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Application of embedded moisture sensors for developing preservation strategies for stone masonry buildings

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The process of preserving heritage buildings is a delicate balance of art and science compounded with requirements to preserve the heritage value of the building and taking into account the harsh nature of the outside environment. Red River College's (RRC) Centre for Applied Research in Sustainable Infrastructure (CARSI) and Structure Monitor Technology Research Limited (SMT Research) worked together on developing a method of testing the moisture content within stone masonry structures to help in the preservation and restoration of a prominent heritage building in Ottawa, Ontario. The laboratory testing replicated three-years of environmental conditions on stone bricks with and without anchoring systems, both traditional steel and grout and glass fibre reinforced polymer and epoxy resins were used. The results showed that there was minimal impact on the moisture and temperature profiles in the bricks with and without the anchors.

The process of preserving heritage buildings is a delicate balance of art and science compounded by the requirements to maintain the heritage value, including the character-defining materials, forms, location, spatial configurations, uses and cultural associations or meanings (Parks Canada, 2003) with the harsh nature of the outside environment, which can be exaggerated in the Canadian climate. The extreme temperatures and high humidity, common to most of Canada, can pose a major threat to any heritage building.

Humidity and temperatures can potentially lead to damage from freeze-thaw, mould growth, and other types of stresses on stone masonry building and structures. Therefore, it is important to develop a restoration and preservation plan of action that helps to minimize or at least take into account the environmental strains on the structure itself. However, the humidity and temperatures of the external environment is only a portion of the issue. Many of the heritage stone masonry structures have little to no insulation, which makes the masonry cavities or other internal structures at risk of damage due to excess moisture. If these factors are taken under consideration, it will be possible to determine improved practices for conducting these types of restoration and preservation projects in the future.

Red River College's (RRC) Centre for Applied Research in Sustainable Infrastructure (CARSI) and Structure Monitor Technology Research Limited (SMT Research) worked together on developing a method of testing the moisture content within stone masonry structures to help in the preservation and restoration of a prominent heritage building in Ottawa, Ontario.

RRC's CARSI is Manitoba's first dedicated laboratory and research facility to study sustainable building methods. It was built in 2005 at RRC's Notre Campus to conduct research with asphalt concrete systems, advanced composite materials, large light-frame wood structures, and building envelope systems under controlled laboratory conditions including environment control chamber with the potential to test from -40º C and 40º C with the capability to control the humidity.

SMT Research designs software and electronics used to monitor various aspects of building health and integrity. These software and electronics can be used in a wide range of applications from the monitoring of residential to commercial to heritage buildings constructed from anything from wooden frame building to glass skyscrapers. The goal of their research is to find durable, efficient and environmental friendly methods to increase the stability and health of building structures.

To monitor the moisture content within stone masonry structures, embedded wooden sensors (also known as Duff's gauges) were assembled and calibrated before being placed inside limestone and sandstone bricks. These bricks were then exposed to both saturated and unsaturated freeze-thaw cycles in laboratory conditions to replicate years of freeze-thaw in the environment. The tests were conducted to determine the impact on the environment on the materials used to strengthen (or anchor) the structures to devise a restoration and preservation plan for a stone masonry heritage building in Ottawa, Ontario.

Literature review

Great effort and expense are put into the preservation of heritage buildings in Canada and around the world. It is done to protect and preserve the health and structure of the buildings so they can be enjoyed by present and future generations. While it is important to preserve the integrity of heritage buildings and ensure their uniqueness is preserved, it is a policy that all federal buildings "must be used and must remain operational" (National Capital Commission, 2011), meaning that heritage buildings should not remain untouched but be recognized for any existing heritage values (National Capital Commission, 2011).

The federal government owns the largest number of Canadian heritage properties. Recognizing the need and importance to preserve Canadian heritage buildings, Parks Canada and the National Capital Commission prepared a Memorandum in 1982 proposing protective measures for federal heritage buildings that was later approved. The Treasury Board Policy for Management of Real Property incorporated these requirements and in November 2006, the Federal Heritage Buildings Review Office (FHBRO) under the authority of Environment Canada became the administrators (National Capital Commission, 2011). Today, FHBRO has classified 14 building and recognized 54 others (National Capital Commission, 2011).

The standards and guidelines issued by Parks Canada (2003) provide the best practices for preserving the character-defining materials, forms, location, spatial configurations, uses and cultural associations or meanings of the building or structure that is in need of work. This means that great care must be taken to use the same materials that the building was made of to undertake any repairs to the structure while maintaining the work and craftsmanship of the surrounding materials. However, it is important to make sure that any conservation or preservation projects are done in a manner that maintains the health and longevity of the building.

