THE BEST MADE PLANS: THE CHALLENGES OF RETROFITTING A HISTORIC SINGLE FAMILY HOME USING A NESTED THERMAL ENVELOPE DESIGN

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ABSTRACT

Unless they have been thermally retrofitted, historic buildings are often expensive to heat and cool. Further, during the heating and cooling months, they are often uncomfortable. This paper describes how an historic single-family masonry home in Toronto Ontario was transformed into a comfortable, very low-energy building using a Nested Thermal Envelope Design. The design and construction of a number of innovative envelope and mechanical retrofits are presented.

Following construction, detailed energy monitoring revealed that that the heating energy consumption was 34 ekWh/m^2. This compares to the original building which would have had a heating energy consumption of 532 ekWh/m^2. Yet, the energy performance fell short of expectations. This paper explores some of the reasons why the heating energy consumption was actually higher than expected. Beginning with an examination of the construction process and construction methods employed, areas where improvements could have been made are identified. Further, three fan depressurization tests were carried out: two during construction and one upon completion. The completed building experienced an air change rate of approximately 3.2 ACH_{50}. Thus, the larger air change rate than expected was likely the major contributing factor to higher than expected energy consumption. To identify where the air leakage was occurring, further tests were carried out. Pressure testing of the fresh air duct systems and smoke testing of the whole building were conducted. After examining these and other test results, it is clear that critical air tightness measures fell short. Construction sequencing that led to design challenges likely contributed to the lack of air tightness. Based on the testing and monitoring results, this paper identifies a few of the best practice design and construction means that could have led to even better energy performance. The lessons learned from this demonstration project are presented so that others may be able to build even better.

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INTRODUCTION

This project, which became known as the Gemini House, was driven by the need to improve the thermal performance of an historic solid masonry home that was built in 1879. The "owner" of the second empire home was the University of Toronto, in Toronto, ON. Prior to retrofit, the home was largely in its original, uninsulated state. The two-storey detached house had a floor area of approximately 113m^2 excluding the basement. The original walls were constructed using double-wythe clay brick and finished with lath and plaster on the interior. The original windows were single-glazed units and some had been modified with storm windows. A pre-retrofit building condition assessment was carried out prior to retrofit (Caesar, 2010). A fan depressurization test was carried out on the original building and an air leakage rate of 16.4 air changes per hour at 50 Pascals (ACH_{50}) was observed. The building was not only "leaky," but it lacked thermal insulation. The home was uncomfortably cool in the winter and not surprisingly, rather drafty. The lath and plaster was crumbling in many areas and the home was damp. In short, it was in need of major repairs so that it could be leased to visiting scholars. Therefore a major retrofit was warranted. However, since the house was a "Listed Historic Property" under the By-Laws of the City of Toronto, the north-facing front façade could not be changed. Innovative ways of improving the energy performance had to be found without compromising the historical elements.

An innovative method of reducing the energy demand of the home, known as the Nested Thermal Envelope Design™ (Pressnail et al. 2009) was chosen. This method, which has been more fully reported by Tzekova et al., consists of constructing a thermally controlled Core zone that is enclosed within a second thermally controlled Perimeter zone. This means that two envelopes were constructed, one within the other. Each envelope was designed to control heat, moisture, and air movement. This method was chosen because the thickness of thermal insulation required for the exterior walls was reduced – a benefit in an historic home that can only be internally insulated. Rooms that would be occupied and conditioned year-round became a part of the Core zone (68.7 m^2). These rooms included the kitchen, the bathrooms, the master bedroom and the foyer/stairway. The Perimeter zone (44.6 m^2) included spare bedrooms, the tower/vestibule, and the ballroom. The Perimeter zone also included the basement which became a crawl-space and was only used to house mechanical equipment. These Perimeter areas would only be conditioned as needed.

