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This paper examines methods of using hygrothermal models, primarily WUFI, to assess the impact of energy efficient enclosure upgrades on the durability of historical buildings. Means of producing and choosing input data for the hygrothermal simulation are discussed. Methods for using the hourly results from the simulations to generate a corrosion index and a freeze thaw count are developed. An example wall is used to demonstrate the type of output that can be expected and how this can be used in making retrofit design decisions.

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Introduction

Increased energy costs, decreasing energy security and fossil fuel reserves, and a growing awareness of the environmental impact of energy use in buildings has resulted in a renewed interest in energy efficiency. Space heating (and even cooling) of buildings is a major consumer of energy, and energy flows through the opaque vertical enclosure (walls) can be responsible for 20 to 50% of the heating/cooling load. There is a growing number of large masonry buildings built in Canada before the middle of the century that owners wish to renovate. Historical significance, increased energy costs, re-urbanization of city centers, and enhanced appreciation of traditional building architecture have generated the need.

A common potential retrofit option considered that can reduce energy consumption in this type of building is an interior retrofit that increases wall insulation and air tightness levels. Such retrofits also allow for a renewal of the interior finishes and distribution of services, important features in creating more useful buildings. It is desirable if renovations of any type can improve durability, indoor air quality, and comfort. Although exterior insulation retrofits are often much easier to design and easily meet most performance objectives, they change the appearance of the exterior and hence are usually not acceptable. This paper only investigates interior retrofits.

It should be noted that other energy-saving retrofit options should be considered in parallel with increased wall insulation. Such options include equipment changes (to more efficient models), window replacement, roof insulation upgrades, and no change at all (for situations in which energy consumptions reductions are impractical to achieve).

Changes in wall insulation and air tightness also bring about changes in the temperature and moisture conditions within walls, and in some cases have been blamed with causing reductions in durability. Regardless of the energy savings realized, it is important to ensure that retrofits undertaken for energy efficiency do not adversely affect wall durability. The durability aspects that are of the most importance for historic masonry buildings include freeze-thaw resistance, efflorescence (caused by salt transport), corrosion (especially of masonry steel ties and embedded structural steel), and rot of embedded wooden components.

The extent to which enclosure wall retrofits can improve, or degrade, durability is a function of both the change in temperature and moisture conditions and the response of the materials that make up the wall. Hygrothermal computer models aim to simplify the former and material damage models are simplifications of the latter.

The moisture and temperature conditions within an enclosure wall are a complex function of parameters such as material properties, indoor and outdoor environmental conditions, mechanical system performance and occupant activities. To account for all such variables, computerized hygrothermal modeling tools can be used to help assess the change in wall performance as a result of the retrofit activities. It has been previously shown that hygrothermal computer simulation models can predict moisture and temperature conditions with a reasonable degree of accuracy (Kuenzel 1994, Straube & Schumacher 2003); however, these predictions do not directly provide an assessment of the durability risks without an understanding of each materials response and interaction with adjoining materials.

However, despite the value of modeling, its using in making retrofit decisions is limited by various factors, including uncertainty or simple lack of knowledge about boundary conditions (climate and exposure) and material properties. A major question is what damage models / performance thresholds should be used to guide the interpretation of the model results.

This paper reports on the assessment, using hygrothermal computer models of the durability implications of energy efficient retrofits wall assemblies used in older Canadian (and northern United States) buildings. Methods of generating weather files and analyzing the data using very simple and approximate damage functions are discussed. A single example of a typical solid masonry wall exposed to the climate of Halifax, Ottawa, Toronto, Winnipeg and Vancouver is presented.

Hygrothermal Modeling Approach

Figure 1 shows the flow of information that is required for a typical modeling exercise (Straube & Burnett 2005). The arrangement and geometry of the enclosure to be modeled is usually known, but significant simplifications must be made: 3-D assemblies approximated as 1-D, cracks and air gaps ignored and lumped into macro properties, etc. The combination of physics and numerics are embodied in the choice of the computer model. The choice of boundary conditions and material properties are major decisions made by the analyst/modeler. Finally, the interpretation of the results requires engineering judgment and an understanding of the inner workings of the models and material response.

The simulation package WUFI3.3 Pro will be used (Kuenzel 1994) in this paper as the authors have had the most experience and success with this package. WUFI is one of the most advanced commercially available hygrothermal moisture programs in use today. Its accuracy has been verified against numerous full-scale field studies of enclosure performance (roofs, walls, foundations, parking garage decks, etc.) over a number of years (e.g., Straube & Schumacher 2003). It is one of the few models in the public domain that can properly account for rain absorption and different water absorption/redistribution for arbitrary material data and boundary conditions. Given the appropriate material data, WUFI calculates heat and moisture flow every hour under the influence of sun, rain, temperature and humidity (see also www.wufi.de). The analysis is, however, only as accurate as the input and the interpretation.

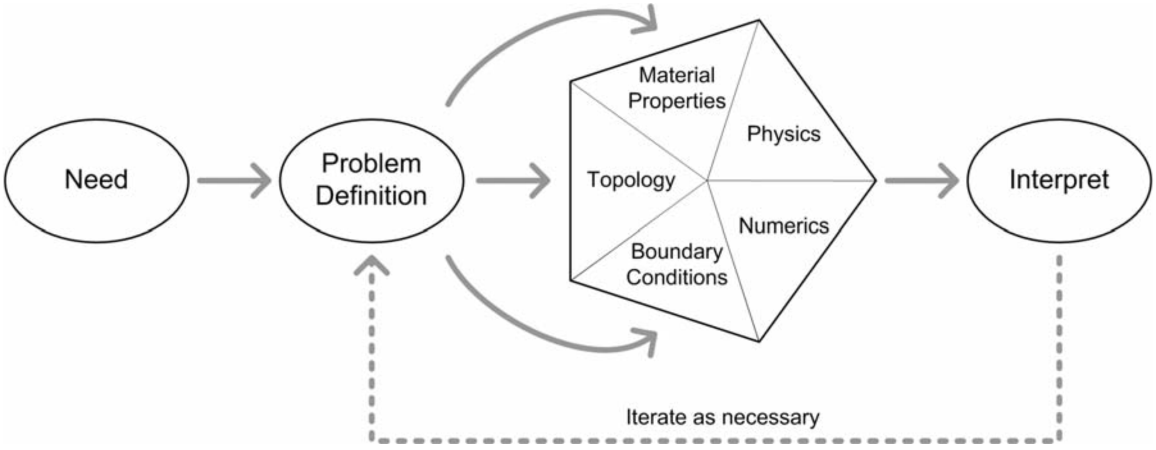


Figure 1: Modeling Approach (Straube & Burnett 2005)

