eSim 2018
«BUILDING SIMULATION TO SUPPORT BUILDING SUSTAINABILITY»
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Integrated Energy and Hygrothermal Analyses of Heritage Masonry Structures in Cold Climates

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Abstract: *The East Block building in Ottawa was built in 1859-1967 and has been suffering from chronic moisture-related deterioration for much of that time. With a major rehabilitation of the building being scheduled, it is an opportune time to assess the hygrothermal characteristics of the building in its current state. The Southwest Tower was fitted with thermocouples, heat flux sensors and RH sensors to collect real-time conditions over the fall/winter. Using this measured data, EnergyPlus and 2D hygrothermal software, an optimization process was used to calibrate important modelling parameters such as thermal conductivity, air infiltration, sorption and permeability. Designers can then extrapolate this knowledge to plausible future retrofit scenarios to be done which address sustainability or durability goals. Simulations can allow designers of the rehabilitation to better evaluate and understand the risk of further deterioration from moisture and increased freeze/thaw cycles; versus the reward of decreased energy consumption.*

Keywords: *Energy Modelling, Freeze-thaw, Heritage Buildings, Hygrothermal Modelling, Masonry, Monitoring, Rehabilitation, Retrofit, Sensitivity Analysis*

INTRODUCTION

The Parliamentary Buildings of Canada are historically significant for their role they have played in Canadian democracy; and as a unique and beautiful piece of Gothic Revival architecture. They have suffered the effects of time for 150 years and with neglected maintenance have begun to need urgent and major repair. Major rehabilitation projects have begun or are being planned for each of the three buildings; starting with current West Block Rehabilitation Project, Centre Block Rehabilitation Project (scheduled to begin 2018) and East Block Rehabilitation Project (Tentatively scheduled to begin in 2025).

Considering the Canadian Federal Government's Long Term Vision Plan (LTVP) (Public Serviced and Procurement Canada, 2016) for the Parliamentary Precinct and Greening Government Strategy ("Greening Government Strategy," 2018) policies to reduce greenhouse gas emissions and improve sustainability; there is a pressure to address the energy performance of the East Block building during its upcoming rehabilitation.

Thermal retrofits of heritage buildings; particularly interior insulation of masonry is a thorny issue. In select sensitive cases, interior insulation has been attributed to a decrease in a wall's durability through freeze-thaw action and an inability to dry. It is imperative to understand both the thermal conditions inside the building and the hygrothermal properties of the envelope before proceeding with a retrofit of these buildings to avoid the risk of compromising the wall's durability.

This paper presents the first stage in a procedure to model both the thermal characteristics and hygrothermal performance of the Southwest Tower of the East Block in its current state. This stage looks at the development of a calibrated EnergyPlus model of the Tower using measured data. Subsequent stages will assess the hygrothermal performance via calibration to measured data, and how plausible retrofit scenarios will positively or negatively impact energy and durability of the Tower.

Southwest Tower

The Southwest Tower rises approximately 47m tall and is the architectural focus of the building. The tower consists of mass masonry walls consisting of inner and outer stone wythes (~225 mm) sandwiching a grouted rubble core. The thickness of the walls varies - tapering from 2100mm at the plinth to 860mm toward the top. The load-bearing walls have been known to experience chronic moisture-related

Figure 1: Example of some damaged mortar joints cause by high water exposure.

ISBN 978-2-921145-88-6

decay for many years. This resulted in problems such as surface staining, displacement, erosion of stones and mortar, and deconsolidation of mortar within the masonry core. The decay mechanisms at play are numerous including uncontrolled water exposure, freeze-thaw and incompatible selection of repair mortars with the stone.

The two-storey lobby of the Tower serves as the ground floor of the Tower and is capped by a groin vault ceiling. An intricate stained-glass window provides light to the space. The fourth level (immediately above the lobby) serves as the base of the upper part of the Tower. The Tower zones are characterized by large floor-to-ceiling heights (~12.0m, 7.9m and 7.9m for the lobby, fifth and sixth floor respectively).

The lobby is served by an air handling unit running from the basement below. The upper parts of the Tower do not have a dedicated HVAC system. The fourth level used to house electrical/electronic equipment which generated significant amount of heat. This equipment has recently been removed. The fifth, sixth and seventh floor have no HVAC equipment. Because of the semi-conditioned nature of the upper stories of the tower the interior conditions fluctuate greatly over the seasons and can not be accurately represented in hygrothermal simulations by fixed values or sine curves over the course of the year. To improve the accuracy of the hygrothermal simulations we must integrate building energy modelling.

METHODOLOGY

This project has four main stages:

1. Sensor Installation and Data Collection
2. Calibrated Energy Modelling
3. Calibrated Hygrothermal Modelling (In progress)
4. Future Retrofit Scenarios (In progress)

SENSOR INSTALLATION

A network of sensors was placed installed in strategic locations in the tower to monitor the changes in conditions over time; and to use for model calibration. Thermocouples were placed to measure zone air temperatures and interior surface temperatures. Heat flux sensors were positioned on the interior surface. 19 mm holes were drilled deep through mortar joints and relative humidity sensors and embedded moisture content sensors were inserted. The RH sensors can measure temperature as well. All sensors were connected to Campbell Scientific data loggers and set to record every 15 minutes. Time and practical restrictions precluded sensor installation on the exterior. Ambient conditions were measured by the data logger's internal sensors.

