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Combining Reinforced Concrete with Masonry: Case-Study on the North Towers of Centre Block

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ABSTRACT

Centre Block, the centrepiece of the Canadian Parliamentary Precinct in Ottawa and a Classified Federal heritage building, is undergoing a multi-year rehabilitation to bring the building up to current code standards and contemporary requirements. The building will undergo seismic upgrades to enable it to resist the 2020 NBC seismic demands with minimal damage. The building has four north towers, all approx. 40 m high, built in mass masonry stone and brick, which will primarily be repurposed to house new mechanical systems, and will remain unconditioned above the roof of Centre Block. The towers are also particularly vulnerable to seismic loading. Multiple structural options for strengthening the towers were considered, with a new reinforced concrete liner selected as the preferred structural option for its stiffness compatibility and ease of connecting the towers to the surrounding floor diaphragms. The towers have experienced significant deterioration over the last hundred years due to their exposure and vulnerabilities in the original design. The preferred structural option raised concerns related to combining reinforced concrete construction with mass masonry construction and that changing the historic conditions could promote further deterioration. Specific concerns included: distress in the masonry due to the initial shrinkage of concrete, distress in the masonry due to differential thermal cycling between the concrete and masonry, and deterioration of the masonry due to migration of salts from the concrete. To address these concerns, the team conducted research, and undertook computer modelling, and analysis, showing that the insertion of the concrete liners, together with some additional provisions, would not create detrimental conditions. This paper describes the existing conditions of the towers, the concerns raised, and the studies undertaken to establish the viability of the proposed approach.

KEYWORDS

Unreinforced masonry, mass masonry, Berea, Nepean, Wallace, sandstone, brick, concrete, seismic, historic, heritage building, thermal movements, finite element analysis, non-linear analysis.

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INTRODUCTION

Centre Block, Canada's Parliament Building, was built between 1916-1927, to the designs of John A. Pearson and J.O. Marchand, replacing the original Centre Block, which was destroyed by fire in 1916. It was designed as a hybrid masonry building, with overall dimensions of 144 m wide x 75 m deep, six storeys high, with the Peace Tower, and four towers on the North side. In 1986, it was designated *Classified* because of its exceptional significance as a national landmark

Centre Block and selected sections of Parliament Hill are undergoing a comprehensive rehabilitation to meet the contemporary requirements of the Parliament of Canada. The Centre Block Rehabilitation (CBR) project, undertaken by CENTRUS (a joint venture between WSP and HOK with support from DFS architects, Architecture 49 architects, ERA architects, and Ausenco), is the centrepiece of the Long-Term Vision and Plan for the Parliamentary Precinct (LTVP), which directs the conservation and modernization of Canada's Parliament Buildings, implemented by Public Services and Procurement Canada (PSPC) in collaboration with the Parliamentary Partners – the Senate of Canada, the House of Commons, and the Library of Parliament. As the largest and most complex rehabilitation project ever undertaken in Canada, the CBR presents extraordinary challenges due to its scope and complexity. Major project components include restoring the building's stonework, heritage elements, upgrading all mechanical and electrical systems, and making the building more accessible for all [1] [2] [3]. In addition, the building will also undergo a full seismic upgrade to meet the requirements of the 2020 National Building Code of Canada (2020 NBC).

The primary focus of this paper is the overview of the seismic upgrades to the four North Towers of Centre Block, which includes the selection of the upgrade strategy, thermal compatibility modelling, and addressing building science concerns.

Masonry and Structural Overview

The exterior walls of Centre Block are all multi-wythe load-bearing masonry and are supported by unreinforced concrete walls below the ground floor. The walls are composed of a common brick backing with an exterior wythe of snecked Nepean sandstone masonry (from Ottawa), having a pitched face, cut stone belt courses, window and door surrounds, architectural stone and sculpture of Berea (from Ohio, USA) and Wallace (from Nova Scotia) sandstone. The Nepean sandstone and architectural stone are keyed into the brick backup, with through stones at windows and door surrounds, and other locations. All stones are hand tooled on joints and beds with an average depth of 150 to 200 mm into the wall. The face dimensions are typically between 65 and 300 mm in height and from 150 to 410 mm in length.