Air Leakage Condensation and Drying

The WUFI model does not predict air leakage induced wetting and drying. This is difficult to account for primarily because the leakage path and driving forces are unknown, and are generally unique. The time scale of wind-induced air leakage is also much shorter than one hour. In all of the cases studied in this project it has been assumed that air leakage across the enclosure has been substantially controlled by standard air sealing techniques. It is not reasonable to attempt to design a retrofit with a significant amount of air leakage. However, experience has shown that air barrier systems formed of spray polyurethane products and fully-adhered membranes are more likely to achieve airtightness than drywall over batt spaces.

In typical retrofit situations, air leakage testing should be carried out to identify air leakage paths and to subsequently confirm that air sealing was successful. (Note that one can make an assessment of the air leakage *potential* by calculating the difference between the predicted temperature of a likely condensation plane such as the inside face of the sheathing or cladding and the interior dewpoint temperature. This is a very conservative method and will always over predict condensation.)

Boundary Conditions: Climate and Exposure

The exterior climate is clearly critical to enclosure wall durability. Five Canadian cities, representing large building markets with a stock of historical buildings and different climate zones are studied in this paper: Halifax, Ottawa, Toronto, Winnipeg, and Vancouver. The former three are wet (over 600 mm per year of precipitation) and have many days with freezing temperatures. Winnipeg is a very cold (average January temperature of -18 C) but dry climate. Vancouver experiences significant amounts of rain, but very few days of freezing weather.

Weather Files

Although WUFI includes some weather files, in some cases, weather files are not available for the project in question. Test Meteorological Years (TMY) Canadian Weather years for Energy Calculations (CWEC) or Weather Years for Energy Calculations (WYEC) files can often be used as these data files are readily available to most practitioners. Such files contain hourly weather data in a consistent form based on many years of real weather data. In general, the most problematic issue is converting the rain flags in the data file to rain fall rates. This can be done by applying average values to each flag and then correcting for annual or monthly average results (Straube 2005).

Note that most weather files are not extreme weather years, but rather average conditions of temperature and solar radiation intended to generate long term average energy consumption values for buildings. Some years will tend to result in worse conditions and some will result in more favorable results. It has been the experience of the authors that the role of driving rain and interior humidity is greater than the variation of performance between abnormally cold or abnormally warm years. Hence, we believe that the use of average year weather data is acceptable.

Driving Rain

The driving rain load is the largest moisture load in most climates for enclosures with absorptive claddings (e.g., wood, stucco, and masonry). The driving rain was calculated by combining the wind speed, wind direction and rainfall rate for each hour using the method described and validated by Straube & Burnett (2000). For all cases a Driving Rain Factor (DRF) of 0.25 and a Rain Deposition Factor (RDF) of 1.0 was used. This represents a relatively high exposure to driving rain (equivalent to the upper edges and top vertical edges of an exposed building). For a three-storey building in a built-up urban exposure, the RDF will be less than 0.5 over much of the façade. However, uncontrolled drainage from windows or other building features can increase the RDF significantly, and these areas of concentration must be avoided in the design and construction of details. The rain deposited over most of the center of a building face or lower down the face where protected by surrounding buildings will reduce the rain deposition factor to 0.1 to 0.5.

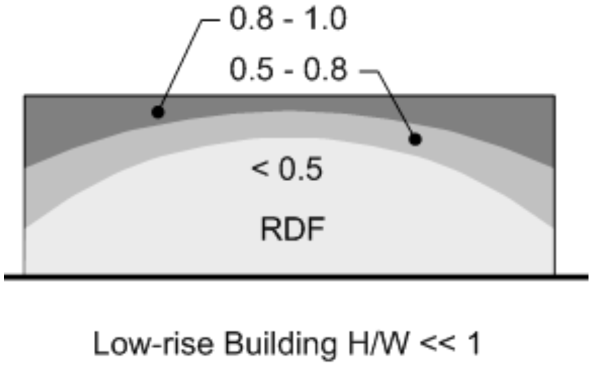
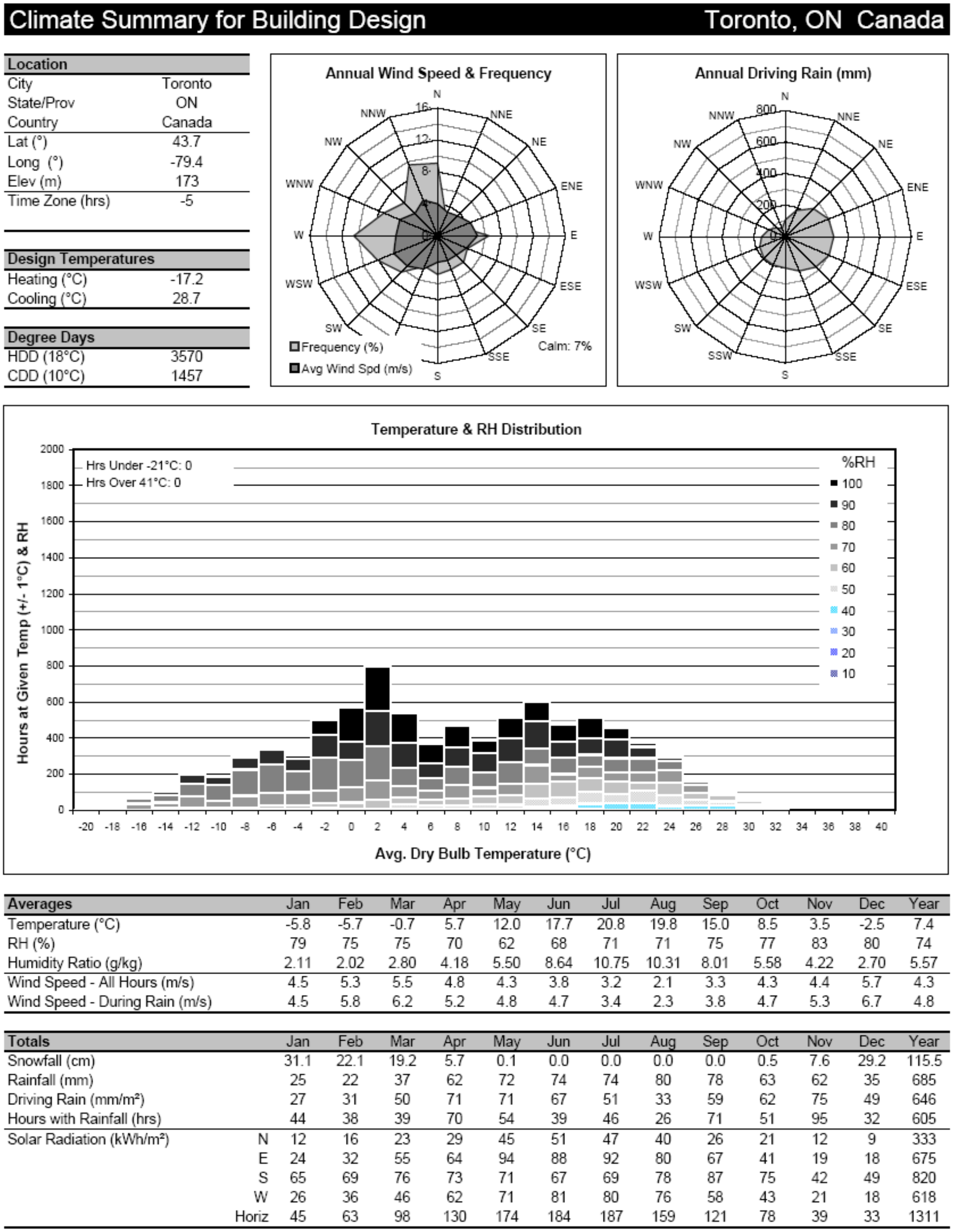