A sectional view showing how the two-storey home was zoned is shown in Figure 1. This figure also shows how solar heated air on the south side was free to move to the north side Perimeter areas. The Core areas were placed on the south side of the building to take advantage of any passive solar gains during the heating season. Fresh air was supplied to the house using two energy recovery ventilators (ERVs): one ERV services the Core zone and one services the Perimeter zone. Space heating was provided by a radiant flooring system with separate loops servicing the Core and Perimeter rooms. When the Perimeter rooms are unoccupied and when there is excess solar heat in the perimeter, an air-source heat pump was used to deliver this excess heat to the Core zone. Although an inter-zonal heat pump seems a little odd, in fact, by operating the heat pump when a smaller temperature difference exists can lead to improved efficiencies. (Touchie and Pressnail, 2014).

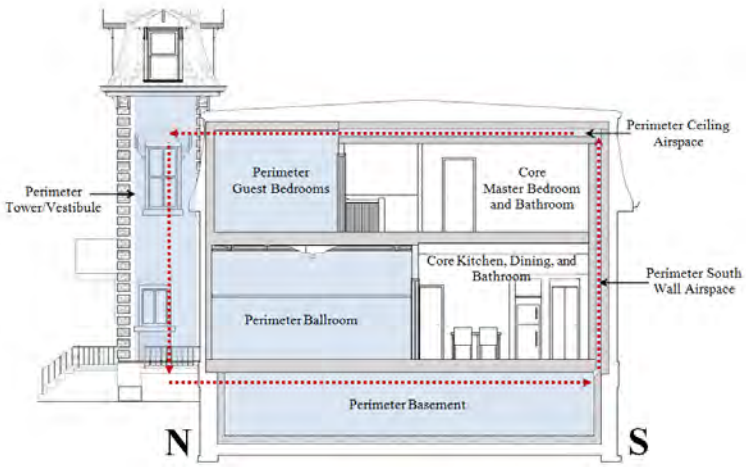

Figure 1: Gemini House Section View Showing Core and Perimeter Areas

CONSTRUCTION CHALLENGES

Following a protracted design process involving restoration design architects, mechanical and building science engineers, a call for tenders was made. While several qualified bids were received, the lowest tender exceeded the budget allowance so a new approach was taken. A construction manager was hired on a 'Cost-Plus' basis to tender a series of work packages. Effectively, the construction manager acted concurrently as a general contractor. As construction proceeded, inevitable changes had to be made to accommodate previously hidden or unidentified challenges. For example, for structural reasons, first and second floor joists had to be doubled-up with new joists. This led to difficulties in subsequently air-sealing the fire-cut floor joists that were embedded in the four wythe foundation and the two wythe above-grade walls. When the first of three fan depressurization tests were carried out, air was found to be flowing through the wall and in between the doubled-up joists. Although two-pound polyurethane foam insulation had been used to provide a thermal, moisture and air control layer in the basement and above-grade walls, air still leaked between the joists. This problem was further aggravated by the existence of a protected air space that was created using a polymer mesh as shown in Figure 2. The mesh was placed between the spray foam and the masonry wall. The air space served as a vented air space and a drainage layer, but it created a potential air leakage path.

One of the challenges faced during construction involved construction sequencing. Since the windows were delivered 8 weeks later than originally scheduled, the walls were foam insulated and the drywall was installed before the windows arrived. This made air sealing the interface between the frame and the window unit more difficult. Further, the original schedule of fan depressurization testing called for testing before the drywall was installed but after the walls were spray foamed and the windows installed. By air testing after the drywall had been installed meant that any deficiencies in the spray foam air barrier identified during testing could not be easily identified or corrected.