Interior load bearing walls are constructed of common brick laid in running bond. The interior faces of the North Tower walls were typically left unfinished.

The floors are comprised of two different structural systems: reinforced concrete and terracotta flat arches with steel beams. The reinforced concrete system is generally found only at the ground floor level, which is supported by the unreinforced concrete walls and columns of the foundation. The floor and flat roof structures at upper levels are comprised of terracotta flat arches that spring from the lower flanges of steel floor beams. The interior structure is steel framing, typically supported on load-bearing masonry walls.

Figure 1: Conditions of towers in 2018. Left photo shows part of Tower 1 in foreground showing extensive stone replacement, and Tower 2 in the background. Centre and right photo show Tower 2 conditions

History & Description of the North Towers

The North Towers comprise the Ventilation Towers (the most eastern tower, Tower 1, and most western tower, Tower 4) and the inner Water Towers. The towers are symmetrical and square in plan and rise approximately 24.2 m above the roof level. These towers are constructed of mass load-bearing masonry walls and rise to support roofs made of reinforced concrete. They are typically open on the inside from grade to the roof. The exterior wythe consists of the same three types of sandstone as the exterior walls. The interior wythes are of common clay brick. Through stones are used at window and louvre surrounds, with large through stones used at strategic locations in the height of the walls.

Towers 1 and 4 served a venting function as part of the buildings mechanical systems, while Towers 2 and 3 were built to house water tanks located at the top of the towers for the building plumbing. Tower 3 also accommodated a freight elevator supported by steel framing. The towers generally had no dedicated heating except for radiation heating for the water tanks to keep them from freezing.

Over the years, the towers received minimal maintenance leading to deteriorated conditions requiring emergency repair works pending a full building rehabilitation. Stabilization work in 1994-96 on the Towers 2 and 3 included the installation of horizontal anchors in the masonry to restore their structural integrity.

Towers 1 and 4 underwent extensive rehabilitation in 2013-17, restoring the exterior sandstone and interior brick masonry, and addressing long vertical cracks observed in the corners. The masonry walls were temporarily strapped to maintain stability, and finally reinforced with horizonal anchors. At the interior, a steel structure was introduced to provide seismic reinforcement.

Observed Issues with the North Towers

As highly exposed building features, the North Towers experience the impact of weather and seasonal changes more than the main body of the building. Since they were built, extreme weathering coupled with the lack of punctual maintenance left the towers in poor condition, refer to Figure 2 below. Reviews over the years up to the present project, have identified common issues including:

- Deteriorating mortar joints.
- Vertical cracks observed between the field stone and the quoins, seen at the exterior and interior.
- Erosion and exfoliation of the stonework.
- Atmospheric soiling.
- Cracks observed at the areas where the towers meet with the Centre Block roof.
- Excessive efflorescence and spalling on the interior brickwork and exterior stone.
- Use of Portland cement based parging mortars for face repair of stone.
- Re-cracking of repaired areas pointing to underlying systemic issues not being addressed [4] [5].

Figure 2: Condition of exterior quoin stones showing cracking efflorescence, re-cracking of mortar joints, and interior brick with efflorescence, around 1998 before major repairs [5].

SEISMIC UPGRADE REQUIREMENTS

The requirement for the Centre Block Rehabilitation project is to ensure that the building can resist the seismic demands outlined in the 2020 National Building Code of Canada (2020 NBC); this is primarily achieved through seismic isolation [6]. However, there were elements of the superstructure which were identified as being vulnerable, even after isolation. Seismic demands on the Centre Block building, including the towers, were determined using finite-element analysis (FEA) models with equivalent static, dynamic and non-linear time history analyses.

The North Towers of Centre Block had two crucial issues which were identified: the flexural (i.e. overturning) capacity and connections to the floor diaphragms were found to be deficient to meet the NBC 2020 demands. Furthermore, there were localized shear and flexural deficiencies found at the openings for mechanical louvres and windows at the tops of the towers. The capacities of the existing masonry walls were calculated in accordance with CSA S304-14: Design of masonry structures, supplemented by non-linear pushover analyses performed in the software Vector2 [7].