The sensors were grouped at three separate stations in the tower each with a unique set of conditions or construction. Each station received one of each type of sensor. The locations of the sensors are as follows:

- South facade fourth floor – Sloped weathering course of the masonry with high exposure to rainwater and freeze-thaw cycling, thicker wall section, conditioned space.

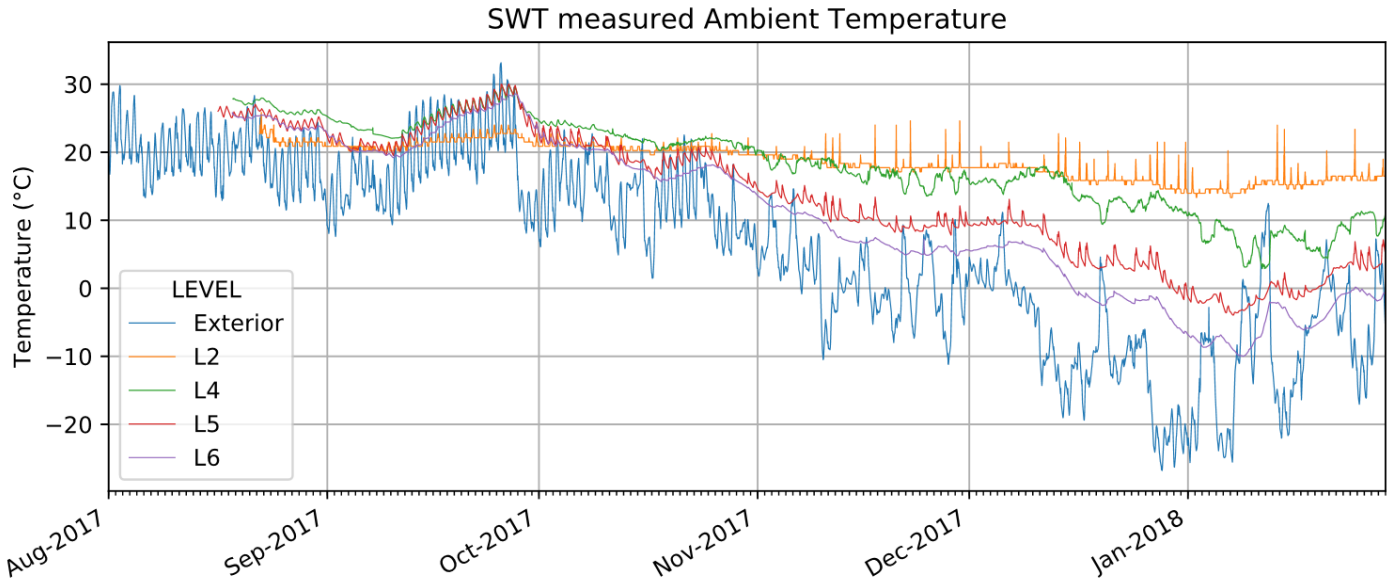

Figure 2: Measured and ambient temperatures for the Southwest Tower.

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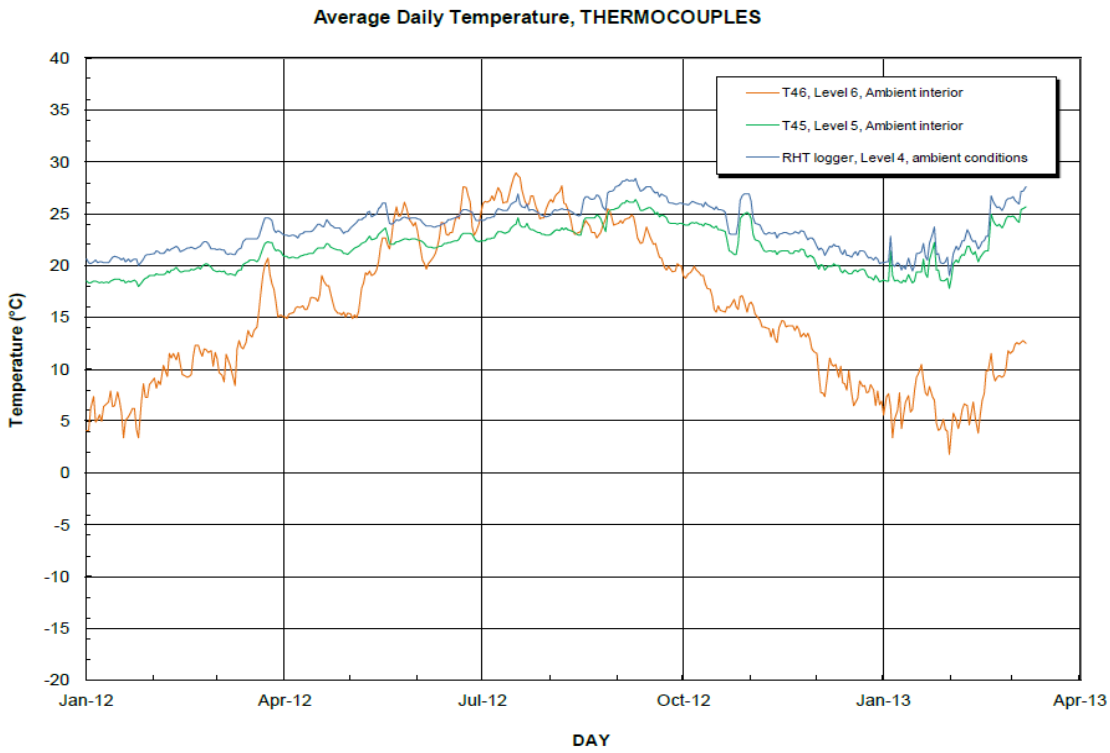