In addition to preserving the culture values of buildings, it is important to find methods to reinforce and strengthen the structure (Parks Canada, 2003). The traditional methods involve anchoring the inner and out surface together or "stitching" which is effective for strengthening of these structures. However, the compatibility of the anchoring material to the surrounding must be examined to determine the overall health of the building so there is no further damage the structure or masonry (Uddin, Mufti, Polyzois, Shrive, Jaeger, Stephenson, Duchesne, & Paquette, 2009).

Before undertaking any conservation or preservation project, the standards and guidelines encourage research to be done on a heritage building to fully understand the nature of any threat or problem before developing a restoration or conservation plan. This ensures that the work being done helps the health and longevity of the building or structure by finding the more effective means of repair (Parks Canada, 2003).

Moisture monitoring practices for heritage buildings

The environment can pose a threat to the health of buildings, structures, and contents; therefore, any conservation or preservation project needs to take into account the original envelop of the building, its original context, and its new or proposed purpose. One of the largest threats from the environment is the moisture content since excess moisture content in interior and exterior of the structure and components can lead to

- potential frost damage from freeze-thaw cycles, cooling rate, and water content
- salt crystallization on the surface and interior of the structure
- leaching of components of the mortar
- potential damage from moss, climbing plants, and moulds (Maurenbreacher, Saïd, & Fontaine, 2001).

In recent years, the National Research Council of Canada has taken part in some important research projects to determine the effect of moisture and other environmental threats on heritage buildings such as the Peace Tower and the

Winnipeg Customs Examining Building in Ottawa, Ontario and Winnipeg, Manitoba, respectively.

The Peace Tower was built between 1919 and 1927 and over the course of time, it was recognized that the environment was damaging the exterior and interior masonry. Therefore, a longitudinal, in-situ monitoring and research project was undertaken to gain a better understanding of all the environmental effects on the structure and decorative features. This ongoing study provides the required information for determining what types of repairs need to be done to ensure the health and longevity of this structure (Saïd, Duchesne, Maurenbrecher, Ibrahim, Lumsdon, & Stephenson, 2005).

The Winnipeg Customs Exchange Building was built in 1911 as a four-storey warehouse, and in 1993, was converted into office and laboratory space. The change from warehouse space to laboratory space required the building to be insulated to provide stable temperature and humidity. To effectively make this change, a research and monitoring project was conducted to ensure the health of the building and to ensure the temperature and humidity could be controlled with no harm to those working in the building (Maurenbrecher, Shirtliffe, Rousseau, & Saïd, 1998).

Moisture content measurement methods

Any of these threats can be detrimental to the compatibility of the anchors, anchor materials, and surrounding structures. Therefore, it becomes important to monitor the moisture content within the structure using one of any number of methods:

Thermal-based methods are based on the examination of the temperature differences seen in moist versus dry material. The premise behind thermal-based methods is that moist or wet material is colder than the surrounding dry material. The surface of the structure would be cooled by the circulation of the moisture of the interior components. The majority of thermal-based methods are done in situ (on location) for determining the moisture content of soil and in some cases, of building (Saïd, 2007).

Infrared thermography (IRT) involves an examination of the changes in temperature visible with infrared light. It is relying on the same premise of the thermal-based methods where the dry material will appear warmer than the surrounding wet material, and in turn, the dry material will display more infrared light than the wet material. One of the main advantages of IRT is that it is possible to scan the moisture content for a large surface of the building; however, it must be done by qualified individuals and under optimal weather conditions (Saïd, 2007 and Rosina, Avdelidis, Moropoulou, Della Torre, Pracchi, & Suardi, 2004).

Resistance-based methods determine the moisture content of materials by testing their electric resistance as they vary with the moisture content. Materials with higher moisture content will exhibit less electrical resistance while increasing the conductivity. To measure the electric resistance of an object, a sensor is attached to the structure or object and to a monitoring device to calculate and monitor the moisture content (Carll & Ten Wolde 1996; Saïd 2007; Uddin et al., 2009; Uddin, Mustapha, Mufti, & Thomson 2010).

Voltage-based methods measure the direct current voltage across a known resistor. Just as the electrical resistance increases with the moisture content of the material, the voltage increases with high moisture content (Saïd, 2007).

The resistance-based methods which include the embedded wooden sensor (Duff's gauge) are used for determining the moisture content in a wide range of applications. They are often selected since they

- Are inexpensive to produce
- Can vary in size to suit the purpose of the project
- Can collect data over a long time frame (Duff, 1966).