Figure 2: Distribution of Rain Deposition on Buildings

In using the WUFI model, a slightly different and more empirical approach is taken, also with two factors. If the R2 rain factor in the orientation section is used as the DRF and the Rain Water Absorption Factor in the surface transfer section is used as the RDF and, exactly the same results can be calculated. We have found this a successful means of comparing WUFI calculations to measured data.

Orientation and Climate

The orientation of a wall will often have a significant effect on the exposure of the enclosure to wind, rain, and sun. As it is often onerous to conduct simulations of each orientation, it is desirable to pre-select the critical orientation based on a climate analysis. To this end, the climate for each site should first be analyzed by calculating driving rain direction and intensity, temperature, and relative humidity, solar radiation, wind speed and wind direction frequency. Driving rain was given the most importance, but solar radiation is also important, as it increases the drying capacity of masonry and elevates the temperature (which reduces freezing)



Climate Summary for Building Design — **Toronto, ON Canada**

Location	
City	Toronto
State/Prov	ON
Country	Canada
Lat (°)	43.7
Long (°)	-79.4
Elev (m)	173
Time Zone (hrs)	-5

Design Temperatures	
Heating (°C)	-17.2
Cooling (°C)	28.7

Degree Days	
HDD (18°C)	3570
CDD (10°C)	1457

Averages	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (°C)	-5.8	-5.7	-0.7	5.7	12.0	17.7	20.8	19.8	15.0	8.5	3.5	-2.5	7.4
RH (%)	79	75	75	70	62	68	71	71	75	77	83	80	74
Humidity Ratio (g/kg)	2.11	2.02	2.80	4.18	5.50	8.64	10.75	10.31	8.01	5.58	4.22	2.70	5.57
Wind Speed - All Hours (m/s)	4.5	5.3	5.5	4.8	4.3	3.8	3.2	2.1	3.3	4.3	4.4	5.7	4.3
Wind Speed - During Rain (m/s)	4.5	5.8	6.2	5.2	4.8	4.7	3.4	2.3	3.8	4.7	5.3	6.7	4.8

Totals		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Snowfall (cm)		31.1	22.1	19.2	5.7	0.1	0.0	0.0	0.0	0.0	0.5	7.6	29.2	115.5
Rainfall (mm)		25	22	37	62	72	74	74	80	78	63	62	35	685
Driving Rain (mm/m²)		27	31	50	71	71	67	51	33	59	62	75	49	646
Hours with Rainfall (hrs)		44	38	39	70	54	39	46	26	71	51	95	32	605
Solar Radiation (kWh/m²)	N	12	16	23	29	45	51	47	40	26	21	12	9	333
	E	24	32	55	64	94	88	92	80	67	41	19	18	675
	S	65	69	76	73	71	67	69	78	87	75	42	49	820
	W	26	36	46	62	71	81	80	76	58	43	21	18	618
	Horiz	45	63	98	130	174	184	187	159	121	78	39	33	1311

Figure 3: Climate Summary for Toronto, Canada

Climate summaries for each city can be developed, (including temperature, driving rain and solar exposure) and are presented for one climate (Figure 3). Each climate zone has a somewhat different direction for peak driving rain, and all are affected similarly by solar gain variations. Based on preliminary runs and inspection of the climate summaries, the worst-case direction was chosen for each climate. The choices are summarized in Table 1. It can be seen that the directions can vary. The newer versions of WUFI (version 4.0 and higher) provide tools to conduct some of this pre-analysis within the program itself.

City	Critical Direction
Halifax	East
Ottawa	South
Toronto	South
Winnipeg	South
Vancouver	East

Table 1: Worst-case Orientations for Five Climates

Interior Conditions

Interior conditions (especially humidity) can play a significant role in the performance of some walls. If the walls have a poly vapor barrier on the interior, RH matters little for diffusion calculations, but air leakage condensation will vary depending on the interior RH. Since air leakage should be controlled by any retrofit this variable is not usually directly assessed. A standard interior climate variation for office spaces is chosen in this paper: a sinusoidal variation from a low of 30%RH in winter to a high of 60%RH in summer. This is a reasonable level of interior humidity for a cold climate building, but may be low for warmer climates, such as Vancouver. An important role of hygrothermal modeling in assessing retrofits is that of examining the impact of changes in interior humidity on the conditions experienced by the wall. In almost every case, the mechanical systems designer should be informed of the temperature and RH conditions that have been assumed for the design of the retrofit enclosure.