Figure 3:Measured and ambient temperatures for the Southwest Tower from 2012-2013

- East facade fifth floor – A portion of this wall has been recently reconstructed with a Portland based mortar. An RH and MC sensors were each inserted in a repaired patch and section of original mortar. This space is semi-conditioned receiving exhausted air from the fourth floor.
- South facade sixth floor – As close to a clear field assembly as can be found on the tower. Exposure to freeze-thaw cycling. Heat is received from buoyant effects from the fifth floor.
- Ground floor – A stand alone temperature sensor was placed to monitor temperatures

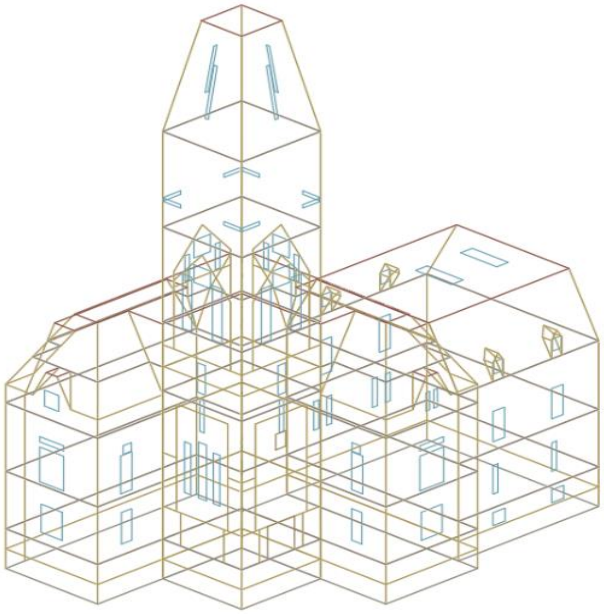

Figure 4:Wireframe of the EnergyPlus model including adjacent pavilions.

Measured Data

Figure 2 shows the measured and ambient temperatures from the period of August 2017 to February 2018. It is seen that as we go higher elevations within the tower, that the ambient temperatures begin to approach the outdoor temperatures. The temperatures on the fifth and sixth levels dip below freezing in December. Compare the 2017/18 data to the temperature data measured from 2012-13 in Figure 3 when the heat generating electronic equipment in Zone-4 was still active (Glazer, 2013). Never was there an average daily temperature below freezing, and the temperatures in Zone-4 and Zone-5 were within a reasonably comfortable range throughout the year. Obviously, the removal of the electronic equipment from the tower has had a significant negative influence on the

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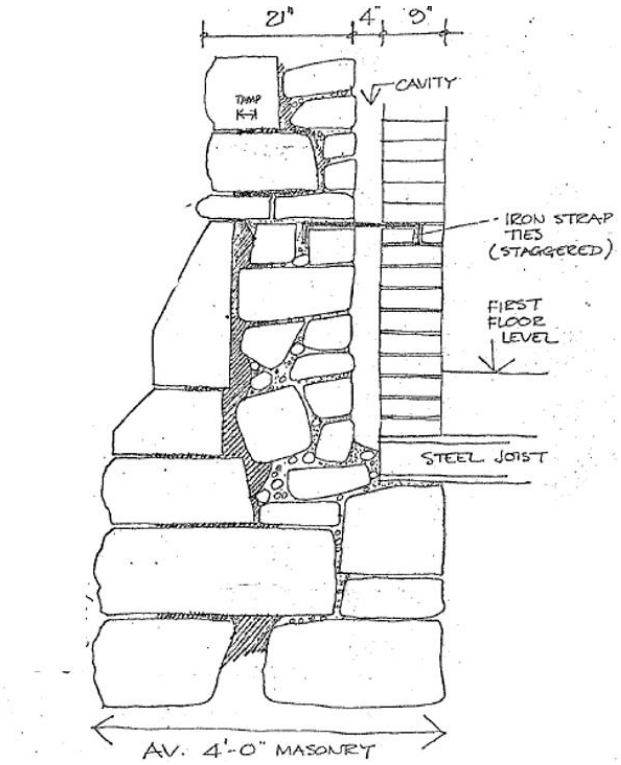

Figure 5: Typical cross-section of the East Block walls. Note that the Tower does not have a cavity and brick inner wythe.

conditions within the Tower. The effect this will have on durability will be explored in later stages of this project.