The sensors are reported to have an accuracy of one per cent moisture content due to various among individual sensors, sensor memory, and calibration difference between species (Duff, 1966). However, a more recent student by Carll and Ten Wolde claim the error is no more than ±10% relative humidity (related to the moisture content in the air surrounding the object) unless the relative humidity drops more than three per cent per hour (1996).

Anchor materials and processes

The traditional anchor process for stone masonry and concrete structures involves using threaded metal bar embedded or "stitched" through the structure and held in place with a cementitous gout (Uddin et al, 2009). While it does provide structural stability to the building or wall, there are some concerns about the breakdown of the steel when exposed to the environment. Over an extended time of being exposed to the elements, the steel can corrode which can weaken the structure and potentially lead to discoloration of the original structure. One solution to prevent this breakdown is to use an epoxy resin around the steel which limits its contact with moisture (Nanni, Bakis, O'Neil, & Dixon, 1996).

However, new technologies such as glass fibre reinforced polymer (GFRP) and fibre reinforced plastic (FRP) composites are starting to be used in construction. These are proving to be more resistant to corrosion, lighter weight, and higher tensile capacity then the traditional steel anchors (Nanni et al, 1996).

Methodology

To test the compatibility of the anchor materials with the surrounding masonry bricks, there were two major steps, the creation and calibration of the embedded wooden sensors and the exposure of the bricks to laboratory conditions that replicated the annual fluctuations in temperature and humidity.

Embedded wooden sensors were created using hemlock dowels that were cut into 3.8cm lengths and fitted with wire leads for the monitoring process (SMT Research, 2011). Once calibrated to ensure constant moisture content in each sensor, the sensors were place inside sandstone and limestone bricks and secured with various commercial anchor materials including threaded steel anchors and glass fibre reinforced polymer (GFRP) with cementitous grout and epoxy resins. Then they were, subsequently, were exposed to a series of freeze-thaw cycles with varying rates of humidity under laboratory conditions to replicate three years' worth of fluctuations in the outside environment. During the experimentation process, all specimens were examined for evidence of stress including the formation of cracks, breakdown of the bonding materials, and any other differences between the control specimens (Uddin et al, 2009; Uddin et al, 2010).

Discussion and results

The use of the embedded wooden sensors revealed that there were notable differences between the moisture profiles of types of bricks used in the laboratory testing as a result of the temperature changes, but there were minimal differences between the controls and the various anchor materials and processes. All the specimens showed no signs of stress or cracking as a result of any of the testing (Uddin et al, 2010).

From the initial testing, it appears the GFRP and FRP technologies may be a suitable option for reinforcing and repairing heritage stone masonry structures within the Canadian climate. The laboratory testing replicated approximately three years' worth of freeze–thaw cycles, with many of the stone bricks showing little significant difference from the moisture and temperature profiles and a slight difference with the grouted samples in the permeability testing (Uddin et al, 2010).

Despite the promising results of the initial testing, there is still more work that needs to be done before it can be used in any preservation or restoration project. The GFRP and FRP technologies can overcome some of the issues associated with the corrosion in steel anchoring systems when exposed to moisture. However, the purpose of the testing done by RRC's CARSI and SMT Research was to test the effects of moisture on the stone bricks used in a prominent heritage building in Ottawa, Ontario—it did not test for the structural integrity or durability of a structure reinforced with the GFRP and FRP technologies.

The GFRP and FRP technologies are currently used to reinforce or add strength to the existing steel anchoring systems by applying external or near–surface internal reinforcement of the buildings and structures (Andrae, Maier, Peters, & Gusia, 2005). Since they tend to be used externally or near the surface of a structure, they may take away from the heritage value and form of the original structure (Parks Canada, 2010). Therefore, additional research and testing needs to be conducted to find a way for the GFRP and FRP anchoring systems to be used without being visible on the surface of the building or structure.

Conclusion

The GFRP and FRP anchoring systems when combined with stone masonry bricks demonstrate similar moisture and temperature profiles as traditional steel and grout anchoring systems. With the exception of some of the grout and steel anchoring systems, there were little significant difference in the results from the permeability testing which may make the GFRP and FRP anchoring systems a viable option for reinforcing stone masonry structures in the future. However, there is more testing that needs to be done to verify both the capacity of the GFRP and FRP anchors as a reliable system to help with the structural integrity and durability without the aid of the traditional steel reinforcements and to minimize the visible impact on the structure.

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