Material Properties

The default material property files provided with the WUFI model are often used as a basis for the inputs. Information from the recent ASHRAE/IRC MEWS material characterization projects are incorporated as necessary. In most solid masonry walls, it is easy and fast to conduct water uptake, free water saturation, dry density, and total porosity (estimated by the 5 hr boil) tests of brick and/or mortar to aid in the approximation of the most important material properties (Krus and Kuenzel 1993). Thermal conductivity can be estimated from the density, and vapor permeance test may be useful in some cases. Parametric computer simulations can be used to assess the impact of material property uncertainties before embarking on an extensive test campaign. In solid masonry walls with interior insulation, the vapor permeance and thermal conductivity of the masonry can vary over rather large ranges and impact the results of the testing very little.

Damage Functions

Interpreting temperature and humidity results in terms of durability is an emerging science and not yet well defined. Although damage functions and damage models are available in the literature, they often require some modification to be used with the hourly data output by simulation programs like WUFI.

We have chosen a number of relations from the literature and modified them to make them more useful. Only the two most common damage functions for historic buildings are described below: freeze-thaw and corrosion. Methods are also available for mold growth, but most historic buildings in Canada are masonry and not very susceptible to mold growth.

Freeze-thaw

Although freeze-thaw (FT) damage is an age-old problem, predicting FT damage is still not precise. For example, physical testing of individual bricks is commonly considered to be the best measure, despite the fact that the CSA brick standard often rejects bricks found from experience to be durable and sometimes accepts bricks that fail in the field (Brampton Brick 1994)

Different materials, such as clay brick, calcium silicate, concrete, and natural stones, exhibit different susceptibility to FT damage. Hence, the approach taken in this project has been to assess the potential for FT damage based on the microclimatic conditions experienced by the material in question.

It is well accepted that two factors have the most importance to FT damage: the moisture content on freezing and the number of freeze-thaw cycles. We have defined a freeze cycle as occurring when the temperature within the material drops below -5 C (a rather high temperature) and a thaw cycle to occur when the temperature rises above 0 C. This is based on the observation that FT is not a problem at temperatures just below freezing – damage tends to require temperatures much colder than -5 C and most test standards require the material to be cooled below -15 C.

The process by which we process hourly data to calculate the number of potentially damaging freeze-thaw cycles is shown in Figure 4. The critical moisture content for FT damage is defined as the moisture content above which FT damage can occur (Bomberg 1994, Fagerlund 1996). Although the critical moisture content can be found from tests, such tests are rather involved and onerous. The dangerous moisture content is often in the range of 75 to 94% of the free water saturation. Given no other information we often choose to use 90% since it is conservative and one of the more common thresholds for brick. The same threshold can often be used for natural stone.

It is important to note that RH is not a good measure of freeze-thaw damage. The sorption isotherm is very steep in the region in which FT damage is possible, and the RH would typically be over 99% regardless of which critical moisture content is chosen. We recognize that a lower or higher number could be used, but regardless of the choice, the differences between the performance of different retrofits should still be evident. In general, the exact threshold is difficult to find, and the approach to analysis is based on the inspection of relative changes brought about by the retrofit, rather than an absolute performance threshold. Hence relative comparisons should be reasonably accurate. Factors that may play a role, but are not considered in the damage function used here include the rate of freezing, the presence of salts, the pore size distribution, and the compatibility of the mortar and masonry.