SIMULATION PROCEDURE

EnergyPlus Model

An EnergyPlus model of the Southwest Tower and adjacent pavilions was created based on drawings and point clouds provided by Public Works - Heritage Conservation Services. An EnergyPlus wireframe of the building is shown in Figure 3.

Thermal zoning in the tower was done on a per floor basis resulting in six thermal zones (B, 1, 4 ,5 ,6 ,7).

Because of the changes in thickness and decorative carved elements it is difficult to define a clear-field assembly. The exterior walls were sub-divided into sections to represent this as best as possible, with an eye towards model simplicity and future hygrothermal analysis. All masonry walls were divided into an outer wythe (225 mm), rubble core (variable thickness) and inner wythe layers (225 mm). The thermal properties of the core were assumed to be the same throughout the building, ignoring the effects of voids and the inconsistent nature of its construction, from one wall to the next. The Conduction Finite Difference algorithm was chosen for all exterior surfaces. A cross-section of a typical wall section is shown in Figure 5 (Ashurst, 1977).

The Southwest Tower's windows are all single pane, stained glass, leaded glass or plexiglass and held in place by stone on the exterior and iron stops on the interior and modelled as such.

For model simplicity, an ideal loads system was entered instead of explicitly modelling an HVAC system. Tower Zone-1 receives ventilation air from an air handling unit running from the basement. There is also air circulation from large open corridor doors on the adjacent wings of the building. Airflow between the corridors and the tower was modelled as a flow rate at room temperature.

Tower Zone-4 and up has no dedicated HVAC system. A constant volume fan exhausts air to Tower Zone-5 and is always operating. The volumetric flow rate expelled by the fan was modelled as a constant Zone Mixing object in EnergyPlus. Replacement air for the fourth level comes from infiltration from the neighbouring conditioned zones of the South and West Pavilions, as well as re-circulation downward from Tower Zone-5 via a large opening in the floor. This replacement air was assumed to be at near room temperature and modelled using a maximum flow rate in the Zone Ideal Loads object.

An airflow network would have been a better method for describing the airflow and buoyant effects happening in the tower. The airflow network would have been able to calculate air flow patterns in Tower Zone-4 and above caused by the exhaust fan and stack effect. However, we ran into a series of severe errors when trying to incorporate a fan without an HVAC system into the network. This combined with the Airflow Network model's incompatibility the Zone Mixing objects led to abandoning this method for the time being.

Tower Zone-1 (a two-storey circulation lobby), Zone-5 and Zone-6 have especially tall floor-to ceiling heights (~12.0m, 7.9m and 7.9m respectively) where temperature stratification means the assumption of well-mixed air is likely invalid, especially during winter. The effects of stratification and stack were modelled via Zone Mixing objects from one level to the level above.

Lighting and occupancy related loads are minimal. The building is sparsely occupied compared to a typical office building. The upper stories of the Tower are only occupied for rare maintenance and downloading data.

Parliament Hill does not have its own weather station at the present moment. Weather data was obtained from the Urbandale Centre for Home Energy Research ("Urbandale Centre for Home Energy Research," 2017) project on the Carleton University Campus and supplemented with data from Environment and Climate Change Canada ("Historical Data," 2017). The Urbandale Centre has

ISBN 978-2-921145-88-6

Table 1: Parameter ranges for Sensitivity Analysis.

Run	Parameter	Min Range	Max Range	Initial	Run	Parameter	Min Range	Max Range	Initial
1	Tower1SupplyTemperature (°C)	18	24	21	15	DesignFlowRateTemperatureCoefficient(--)	0	0.075	0.036596
2	Tower4SupplyTemperature (°C)	18	24	21	16	DesignFlowRateVelocityCoefficient (--)	0	0.25	0.1177
3	Tower1SupplyFlowRate (m^3/s)	0	1.5	0.75	17	ConductivityLimestone (W/m-K)	1	4	2.5
4	Tower4SupplyFlowRate (m^3/s)	0	1.5	0.75	18	HeatCapacityLimestone (J/kg-K)	640	1040	840
5	Tower4to5Mixing (m^3/s)	0	5	2.5	19	ConductivitySandstone (W/m-K)	1	4	2.5
6	Tower5to6Mixing (m^3/s)	0	5	2.5	20	HeatCapacitySandstone (J/kg-K)	640	1040	840
7	Tower6to7Mixing (m^3/s)	0	5	2.5	21	ConductivityLimeConcrete (W/m-K)	0.5	1.5	1
8	TowerBACH (ACH)	0.1	0.9	0.5	22	HeatCapacityLimeConcrete (J/kg-K)	640	1040	840
9	Tower1Infiltration (ACH)	0.1	0.9	0.5	23	ConductivityCore (W/m-K)	1	4	2.5
10	Tower4Infiltration (ACH)	0.1	0.9	0.5	24	HeatCapacityCore (J/kg-K)	640	1040	840
11	Tower5Infiltration (ACH)	0.1	0.9	0.5	25	SandstoneSolarAbsorptance (--)	0.5	0.9	0.7
12	Tower6Infiltration (ACH)	0.1	0.9	0.5	26	GlassConductivity (W/m-K)	0.5	1.5	1
13	Tower7 Infiltration (ACH)	0.1	0.9	0.5	27	GlassSolarTransmittance (--)	0.6	0.8	0.716
14	DesignFlowRateConstantCoefficient(--)	0.4	0.8	0.606	28	Tower1People (number of occupants)	0	1	0.5

recorded Global Horizontal and Diffuse Horizontal solar data as well as ambient temperature and relative humidity. Precipitation data was obtained from the Central Experimental Farm weather station. The weather stations are approximately 4 and 5 km from the site respectively.