STRUCTURAL OPTIONS FOR STRENGTHENING

It was not possible to resist the seismic demands of the NBC 2020 without structural intervention. There were additionally a number of architectural constraints which had to be respected, including:

- The exterior appearance of the towers had to remain unchanged, and the mass masonry walls preserved.

- To not create conditions that would cause future deterioration to the masonry.
- The louvre openings at the tops of the towers had to be usable for mechanical exhaust.
- Window and door openings were to be preserved.
- Any interventions on the interior faces of the tower walls needed to be 350 mm or less in thickness to leave space for new mechanical, electrical and elevator systems.

The tower walls must also be connected to the floor diaphragms to transfer lateral forces into and out of the walls. The structural diaphragms of Centre Block adjacent to the towers are typically being upgraded with a thin reinforced Ultra-high-performance concrete (UHPC) topping. Connections to the topping are done via rebar dowels or concrete anchors.

Two structural reinforcement options emerged as the main contenders, both applied to the interior face of the tower walls: steel bracing or reinforced concrete laminations.

Option 1: Steel bracing

There were already steel members installed vertically in the corners of two of the towers to address flexural strength deficiencies, and initially it was thought that supplementing this with some additional bracing and new connections to the floor diaphragms would be the preferred option.

The steel bracing option offers several advantages, mainly that it is considered to be more "reversible" and that it allows for easier inspection of the inside face of the masonry walls. However, during the development of the steel bracing design other issues became apparent:

Firstly, there is a lateral stiffness incompatibility between the existing masonry walls and the steel bracing. The displacements required to fully engage the strength of the steel bracing would mean that the masonry walls would have experienced significant levels of damage. While it is possible to design steel bracing to prevent the collapse of the towers, it would not achieve the desired objective for this project of minimizing the need for repairs after a code level seismic event.

Secondly, large portions of the towers are to remain as unheated spaces, meaning that thermal movements, particularly of the horizontal steel members, would need to be accounted for. The coefficients of thermal expansion/contraction of steel and brick masonry are significantly different from one-another, meaning that differential movements between the two materials would need to be accommodated. However, with the primary goal of the steel framing being to protect the existing masonry walls during a seismic event, having slotted connections and gaps between the steel and masonry to allow for thermal movements was not desired. Should the steel be rigidly connected to the masonry, the forces resulting from restraining thermal movements would have governed the design of some the members and their connections.

Option 2: Reinforced concrete laminations

The reinforcement option which was ultimately selected is to build a liner within the tower of reinforced concrete laminated to the masonry.

The primary structural advantage of the concrete liner is that the lateral stiffness of the concrete is more similar with that of the masonry. This compatibility means that the stresses are more evenly distributed between the two materials, reducing the risk of localized failures and offering better overall protection to the historic structure.

Moreover, the thermal expansion properties of reinforced concrete are closer to that of masonry when compared to steel, reducing the potential for distress caused by differential thermal movements. Refer to the following section for more information.

Finally, the connections between the historic masonry, concrete liners and new floor diaphragms are easier to design and construct than the steel option as rebar dowels can simply be installed through the masonry walls wherever needed.

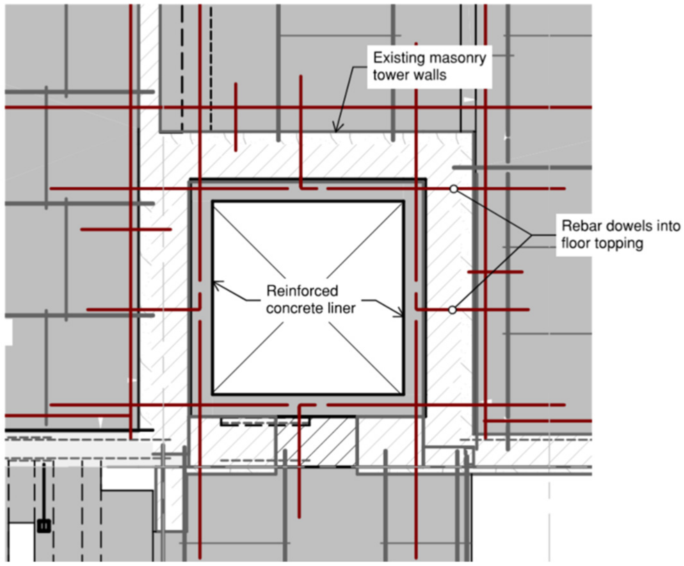

Figure 3: Plan view of reinforced tower at a floor level.