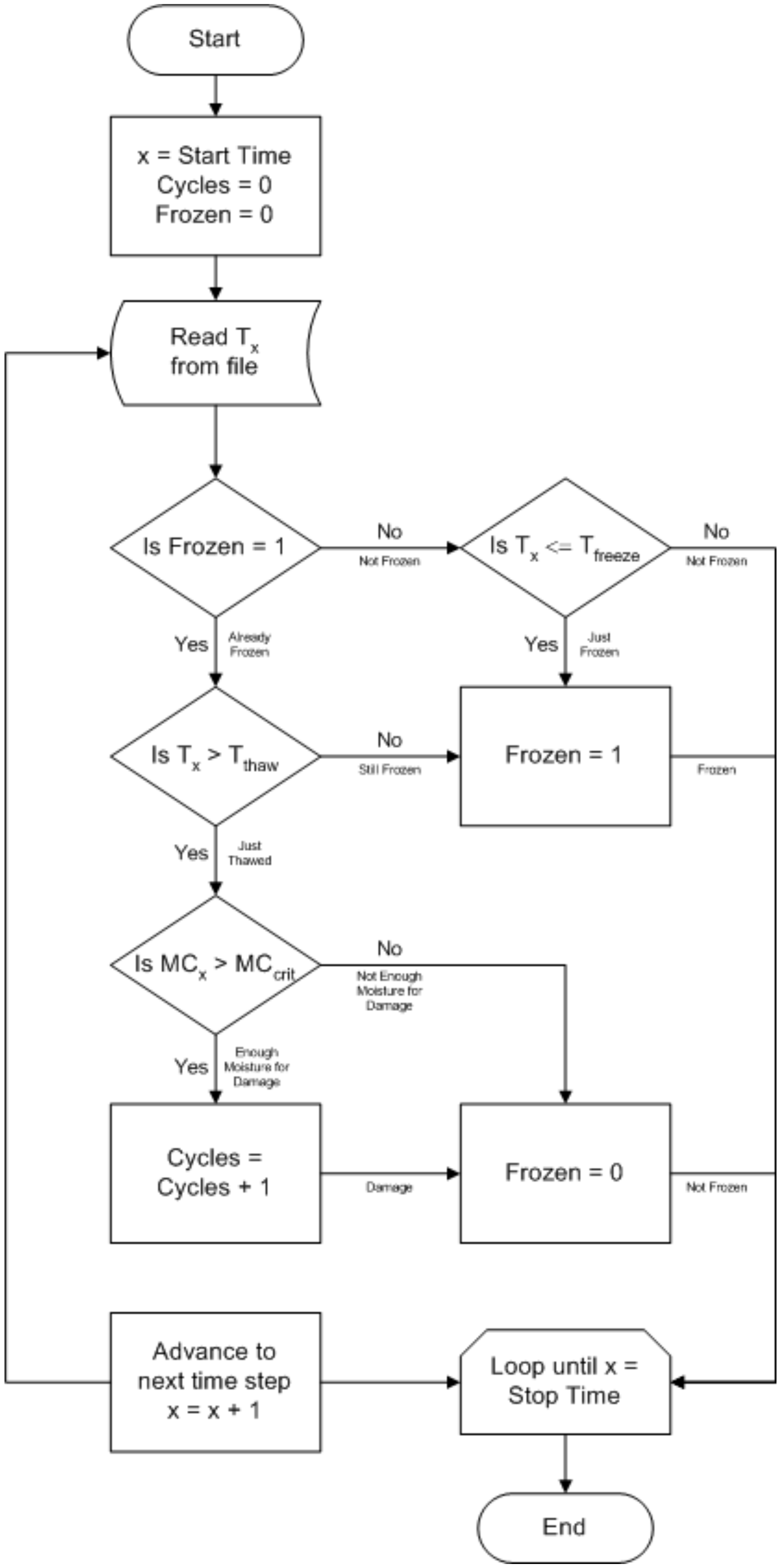


Figure 4: Freeze-thaw Damage Potential Assessment Procedure

When assessing damage potential, the choice of the location of the moisture content measurement is also important. In general, the worst conditions are usually just below the surface, an observation long ago made by Kuenzel. In the work reported here, freeze-thaw damage was assessed at the exterior face and interior face of exterior cladding. The moisture content and temperature of a 4.5 mm slice at the point of interest were used. Inspection of the hourly film data is very important for choosing the layer with the most extreme conditions.

Corrosion

Corrosion is a concern for many wall systems because masonry ties, precast concrete anchors, and light-gauge studs are all susceptible to corrosion and critical to safe performance. All ferrous metals, including those coated with zinc, are susceptible to corrosion. The zinc coating is a sacrificial layer that tends to corrode more slowly than steel.

The two factors that have largest affect on corrosion rate are the temperature and the relative humidity *at the surface* (i.e., time of wetness) of the metal component. As the RH exceeds about 75% to 80% corrosion rates become more significant. As shown in Figure 5 corrosion can begin at lower RHs, and is often below its peak at 100%. The latter effect is due to the oxygen-limiting effect of thick films of surface water. This is important in steady-state conditions, but in the variable conditions within walls, very high RH conditions alternate with lower RH, thereby allowing oxygen access and increasing the corrosion rates even at 100% RH. Temperature also plays an important role as it provides the energy required to activate chemical reactions.

A corrosion index was developed that was adapted from the field work of Norberg (1998). The model was enhanced to include other information, such as the Arrhenius relation, and other data sources. This index is based on a value of 1.0 for 20 C and 80%RH, considered the start of noticeable corrosion by numerous authorities, including the ISO 9223 standard on atmospheric corrosion (ISO 1992). The corrosion index doubles for an increase in temperature from 10 to 20 C and from 20 C to 40 C. The index also doubles when the RH increases from 80%RH to 90% and increases by a factor of 2.5 for a rise of RH from 90% to 100%. Although these values have little quantitative meaning, they do reflect what is known about corrosion rates, and will provide a strong relative indicator of corrosion potential. The corrosion potential below 80%RH (unlike Norberg's work) and below freezing temperatures is defined as zero. The corrosion index proposed is plotted in Figure 6 for a range of temperatures and humidities.

Data from simulations can be interpreted by summing the hourly corrosion values (cumulative CI) for each point of interest and dividing by 100 to reduce the value to a more manageable number. For reference, a CI of 240 is intended to reflect the corrosion potential of one thousand days (almost 3 years) at 20 C and 80%RH (= 1 x 24 hrs x 1000 days / 100 = 240) or 100 days at 40 C and 100%RH (=10 x 24 hrs x 100 days/100 = 240) or some other combination.

The data can be presented in the form of plots of cumulative CI versus time to provide an appreciation of when corrosion occurs and at what rate. Steep positive slopes in these plots indicate fast increases in the cumulative CI over time and hence periods of high corrosion potential. Horizontal parts of the cumulative CI curve indicate periods during which there is no potential for corrosion. As corrosion is not a reversible process, there can be no negative CI value and hence no reduction in the cumulative CI plot.

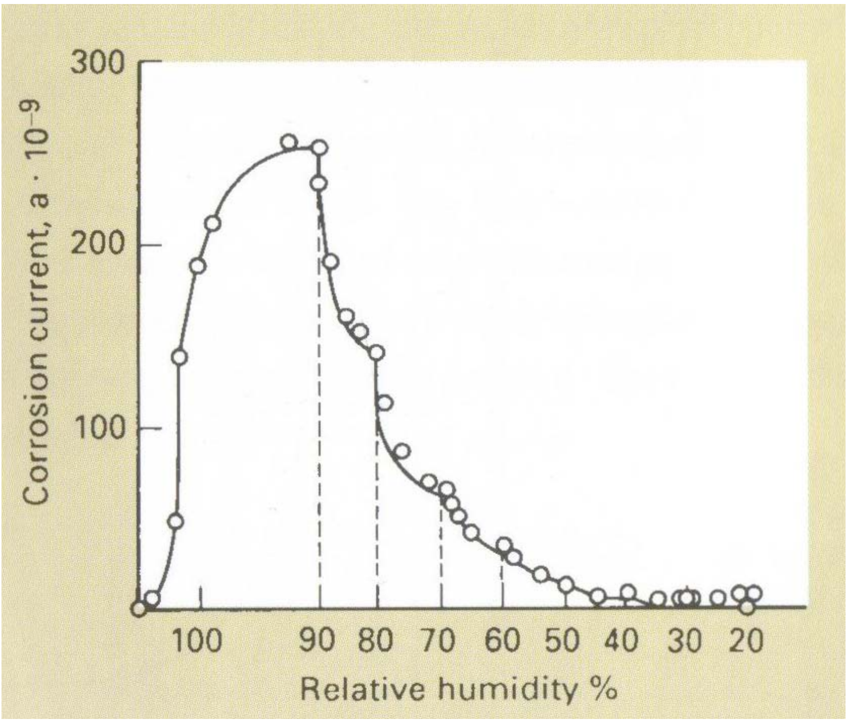


Figure 5: Example of Measured Field Corrosion Rate versus RH (Harriman 2003)