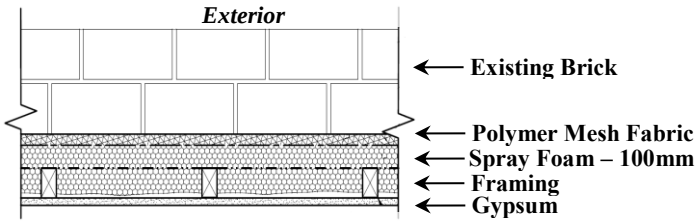

Figure 2: Plan View of the Retrofitted Above-Grade Perimeter Wall

Finally, one of the largest construction challenges involved the installation of the two ERVs and the associated duct work. Although attempts were made to seal the ducts with self-adhesive foil tape, subsequent testing revealed that the supply and return air ducts leaked air at rates that were above average for normal residential construction. Testing of the duct leakage rates occurred at the commissioning stage, but by then it was too late to easily repair any identified deficiencies. Further, when the ERV supply and exhaust ducts for the Perimeter and Core zones were installed, they were installed after the spray foam air barrier had been placed. Although attempts were made to air seal these penetrations, air sealing these penetrations was largely unsuccessful.

ENERGY PERFORMANCE

Figure 3 shows the results of the heating energy use during the monitoring period between December 1, 2013 and November 30, 2014. Depicted in this figure are several energy use intensities based on HOT2000 modelling using the actual weather file from the monitoring period. The pre-retrofit intensity of 532 ekW/m^2 shown here is based on modelling that incorporated the characteristics of the original home. The next home modelled was an Ontario Building Code home. The home was modelled as if it had been retrofitted to meet the requirements of Ontario Building Code 2012 for new construction. Modelling showed that the heating energy use intensity for this model home would have been 96 ekW/m^2. Next, the Gemini home was modelled as if both the Core and Perimeter zones were heated throughout the heating season to the same interior set point. Termed the 'Standard Mode of Operation,' modelling showed that 67 ekW/m^2 would have been used during the monitoring period. Next, the actual heating energy use intensity of 56 ekWh/m^2 is shown. This is the actual amount of heating energy used during the monitoring period. It should be noted that in the monitoring period, both the Core and Perimeter zones were heated to the same temperature in December 2013, January 2014 and during the first half of February 2014. Then the Perimeter zone temperature was gradually decreased. Finally, in Figure 3, a 'Lower-Energy Operation' intensity of 34 ekWh/m^2 is shown. This value depicts the amount of heating energy that would have been used in the monitoring period, if no system heat had been supplied to the Perimeter zone. Under such circumstances, only passive heat losses from the Core zone and solar gains would have warmed the Perimeter. This value was estimated using the actual energy use, and the temperature when the Perimeter was only passively heated. It was found that the Perimeter air temperature would have been approximately half way between the Core set point temperature and the outside air temperature. To reach this conclusion, extensive analysis of the monitored temperature data were carried out.

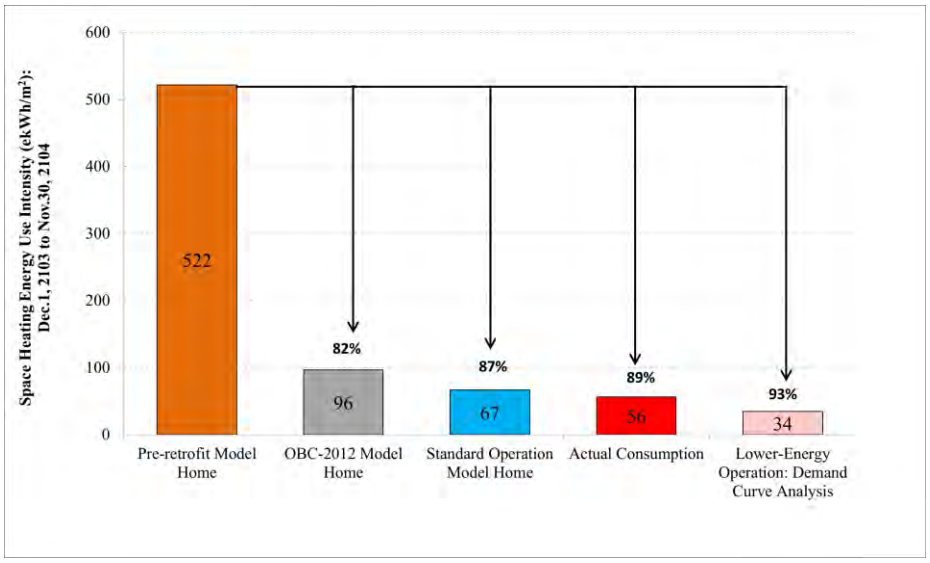

Figure 3: Space Heating Energy Use Intensity for Various Model Homes in the Period December1, 2103 to November 30, 2014