Sensitivity Analysis and Calibration

The calibration process was based on a procedure developed by Roberti et al (Roberti, Oberegger, & Gasparella, 2015) adapted for use in this project. The first step (1) was to develop a baseline model with assumed material properties and modelling parameters retrieved from ASHRAE, WUFI etc. or professional judgment; (2) perform a sensitivity analysis to determine which parameters had the greatest influence on results; (3) calibration of the model against measured zone air temperatures over the specified time range by adjusting values for key parameters identified in the previous step.

The GenOpt optimization software will be used to calibrate the EnergyPlus model against measured interior ambient temperatures (Lawrence Berkeley National Laboratory, 2016). The Particle Swarm Algorithm in GenOpt is used to minimize the Root Mean Square Error (RMSE) of the model's results compared to measured data. The cost function in GenOpt will be the RMSE for all 4 zones with measured temperatures. The RMSE will also be reported for each level so it can be seen if specific zones are better calibrated. In addition to that, the RMSE will be monitored over the course of a hot week, cold week and a week with average temperatures. The theory is that different parameter values will predict what is happening in the tower better in summer than in winter, specifically parameters relating to infiltration, stack and air movement within the Tower. If true, this could be a chance to further fine-tune the model after calibration.

Before calibrating the model, a sensitivity analysis was performed to determine which EnergyPlus parameters have the most influence on results. The sensitivity analysis was done by changing only one variable at a time over a predetermined range. Parameters which do not significantly affect the results will not be included in the final calibration model.

Parameters which were analysed include EnergyPlus objects related to HVAC, zone mixing, infiltration, conductivity, heat capacity and optical properties. Table 1 shows the parameters which were analyzed. Minimum and maximum values were judged from plausible values in documentation and from pre-calibration trials.

Zone infiltration was modelled using a constant ACH with temperature and velocity coefficients based off the BLAST default model ("EnergyPlus Version 8-8-0 Documentation - Engineering Reference," 2017). Pre-calibration trials showed that zone mixing had a significant on the accuracy of the model's zone air temperatures when compared to the measured temperatures. The pre-calibration trials also showed that very high flow rates up to 5 m^3/s were plausible solutions to the optimization solution, so were included in the sensitivity analysis.

A wide range was given for the conductivity of masonry materials was inserted into the sensitivity analysis. This

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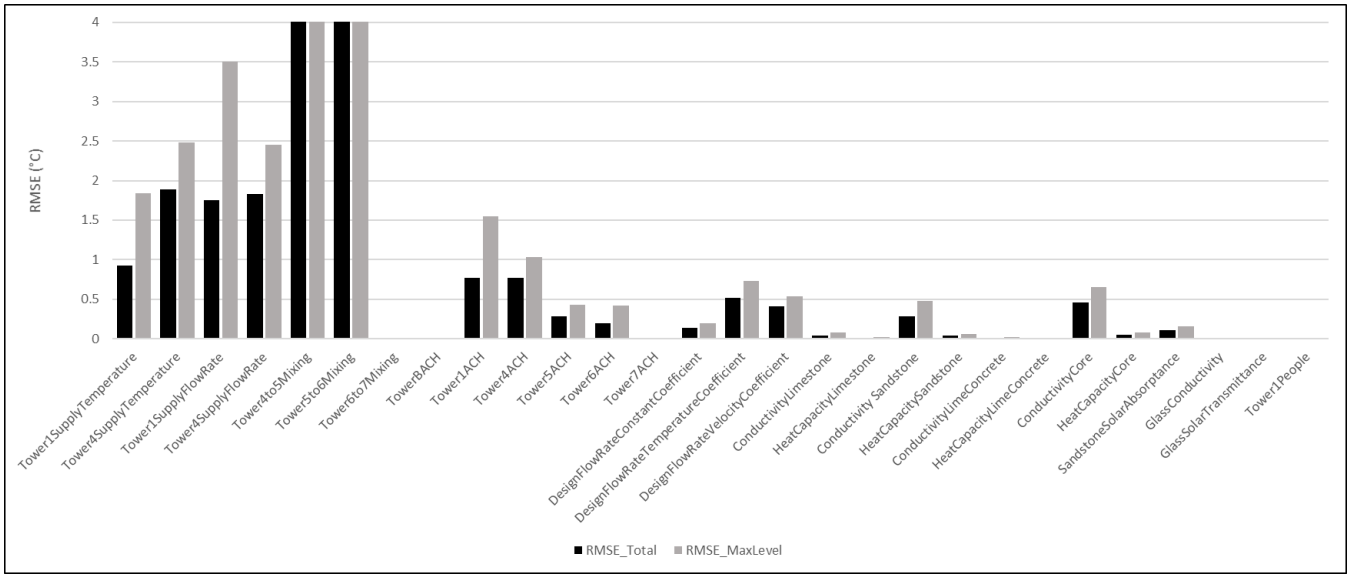