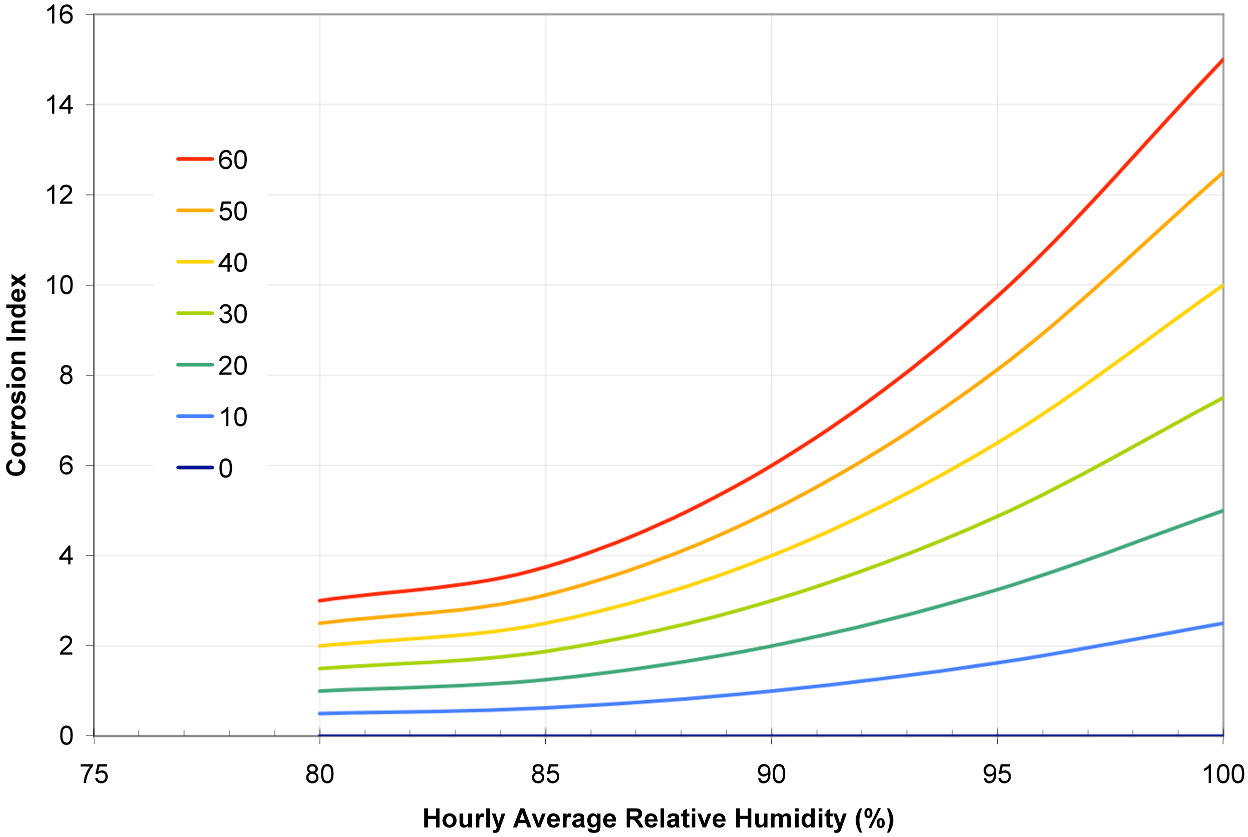


Figure 6: Corrosion Index Values for Different Temperature and RH Conditions

Factors that have a major affect on corrosion, but are not included in the damage function, include the level of acidic corrosion, salts (from the sea or building uses) and the buildup of corrosion products. The type of metals, surface finishes, and many other factors play a role. These are situation specific conditions that are difficult to account for in a general way, but can alter the actual corrosion rate by an order of magnitude. Again, it must be emphasized that the corrosion index used is purely indicative.

Certain climates have lower pH (i.e., acidic) rain than others. According to the CSA Guideline on Durability (Figure C2) (CSA 1995) all of the Canadian climates studied except Winnipeg have rain pH values of between 4.5 and 5.0. Other countries also have rain pH maps. Winnipeg rainwater is over 6.0, which should result in lower corrosion rates. Airborne salt in buildings within a few kilometers of the ocean (Vancouver and Halifax) will also have noticeable effect on corrosion, and should be considered in a site-specific manner.

Corrosion is often an important deterioration mechanism for walls with metal anchors and ties in any cavity; at the outer edge of metal studs at the inside edge of the exterior cladding for walls with interior framing; and for walls with reinforcing within the brick masonry or in the core of concrete masonry units.

Example Wall

An example wall was chosen as representative of a wall for a large monumental and historically significant building of about 100 years age. It is comprised of 200 mm thick sandstone and 600 mm of load bearing brick masonry with an interior of a terra-cotta hollow clay tile and gypsum plaster (Figure 7). The two retrofits considered (Wall A and B) include adding 50 mm of XPS (adding RSI 1.76) and 90 mm batt insulation between steel studs (adding about the same insulation level when thermal bridging through the studs is considered). The make up of the two retrofit walls can be seen in Figure 8 and Figure 9.