Challenges and Concerns

When rehabilitating historic mass masonry building to meet contemporary seismic standards, it may become a necessity to introduce concrete. Introducing concrete is generally not considered acceptable due to the degree of reversibility; potential incompatibility between the materials; salt migration into the masonry causing efflorescence and deterioration; different thermal expansion rates; changing drying patterns; and the possible need to remove masonry to make space for the concrete. Sensitive design though can alleviate these concerns.

The proposal to install concrete liners as part of the seismic upgrades initially raised concerns within the design team about the compatibility of the concrete with the tower mass masonry. There were several concerns raised:

- Historic examples of concrete upgrades in historic mass masonry buildings, where interventions made buildings perform worse than expected in subsequent seismic events.
- Cracking from differential thermal movement.
- Concrete creep/shrinkage over time.
- Migration of salts from the concrete into the masonry.
- Reduction of effective drying area for the masonry.

Mitigation of Identified Risks

The following section outlines some of the research and analysis undertaken to address and mitigate the risks commonly associated with laminating concrete to historical masonry.

Efflorescence and moisture

Efflorescence on the exterior and interior masonry has been a chronic problem, caused by the ingress of moisture from failed mortar joints, and humid air exhausted from the building via the towers. Drying to the exterior or interior draws the soluble salts in the mortar to the face of the masonry. Efflorescence can be cleaned off or left to weather away, usually with no harm to the masonry, however, a condition known as sub-florescence can develop, where salt buildup below the surface causes damage and spalling, significant at the brick interiors.

The addition of the concrete liner will reduce humid air from within the building infiltrating into the masonry and largely eliminate drying to the interior. Furthermore, a fibre-reinforced flexible cementitious waterproofing layer will be applied to the inside face of the brick before the concrete liners are cast. This membrane was specifically selected to restrict the transmission of salt between the concrete and brick.

However, the addition of the concrete layer also reduces the drying area of the brick masonry, creating the concern that moisture could be trapped at the inner surface. WSP's Building Science department has also conducted additional hygrothermal analysis of the condensation potential and moisture migration to confirm that the addition of the liners and membrane selection were appropriate. While modelling confirmed an increase in moisture levels, additional interventions to improve the water-shedding on and around the towers will also help mitigate risk. The details of these analyses and interventions are beyond the scope of this paper.

Finally, deep pointing and face pointing of masonry will use cement-lime-sand mixes that will use non-staining Portland cement, low in salts, and designed to be more porous than the original Portland cement-sand mortars, promoting drying through the mortar joints instead of through the stone.

Thermal Incompatibilities

All materials change length as temperature changes. However, different materials expand and contract at different rates. Issues can arise when different materials are restraining each other against expanding or contracting at their respective rates. The change in length of a material can be calculated using the following equation:

(1) $\Delta L = c \times L \times \Delta T$

c is the coefficient of thermal expansion and is material specific; L is the initial length of the material; and ΔT is the change in temperature. It is important to note that the longer a material is, the more it will expand/contract.

Table 1: Coefficients of thermal expansion

Material	Coefficient of Linear Thermal Expansion (m/m/°C)
Sandstone	11.0 x 10-6
Brick Masonry	6.1 x 10-6
Concrete	10.0 x 10-6
Stainless Steel	17.8 x 10-6

The coefficients of thermal expansion indicated above are average values from various sources [8]. A sensitivity analysis was conducted, and coefficients from different sources did not change the overall conclusions. The effects of mortar joint thicknesses were also determined to be insignificant.