Figure 6: Sensitivity Analysis results.

reflects the typical uncertainty involved with the hygrothermal properties of masonry materials. As an example, the ASHRAE Handbook gives the thermal conductivity of sandstone from 1.88 to 6.2 W/m-K (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2013), while a study by Pechnig et al gives values ranging from 1.5 to 4.0 W/m-K (Pechnig, Mottaghy, Koch, Jorand, & Clauser, 2007). The Nepean sandstone used in the majority of the exterior walls is a dense, high quartz stone, which would tend to indicate a higher conductivity. Likewise, the thermal conductivity of the core was cast with a wide range. The 1861 specs of the East Block describe the composition of the core as *"The interstices of the stonework to be filled with stone chips or spalls, and grouted with lime and sand in a liquid state every foot"* (*Contract, Specifications and Schedule of Prices of Departmental Buildings, Ottawa City, C. W.*, 1861). Considering that the core is a higher percentage of mortar with known voids. It is likely that the core has a conductivity at the lower end of this range.

Lime Concrete refers to the Fox and Barrett flooring system of the building. Essentially a concrete slab poured on top of an iron joist system. This was included in the sensitivity analysis to see if thermal mass storage was significant or not. The ranges for optical properties were estimated from WINDOW assuming a 3 mm single-pane clear glass.

The sensitivity analysis was performed over time range of 1 September 2017 to 17 December 2017, encompassing a wide swathe of weather conditions in Ottawa.

Sensitivity Analysis Results

The sensitivity analysis results can be seen in Figure 6. Black bars indicate the RMSE for all four measured zone temperatures and grey bars represent the maximum RMSE for a zone. The largest RMSE's were for parameters related to air transfer into a zone and zone mixing. Of note, the RMSE's for Zone Mixing are exaggerated. Interzone mixing at very low rates produced very high RMSE's over 9 for "Tower 4 to 5 Mixing" and "Tower 5 to 6" mixing; whereas, flow rates around 1 m^3/s returns an RMSE around 0.7. From this we can infer that stack and vertical transfer plays a significant role and that an assumption of zero vertical mixing is incorrect.

Infiltration rate, and the coefficients used to predict it have a moderate effect on results and will be included in the final calibration.

Building envelope parameters had a surprisingly low influence on the temperatures of the building compared to other factors. The conductivity of sandstone and the core have a measurable influence on results and will be included in the final calibration model. Heat capacity had little effect on the model and will not be included in final calibration. The lime concrete of the floors had little influence and will not be included in the final calibration as well.

Optical properties did not have a significant impact on results. Other than on the fifth level, the window-to-wall ratio is quite low on the building (Max 0.12). The lack of impact was to be expected. Parameters relating to the Basement or the seventh storey have little effect, largely

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Table 2: Final Calibration Model Values

Run	Parameter	Min Range	Max Range	Initial	Interval	Calibration Results
1	Tower1InflowAirTemperature	18	24	21	0.25	20.75
2	Tower4HotInflowAirTemperature	24	29	26	1.0	28.0
--	Tower4WarmInflowAirTemperature	20	25	22	1.0	25.0
--	Tower4MediumInflowAirTemperature	18	24	20	1.0	24.0
--	Tower4ColdInflowAirTemperature	15	20	17	1.0	20.0
3	Tower1InflowAirFlowRate	0	1.5	0.75	0.125	0.5
4	Tower4InflowAirFlowRate	0	1.5	0.75	0.125	0.1
5	Tower4to5Mixing	0	5	2.5	0.25	0.25
6	Tower5to6Mixing	0	5	2.5	0.25	0.25
9	Tower1ACH	0.1	0.9	0.5	0.1	0.4
10	Tower4ACH	0.1	0.9	0.5	0.1	0.1
11	Tower5ACH	0.1	0.9	0.5	0.1	0.15
12	Tower6ACH	0.1	0.9	0.5	0.1	0.15
15	DesignFlowRateTemperatureCoefficient	0	0.075	0.036596	0.01875	0
16	DesignFlowRateVelocityCoefficient	0	0.25	0.1177	0.0625	0
19	Conductivity Sandstone	1	4	2.5	0.25	1.5
23	ConductivityCore	1	4	2.5	0.25	2.75

because there are no measured data in those zones to compare to.

Final Calibration Results

The 14 most significant parameters found in the sensitivity analysis were included in the final calibration model. The decision on the threshold for how many parameters is up to the modeller's judgement. Including more parameters in the calibration increases computational time at the cost of diminishing returns in terms of solution accuracy. Parameters which were not included typically had an RMSE less than 0.2°C.

Discrete values were used in GenOpt's Particle Swarm algorithm. The most sensitive parameters were defined with finer intervals between consecutive values while the least sensitive were defined with coarser intervals. A summary of the parameters is shown in Table 2. The timeframe of the final calibration model will be from 1 September to 30 January. The extended timeframe compared to the sensitivity analysis gives greater weight to winter conditions where conditions are more critical. An improvement over the sensitivity model was to have the inflowing replacement air temperature to Tower-4 fluctuate over the course of the year, assuming it enters at varying temperatures whether it's the middle of summer, autumn or winter.