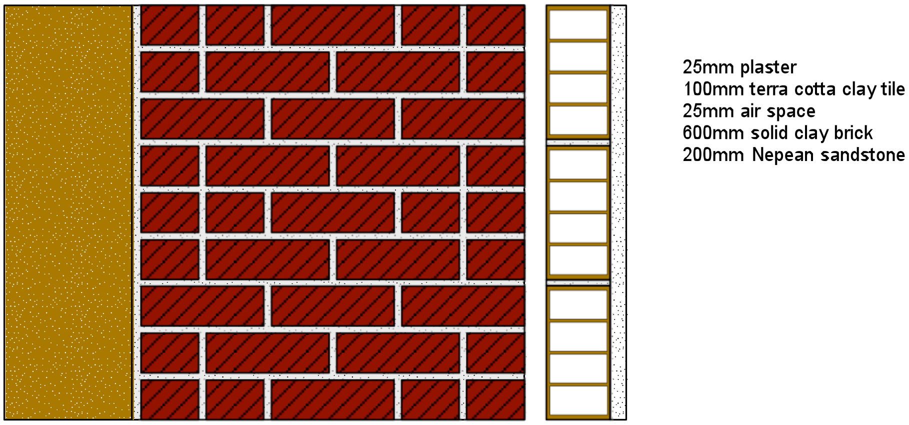


Figure 7: Arrangement of Original Wall

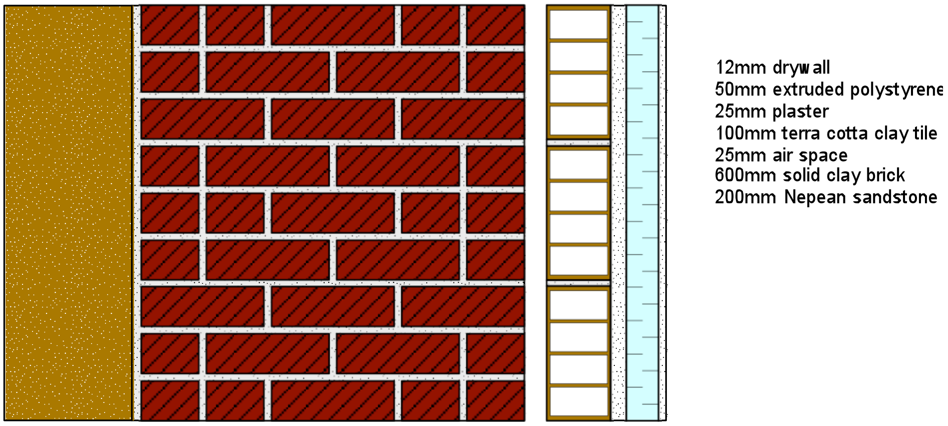


Figure 8: Arrangement of Upgrade Wall A

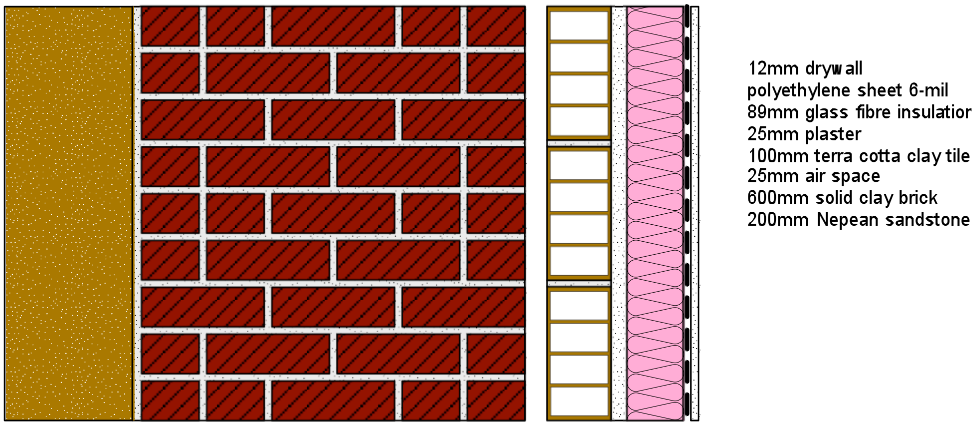


Figure 9: Arrangement of Upgrade Wall B

The wall was discretized as shown in Figure 10. The interfaces of the masonry layers were chosen as the layer of interest for the corrosion index as this is where metal ties and reinforcing would be embedded.

The moisture storage capacity of the wall is significant, as it is for many solid masonry walls. Even starting at 80%RH equilibrium and running for 4 years did not result in equilibrium. The starting RH was increased in a series of parametric runs until equilibrium was reached after two years of simulation.

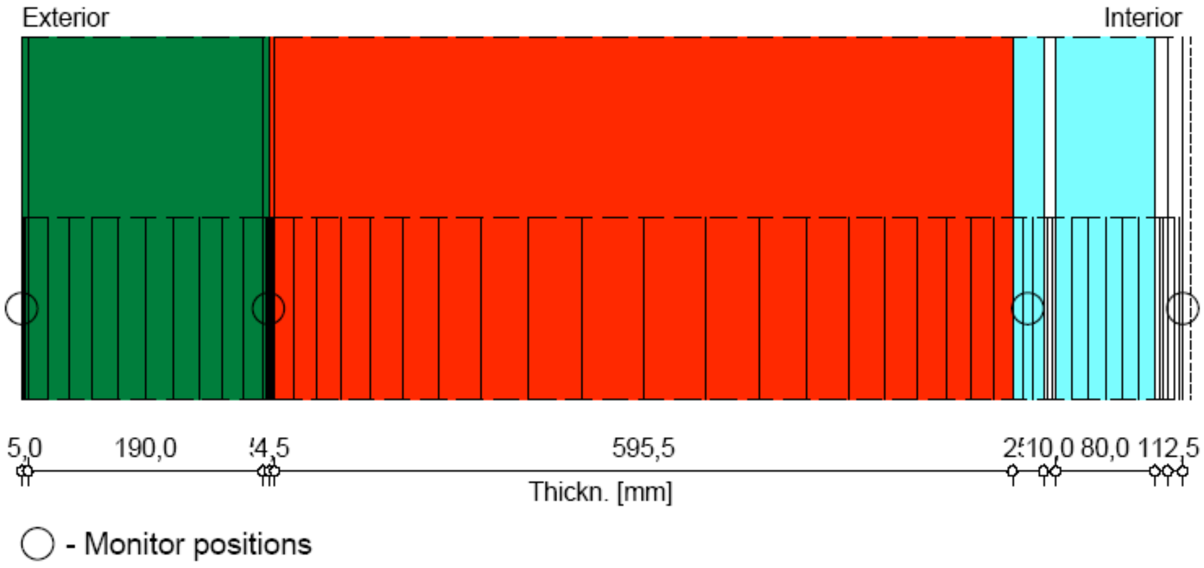


Figure 10: WUFI Model of Original Wall

Results

The summary damage indices, calculated as described above, are presented in Table 2. The retrofits (Retrofit A and B) do not result in significant changes to the damage indices. It can also be seen that the cold and wet climates (Halifax, Toronto, and Ottawa) have higher damage indices both before and after the retrofits than the cold and dry (Winnipeg) climate and the wet and warm (Vancouver) climate. This observation is in broad agreement with experience in the field.