In the case of the North Towers of Centre Block, the shape of each tower is a doubly symmetric closed box. Therefore, it can be expected that the tower walls will expand and contract evenly about its centrelines. To simplify the approach for an initial assessment, the lengths of each material component of a wall were measured from the centreline. The lengths, measured to the inside faces, are approximately 2.88 m and 1.92

m for the sandstone and brick layers respectively. The expected changes in length for each material were then calculated assuming a ±35°C temperature swing uniformly applied to all layers, and that they were not providing any restraint to one another. The concrete layer will experience smaller temperature differentials to the masonry due to it being on the inside, however the approach taken is conservative for this configuration. The results are displayed graphically below:

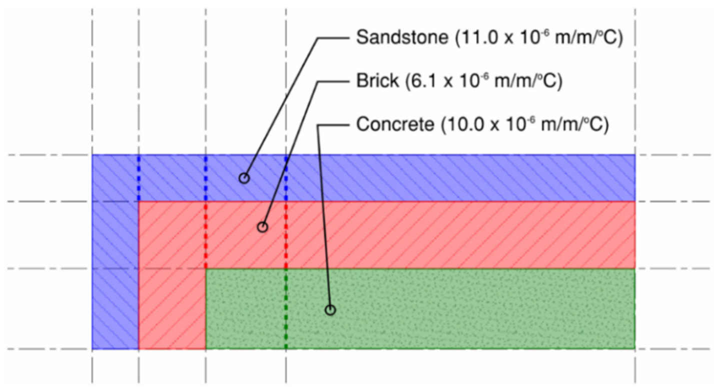

Figure 4: Layout of wall components for simplified thermal analysis.

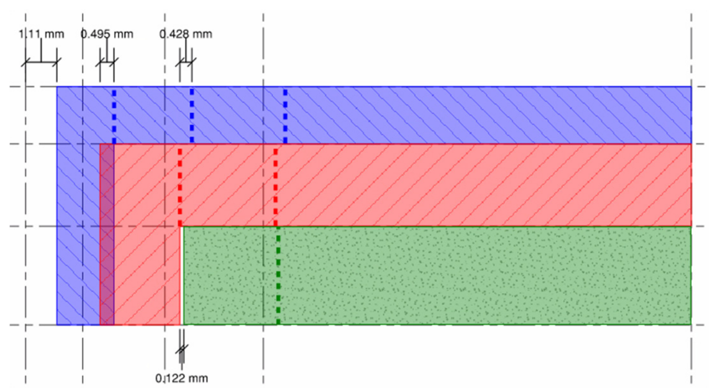

Figure 5: Relative thermal movements for ΔT = -35°C

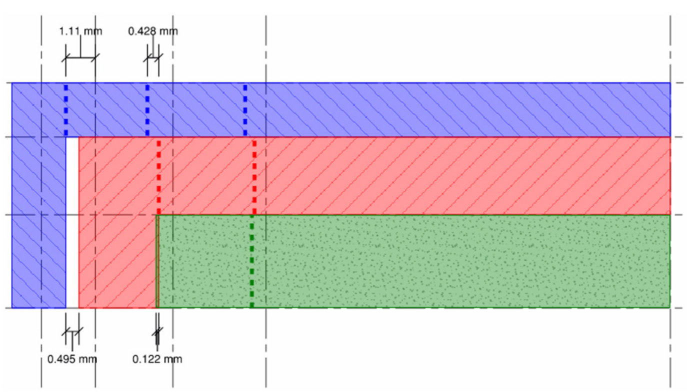

Figure 6: Relative thermal movements for ΔT = +35°C

Note: for clarity, all displacements are magnified and only shown on the horizontal axis.

For this configuration, the unrestrained thermal movements of the sandstone layer would be approximately 0.5 mm more than the brick layer; and that the concrete layer would move approximately 0.1 mm more than the brick layer. From this, it can be concluded that there was an existing thermal incompatibility between the sandstone and brick layers which is greater than the potential incompatibility between the brick and a new concrete layer.