DISCUSSION

Final values from the calibration are summarized in Table 2. Figure 7 shows the measured v. calibrated curves for each of the four storeys. Tower-4 has the weakest correlation (RMSE=1.753) between measured and modelled data, particularly in the cold winter months of December and January. The model also lacks the diurnal temperature fluctuations of the measured data. Possible reasons for this could be excessive thermal mass, underestimated air infiltration and the fact that inflowing air into Tower-4 fluctuates diurnally, whereas the model is at a fixed temperature. Tower-5 (RMSE=1.078) has and Tower-6 (RMSE=0.957) has a much stronger correlation than Tower-4. The Tower-6 calibrated model shows noticeable diurnal fluctuations whereas the measured data does not. Further dissecting, the calibration results, the RMSE during a cold week was much higher than the rest of the calibration period. The parameter which seems to improve the RMSE during cold periods the most is the volume of inflowing air into Tower-4.

Further refinements can still be made to improve the fit of calibrated model compared to the measured data. Airflow and infiltration patterns may be different in the tower during warm days than on cold days. Changing certain parameters related to airflow on a schedule dependant on the time of the year may further improve the model.

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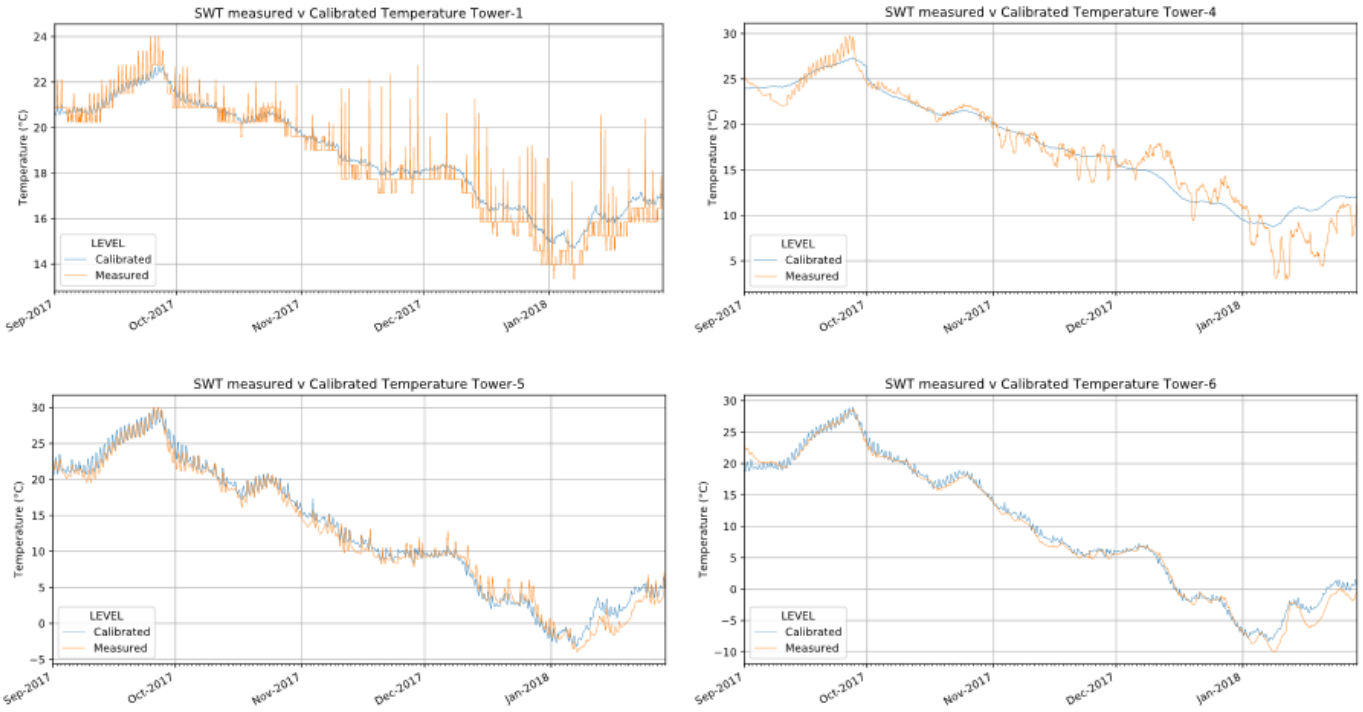

Figure 7 Measured v. calibrated model temperatures for Levels 1, 4, 5 and 6

Beginning in January, thermocouples have been placed at quarter-height, mid-height and three-quarter height of the fifth and sixth storeys. The vertical temperature profiles have been found to not be linear with temperatures at mid-storey height consistently warmer than floor or ceiling level. There are some convection currents at play which are caused in part by the way the warm exhaust air from the fan diffuses into the room. This effect could be better understood and applied to an EnergyPlus model which better handles the inherent stratification, such as the subdividing the zones vertically or room air models.