The number of freeze-thaw cycles was remarkably low given the expected severity of the climate and exposure. The freeze thaw counts increased slightly for the brick (not the stone) only in Halifax and remain unchanged elsewhere. Hence, the FT index indicates the upgrade of these particular walls does not greatly increase the likelihood of freeze-thaw damage.

It can be seen that the corrosion index of the wall is high but the retrofits result in a small reduction: this is due to the reduced temperature of the exterior portions of the wall. The moisture storage capacity of the masonry ensures that the RH is held high for many hours per year. Balancing the high CI is the fact that most metal components will be embedded in mortar, which reduces the access of moisture and helps maintain a high alkalinity.

The corrosion index for the outer flange of the metal stud in Retrofit B is surprisingly high. This is a result of water wicking through the mass of the stone and brick. The metal is kept warm at this location by the insulation value of the masonry in the wall and hence corrosion of this thin zinc-coated metal can occur.

The key conclusion from the CI analysis is that the corrosion potential of the existing wall is reduced slightly by the retrofits, not increased, and so this damage mechanism is not a concern for either retrofit. The CI analysis also focuses on the importance of corrosion resistance for some of the retrofit components, primarily the steel studs.

The large storage capacity of the masonry protects the wall from too many freeze thaw cycles (by storing the amount of rain it sees without becoming saturated) but increases the corrosion risk (by maintaining the RH at rather high levels while the materials dry).

No mould index numbers are presented since this wall system has essentially no materials that can support significant mould growth (i.e., act as a food source). Dust, dirt and construction debris may act as a food source capable of supporting a small infestation of mould but this would only occur in limited areas.

Original	**Sandstone Brick**	**As-Built Condition**				
		Halifax	**Ottawa**	**Toronto**	**Winnipeg**	**Vancouver**
CI	Stone-Brick Interface	213	227	236	211	260
	Brick-Tile Interface	245	252	259	232	279
FT	Outside of Stone	1	0	1	0	0
	Inside of Stone	0	0	0	0	0
	Outside of Brick	0	0	0	0	0
Retrofit A	**Interior Insulation**	**Interior Rigid Foam Insulation**				
		Halifax	Ottawa	Toronto	Winnipeg	Vancouver
CI	Stone-Brick Interface	201	220	228	207	246
	Brick-Tile Interface	217	229	244	210	261
FT	Outside of Stone	1	0	1	0	0
	Inside of Stone	0	0	0	0	0
	Outside of Brick	0	0	0	0	0
Retrofit B	**Interior Studwall**	**Interior steel stud frame with fiberglass**				
		Halifax	Ottawa	Toronto	Winnipeg	Vancouver
CI	Stone-Brick Interface	200	220	228	207	245
	Brick-Tile Interface	213	225	239	207	258
	Outside of Stl Stud	157	179	189	164	185
	Inside of Stl Stud	50	105	120	104	50
FT	Outside of Stone	1	0	1	0	0
	Inside of Stone	0	0	0	0	0
	Outside of Brick	2	0	0	0	0

Table 2: Summary Damage Indices for Base Wall and Retrofits

Limitations

As described earlier, this analysis does not account for air leakage condensation, under the assumption that significant efforts will be undertaken to airtighten the retrofit. Given the relatively high thermal resistance (and massive safe moisture storage capacity) of the existing wall, the addition of interior insulation will not significantly increase the possibility or quantity of exfiltration condensation. Maintaining the RH of the interior air below 30 to 40% (depending on the exterior temperatures (during cold weather) can greatly reduce the potential for air leakage condensation.

One-dimensional analyses ignore details of penetrations through the enclosure wall. In older buildings, floor joists (often wood) and floor slabs (often wood or concrete) are often embedded in the wall. The temperature and moisture conditions at these locations may need to be analyzed using

2-D methods, although if the results of the clear wall are dry enough, or the embedment depth small enough, no further analysis may be required. Windows and exterior architectural details can be critical locations since these can act to concentrate rainwater. It almost all cases these details should be restored or modified in such a manner as to shed and drip water clear of the building façade rather than concentrating water.

The analysis presented is quite generic. It should be conducted for each specific case given the appropriate material properties (as even approximate measured properties greatly increased reliability) the specific site exposure, and the interior conditions.

Conclusions

This paper has investigated the process by which one chooses the inputs for using hygrothermal modeling to assess the durability implications of energy efficient interior retrofits and methods for interpreting the results. Simple damage models have been developed to aid in the interpretation of the data. One example of a hygrothermal computerized analysis of solid masonry wall, and two types of common retrofit, was presented to demonstrate the process.

The retrofits (Retrofit A and B) do not result in significant changes to the damage indices. As supported by experience, cold and wet climates (Halifax, Toronto, and Ottawa) have higher damage indices both before and after the retrofits than the cold and dry (Winnipeg) climate and the wet and warm (Vancouver) climate.

The freeze thaw index indicates the upgrade of these particular walls does not greatly increase the likelihood of freeze-thaw damage. The corrosion analysis showed is that the corrosion potential of the existing wall was reduced slightly by the retrofits, not increased, and so this damage mechanism is not a concern for either retrofit.

Damage models such as those discussed need to be developed further and correlated to real world results. However, future developments must maintain the simplicity of the damage models to allow for their practical application to the large number of cases that can benefit from hygrothermal analysis in retrofit design.

It must be emphasized that the conclusions generated by the example case are general, and relate to the major areas of a building's enclosure wall. Surface details that concentrate rainwater and enclosure details that allow rain penetration or exfiltration condensation are usually found to be the source of failure in practice and will require detailed inspection on a case-by-case basis. Thermal bridging and interfaces between building enclosure components and systems are also a problem in practice and should be considered individually.

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