Furthermore, from examining the results of this simplified approach, the following behaviors could be expected:

- During cooling, there is the potential for vertical cracks to form in the sandstone layer due to the tensile stresses which would develop as it tries to contract more than the brick layer.
- During cooling, compressive stresses would develop in the concrete layer.
- During cooling, the brick layer would develop compressive stresses as it restrained the contraction of both the sandstone and concrete layers.
- The inverse of the above behaviors would be expected when the wall is heated, with the potential for tensile cracks to develop in the brick layer.

FEA Validation

To validate the conclusions from the simplified approach, 2D finite-element analyses (FEA) were done using the SAP2000 software by CSI for both the existing and new conditions. The materials were modeled using non-linear properties to properly account for the loss of strength and stiffness should a tensile crack form. The three material types were meshed to account for the effects of restraint on the thermal movements. The results for this analysis were also compared at a ±35°C temperature range.

The results of the analysis for the existing condition show a behavior consistent with the conclusions from the simplified approach. Furthermore, the locations where cracking appeared in the stone layer during the cooling phase were consistent with the vertical cracks which historically appeared on the towers; suggesting that some of the observed cracking was due to thermal cycling. The results of the analysis of the existing condition are shown in Figure 7 below. Note: the red lines were overlaid onto the outputs to more clearly show the direction of the cracks; they are not precisely drawn to scale.

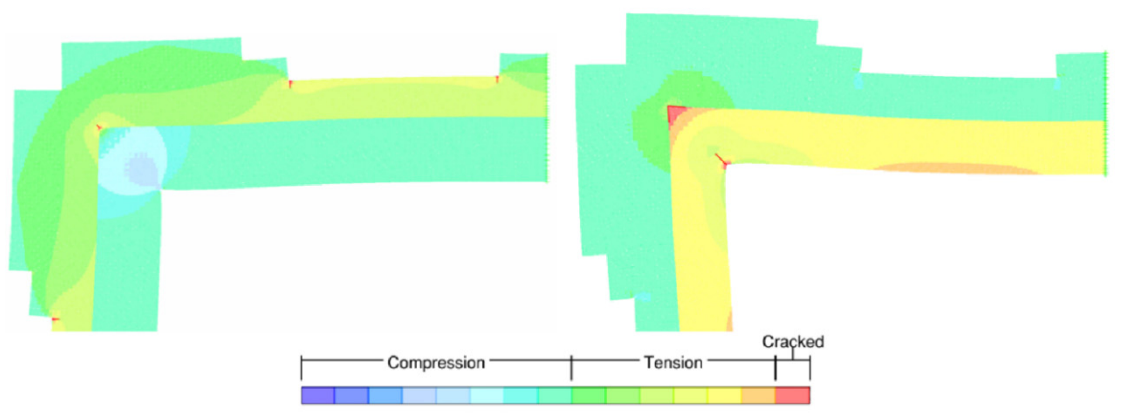

Figure 7: FEA Output for Existing condition; cooling (left), warming (right)

The new condition was modeled by taking the existing condition model and adding a 350 mm thick concrete lamination to the inside face of the walls. For the cooling phase, the addition of the concrete liner showed only subtle changes in the stresses within the masonry elements; the locations of the cracks in the stone layer remained the same, and the addition of the liner did not increase the size of the cracks. For the warming phase, the addition of the concrete liner did increase the tensile stresses within the brick layer by up to 0.09 MPa, but no new cracks were observed. The results of the analysis of the new condition are shown in Figure 8 below.

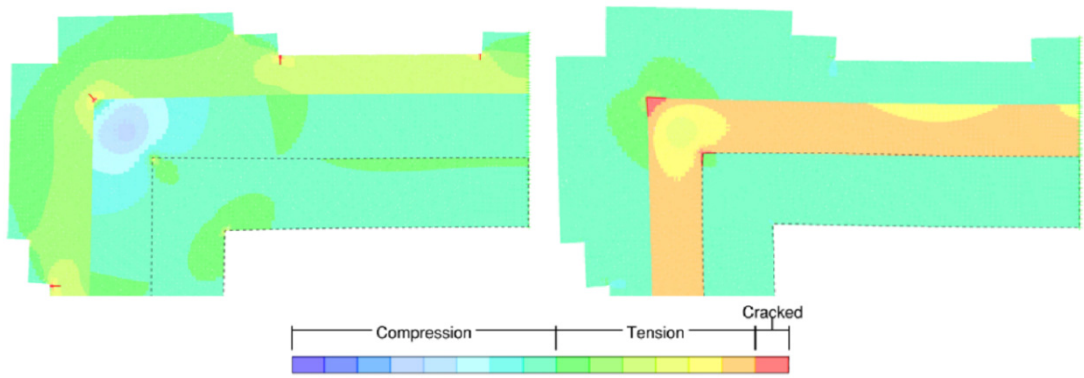

Figure 8: FEA Output for New condition; cooling (left), warming (right)