FUTURE STAGES

WUFI 2D Modelling

The end goal of the project is to analyze the hygrothermal performance and durability of the walls using WUFI 2D. Information gathered from the EnergyPlus calibrated model to be used in the hygrothermal modelling stage includes the thermal conductivities of the stone and core, as well as the interior environmental conditions. Using a similar calibration process to what was done with the EnergyPlus model, the measured RH and %MC data will be used to calibrate important and uncertain hygrothermal parameters such as sorption, capillarity and vapour permeability will be calibrated using WUFI 2D and an optimization program.

The goal of this process is to both characterize the building's performance in its current state and to help define hygrothermal properties of the mass masonry walls in-situ. The rubble core of the masonry is a notable area of hygrothermal uncertainty. When drilling through from the interior to insert sensors, it was found that there were large voids hidden behind and the mortar had a soft, damp and sandy consistency. The presence of air pockets and the disaggregated mortar will alter the hygrothermal performance compared to a sound and solid core. Because of the irregular and randomness of the core may behave like mortar, stone or sand hygrothermically. It may also exhibit some rainscreen like behaviour with the voids acted as a capillary break. Instead of explicitly simulating the complex 3D relationship of a "randomized" matrix of stone, mortar and voids to represent the core an idealized homogenous material needs to be assumed.

A few hygrothermal properties for the stone and mortars have been measured through the National Research Council and through lab testing with RDH Laboratories and were inserted into the model. Other material properties were estimated based off equivalent WUFI library materials.

Freeze-thaw resistance and freeze-thaw cycling is a big concern in the durability of this building. Mortars are of more concern than the stone. Using the finite grid of the hygrothermal model we can count the number of freeze-thaw cycles that would have occurred over the monitoring period at particular depths in the wall. The number of critical freeze-thaw cycles which where the moisture content exceeds the critical degree of saturation (S_{CRIT}) can

ISBN 978-2-921145-88-6

also be counted. Three different types of potential replacement mortars (NHL3.5, NHL5, and 1:2.5:8 mix) was tested for S_{CRIT} at RDH Laboratories in October. The S_{CRIT} value was found to be between 75-79% of saturation. As discussed in the next section on retrofit scenarios, we can monitor how the "freeze-thaw front" moves with in the wall has moved as an indicator of improved or compromised durability.

Retrofit Scenarios

As part of the planned rehabilitation, retrofits specific to the Southwest Tower and thermal retrofits for the whole building are likely to be considered. By applying changes to the calibrated energy and hygrothermal models, we can better judge the effects this will have to the performance of the walls. This will allow designers to make more informed decisions regarding the risk of increased deterioration of the walls versus the reward of decreased energy consumption and better thermal comfort.

Examples of plausible retrofits scenarios to be modelled include:

- **Reinstating heat generating electronic equipment in the fourth level.** As seen from the changes in temperatures from 2012 to 2013 to present (Figure 2 and Figure 3), this had a positive benefit to the interior conditions by reducing the risk of freeze-thaw deeper into the wall. Furthermore, this a dry source of heat and is a by-product of another system.
- **Converting the tower to a fully-conditioned space.** This was done in the Northwest Tower during its rehabilitation project in 2013. This would provide more ideal and consistent interior conditions but would have an energy consumption cost.
- **Interior insulation of the occupied spaces of the building.** This would improve the energy losses through the envelope but would be likely be coupled with a decrease in the durability of the building.
- **Selection of mortars**. Durability of the mortars is a constant discussion of stone conservators, who are looking for a balance between the "breathability" and flexibility of traditional lime mortars, against the strength and wear-resistance of Portland mortars. Hygrothermal simulations can examine the long-term moisture contents of different mortar types.
- **Controlling Exposure**. The Tower has poor water shedding characteristics, especially at plinth and weathering courses. Hygrothermal simulations can better demonstrate the effect that this has on susceptible areas (South Facade Fourth Floor)

CONCLUSION

The Southwest Tower of the East Block was fitted with sensors to measure interior temperatures, relative humidity and hygrothermal conditions in the stone masonry walls. This information was used to make calibrated energy and hygrothermal models of the Tower with the aid of GenOpt optimization software. This process allows to ascertain the values of certain key modelling parameters such as air infiltration, stack effect or material properties of the stone and grouted core of the wall.

A sensitivity analysis on the Southwest Tower EnergyPlus model showed that zone to zone mixing and stack effect have the greatest influence on the model. Parameters related to air infiltration and wall thermal conductivity had a moderate influence on the EnergyPlus model. Heat capacity and optical properties had little influence.

A calibration model using GenOpt optimization software was used to determine the unknown thermal properties and better understand the stack effect inside the Tower. Figure 7 shows the results of the calibrated model from 1 September to 30 January. An RMSE of 1.753, 1.078, and 0.957 were achieved for the levels Tower4, Tower-5 and Tower-6 respectively.

Similar to what was done for EnergyPlus, a calibrated hygrothermal model of the masonry walls will be done to better understand the uncertain hygrothermal properties of the masonry. This knowledge can then be applied to plausible retrofit scenarios. This will allow designers of the rehabilitation to better evaluate and understand the risk of further deterioration from moisture and increased freeze/thaw cycles; versus the reward of decreased energy consumption.

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