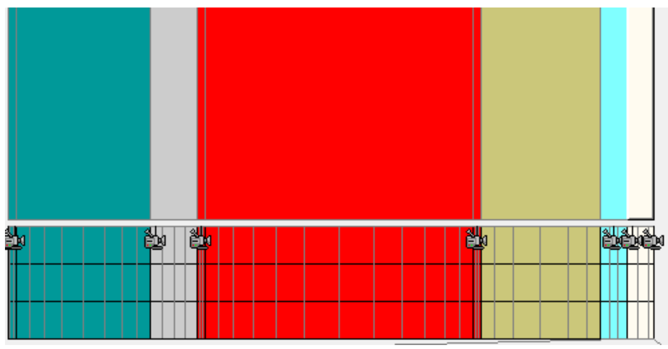

Image 10: Example WUFI wall assembly from exterior to interior (façade stone, mortar collar joint, brick, spray foam insulation, air cavity, plaster interior finish) (WUFI Pro 6.4, 2022)

The exterior climate and exposure to driving rain impacts the moisture load of the wall greatly. A typical weather file can be selected from the WUFI database, or a custom file can be created to represent the local climate conditions more accurately. A weather station measuring hourly local climate data will typically be the most accurate way to reflect site-specific climate conditions. This can be incorporated as part of a pre-construction monitoring program but will require a year or more of lead tome to install the equipment and measure and process the data. The orientation and wall exposures defined in the models should align with the site orientation and exposures to ensure the models are reflecting real world conditions.

The interior operating conditions should accurately reflect the existing and proposed new operating conditions. WUFI has several methods for modeling this. Understanding site specific information, gathered through interviews with facility staff, visual reviews of the heating/cooling equipment and distribution plans will help determine the most appropriate method to select.

Exploratory openings and visual reviews will assist in confirming the exact wall assembly. In addition to determining the wall composition and dimensions, the openings can also identify whether moisture sources need to be added to the model to simulate the penetration of driving rain through cracks or voids present in the existing condition.

Hygrothermal models produce hourly outputs including temperature, relative humidity, moisture content, and vapour pressure for pre-selected locations within the wall assembly. Visual reviews and exploratory openings will assist in determining locations of embedded steel or wood elements, such as beams, joists, and masonry ties. These elements should be evaluated for corrosion or decay when considering any thermal upgrades. Deterioration such as corrosion and decay can be determined using the "time of wetness" method which evaluates the temperature and relative humidity at the surface of the components. Data from the models can be used to estimate the number of annual hours that corrosion-promoting (or decay-promoting) conditions are estimated to occur. By comparing the baseline predictions to the proposed upgrades, the impacts of proposed changes can be predicted. If the hygrothermal model of the baseline assembly indicates that corrosion promoting conditions are occurring, visual reviews and exploratory openings should support this finding. Inconsistencies between the model and in-situ conditions mean that further calibration to the model should be made so it aligns more closely with the existing building performance.

Hourly moisture and temperature outputs are used to determine the risk of freeze-thaw deterioration by observing the number of critical freeze-thaw cycles predicted. Using S_{crit} results from material testing, critical freeze-thaw cycling can be predicted. If the material testing was not completed, the critical moisture content can be estimated as a function of the free-water saturation and vacuum saturation, but this greatly reduces the accuracy of the results. Again, baseline model predictions should be supported by the material testing and visual reviews.

Potential for organic growth on interior finishes can be assessed by several means including time of wetness and the ASHRAE 160. ASHRAE 160 accounts for substrate susceptibility which ranges from very sensitive materials like untreated wood to resistant materials such as glass and metal. It is generally accepted as an accurate means of assessing organic growth potential. Interior visual reviews can confirm the existing interior finish material and condition including paint layers. If the interior paint type and number of layers are unknown, material testing can determine the permeability of the paint layer which can be inputted into WUFI to help refine the model's accuracy.

As with any modelling exercise, hygrothermal model outputs are only as accurate as the inputs. The use of visual reviews, material testing, and monitoring can help refine the model's accuracy by providing measured data and site information. The use of generic materials and assumptions will not provide site specific information required for accurate results which can lead to uninformed design decisions.

CONCLUSION

Load-bearing mass-masonry buildings are abundant on the Canadian landscape, many of them carry a heritage designation and many of them are due for retrofit. Retrofitting this building stock to modern standards presents many challenges. The heritage fabric of the building must be maintained without altering the outward appearance or compromising long-term durability. With the clock ticking on Canada's ambitious plan for achieving its 2030 and 2050 carbon reduction targets, the drive for building envelope improvements is urgent; it is critical that we understand how to accurately assess the candidacy of these buildings for thermal upgrades.

Hygrothermal modelling software is an excellent tool for assessing and comparing hygrothermal performances of different assemblies. However, when used as a tool to evaluate an existing masonry building and proposed upgrades, a significant amount of site-specific information is required to construct a well-calibrated hygrothermal model. The preliminary investigations outlined in this paper including background document review, visual reviews, exploratory openings, material testing, and potentially monitoring can provide the necessary information to draw informed conclusions about the existing building performance and the impact of proposed changes.

In an ideal world, each of these investigations would be possible. However, carrying out all the possible preliminary investigations is not always realistic. Background documents or information may be unavailable, site access may limit the extent of visual reviews, exploratory openings may not always be possible and often, budget and time restraints prevent the implementation of a hygrothermal monitoring program. The analyst must make informed assumptions based on the information available. However, the most critical part of the preliminary investigation is the material testing. Without material test results, material durability conclusion can only be gleaned from visual reviews and the models will assume default material properties that may or may not represent the site materials, resulting in a low level of confidence in the modelling results.

Compiling as much information as possible thorough preliminary investigations is key to reducing the number of assumptions in the analysis process. The elimination of as many assumptions as possible will ensure a baseline hygrothermal model can be constructed with a high level of confidence, resulting in informed design decisions and the development of appropriate long term maintenance strategies.

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