The overall result of the thermal analysis is that the addition of the concrete lamination would not have any significant detrimental effect on the tower, but it would also not reduce the potential for cracking which already exists.

Concrete shrinkage

The contraction of the concrete layer due to shrinkage was considered in a similar method to the thermal analysis, with the exception that the masonry layers would remain static.

By examining the geometry of the walls, it could be expected that the shrinking concrete layer would pull inwards and put most of the masonry into compression. There would also likely be some tensile stresses that would develop directly in the corner where the concrete layer meets the brick. These expectations were validated using the same FEA model as the thermal analysis; the shrinkage was calculated within the software using SAP2000's CEB-FIB 2010 model; the unrestrained shrinkage was estimated at approximately 0.5 mm after 11 years. The graphical results are shown in Figure 9 below.

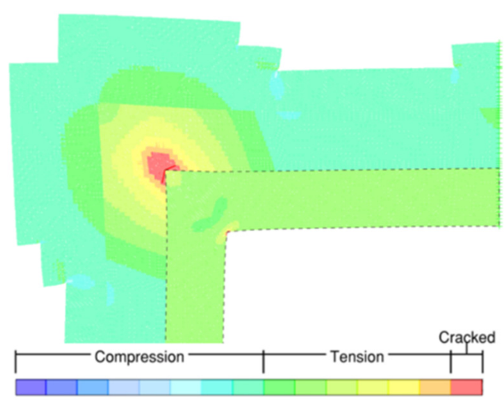

Figure 9: FEA Output for concrete shrinkage.

The analysis shows that the shrinkage would cause compressive stresses to form in the regions where cracks due to thermal cycling are expected, however, the design of the concrete lamination was done ignoring any potential positive effects of shrinkage. A low-shrinkage concrete mix will be used to minimize the potential for tensile stresses to develop in the corner.

Increased Seismic Demands

The additional concrete increases the mass and stiffness of the towers, and thereby also the seismic demands; however, since the building is being seismically isolated, these increases are significantly less than they would have been in a conventional upgrade, and they are manageable. The building's foundations have also been designed to accommodate the additional weight.

Ongoing Challenges

The ongoing challenges associated with the concrete laminations which will not be fully addressed are that it will not be possible to inspect the interior face of the brick masonry walls, and that the concrete laminations are not considered to be easily reversible. Furthermore, while the addition of the concrete provides increased safety to the building's occupants should an earthquake occur, it is not a solution to the existing thermal incompatibilities. It's expected that the program of ongoing inspection and maintenance will continue, and any future cracks will be repaired.

CONCLUSION

The rehabilitation of Centre Block's north towers is an effort to preserve key heritage components of the building while ensuring they meet modern standards. Reinforced concrete liners were chosen as the preferred structural option due to their improved seismic performance, deformation compatibility and thermal compatibility with the existing masonry.

Initial concerns were raised about laminating reinforced concrete to historic masonry given historical examples where this strategy did not perform as intended. The identified risks included that the addition of the concrete could cause distress to the masonry from initial shrinkage, thermal cycling, or moisture. Modelling was able to demonstrate that the addition of the concrete lamination would not have a significant detrimental effect on the structure due to differing rates of thermal expansion. Additionally, hygrothermal analysis has demonstrated that the reduction in drying potential of the masonry can be mitigated with improved water-shedding.

With special consideration and the rational application of scientific and engineering solutions, the risks were able to be effectively lowered for this case, ensuring that the Centre Block remains a safe, functional, and iconic part of Canada's heritage for future generations.

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