PERFORMANCE SHORTFALLS

The data presented in Figure 3 reveal that if the Perimeter zone had only been passively heated, 34 ekWh/m^2 would have been used. This number is higher than expected. The authors predicted a value closer to 25 ekWh/m^2. The largest contributing factor to higher than expected energy use was likely due to air tightness. The goal of 1.5 ACH_{50} for the Core and Perimeter zone envelopes was not achieved. Fan depressurization testing during commissioning revealed that the Core and Perimeter zones experienced 4.1 and 3.2 ACH_{50} respectively. A whole house smoke test under fan pressurization was conducted to visually identify the largest leakage openings. The penetrations where the supply and exhaust ERV ducts pass through the envelope were the single largest source of air leakage. While there was some air leakage between the sub-frame and the windows, generally the extra effort required for air tightness at the windows was effective. A few manufacturing defects were identified in two of the window cam latching mechanisms. Further testing was carried out following the whole house smoke test. The supply and exhaust ducts for both ERVs were tested using a calibrated fan. Testing revealed that these ducts were leakier than an average home. This likely contributed to the overall lack of air tightness of the building. Finally, the home was supplied with a new 200Amp electrical service panel before construction began. Unfortunately the service entrance was not properly sealed when the panel was installed. When the panel area was spray-foamed, the service entrance was essentially inaccessible and the panel box was less than air tight.

Although there were likely other contributing factors beyond the air leakage, the lack of air tightness was likely the single most significant factor affecting energy use. Other factors included the apparent lack of temperature control in the ballroom. Although the ballroom which was in the Perimeter zone was separately supplied by a hydronic loop, we were never able to completely turn the heat off. Thus, we were never able to just passively heat the ballroom. Finally, although an inter-zonal heat pump had been installed in order to remove excess solar heat from the Perimeter and to efficiently deliver it to the Core, the heat pump was never operated during the monitoring period.

LESSONS LEARNED

While there were many, many lessons learned, we will outline a few. First, the lack of air tightness was likely our largest failing. The leakage of the exhaust and supply ERV ducts could have been reduced if we had specified a butyl tape for joints from the onset. Further, post construction, once the problem was discovered, duct air leakage could have been reduced by using a sealing system that involves aerosol polymers that can be sprayed into the duct system.

The gross air leakage that occurred at the electrical and ERV envelope penetrations could have been addressed at the construction stage if greater care had been taken and if construction sequencing had been more favourable. Unfortunately, delays and cost over-runs led to interference and conflicts and once covered up, penetrations were difficult to air seal. Further, the existence of a polymer mesh which created a drying air space was great for improving brick durability, but any penetration from the inside of the building into this air space was a path for air leakage.

Retrofitting an older home so that it is more comfortable and energy efficient is challenging. Applying a Nested Thermal Envelope Design™ approach to a listed historic home is an even more challenging task. It would have been far easier to demonstrate the efficacy of this retrofit method had a new building been designed and built. It is not that it can't be done, it is just a lot more difficult to retrofit an historic building.

While some of the short-comings have been identified here, it should be recognized that overall many aspects of the project were a success. Energy use was greatly reduced. The occupants found that the home was exceptionally quiet and comfortable. A final measure of success? The Gemini House is a home that can be used to inspire future generations of engineers and architects who aspire to build homes that not only meet the needs of the people of today, but tomorrow too.

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