Library of Parliament of Canada – conservation, rehabilitation, upgrade case study presentation

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ABSTRACT: The Library of the Parliament of Canada is considered to be the premier heritage building in Canada, and the only surviving building of the original high-Victorian parliamentary building built in the 1860’s. The building continues to serve its original function as the Parliamentary Library for both the Senate and House of Commons. In 1998, a Consultant Team was retained by Public Works and Government Services Canada to design and oversee a project to conserve, rehabilitate and upgrade the building for a design life span of 50 years. The conservation aspect includes an extensive list of structural and architectural elements. The first part of the presentation will address the specific topic of stone masonry rehabilitation and conservation, with an emphasis on issues related to northern climates, i.e. water penetration and freeze-thaw cycling. The second part, will present some structural interventions addressing upgrading of the building to current code requirements and modern environmental control specific to libraries and archives housing valuable historical documents.

1 INTRODUCTION

1.1 History of the Library of Parliament

The Library of Parliament (Fig. 1) was originally constructed in the 1860’s and extensively rebuilt in 1952–56, following a fire. It is the single remaining original building on Parliament Hill housing the Parliament of Canada. The Library was built to the designs of Fuller and Jones in the form of an English Gothic chapter house, and decorated in an exuberant Victorian manner. It is the premier heritage building in Canada, located on a rugged promontory, high over the Ottawa River. It is linked to the Centre Block (housing the Senate and the House of Commons), which was rebuilt in its entirety after a devastating fire in 1916. Its image is reproduced on Canadian postage stamps and banknotes.

Construction of the Library along with the Parliament Buildings began in December 1859. In June 1866 the Parliament opened its first session in the new building, however the Library masonry walls were only constructed to a height of 13 m. A temporary roof was installed over the ring walls. Construction of the stone masonry walls restarted in 1871, however the main roof structure design was changed from a masonry dome to a wrought iron truss system designed and

Figure 1. Library of Parliament, c1875 (NAC, C-10001).
The main vertical structural elements of the Library Venture Firm as the architects for the Conservation, tresses arching over to the inner ring wall. The inner offices slabs (five levels) and the lower roof. The wall is stiffened by 16 buttresses, with flying buttresses of the inner ring wall is 26.5 m, while the diameter of the outer ring wall is 45 m. The outer ring wall is 1200 mm thick at its base, and reduces to 850 mm above the main floor. The inner ring wall is 1500 mm thick below the main floor, and reduces to 1300 mm for the upper section. According to the original specifications, keystones were placed on a regular pattern to connect the face wythe to the rubble core. However, the investigation conducted by the design team could not clearly identify the keystones.

Between 1956 and 1998 the Library benefited from small maintenance and upgrading projects addressing lighting problems, heating and air conditioning, and fit-up of a rare-book storage room. A number of studies were completed regarding water infiltration, high humidity levels, and the condition of the masonry walls. In June 1998, Public Works and Government Services Canada retained an Architect Joint Venture Firm as the architects for the Conservation, Rehabilitation and Upgrade Project for the Library of Parliament. The Joint Venture retained the engineering sub-consultants, as well as specialty consultants. Construction documents were completed in May 2001. Construction started in March 2002, and is expected to be completed in 2005.

1.2 Structural description

The main vertical structural elements of the Library are the two concentric masonry walls: the outer ring wall and the inner ring wall (Fig. 4). The diameter of the inner ring wall is 26.5 m, while the diameter of the outer ring wall is 45 m. The outer ring wall is stiffened by 16 buttresses, with flying buttresses arching over to the inner ring wall. The inner ring wall provides the support for the arched wrought iron truss system supporting the main roof and the lantern. At its lower levels, together with the outer ring wall they provide the support for the perimeter offices slabs (five levels) and the lower roof. The walls also provide the resistance for lateral loads, i.e. wind and earthquake. The walls are founded on large slabs of limestone positioned on limestone bedrock. The bedrock has significant jointing with variable directions and angles.

The ring walls are of random rubble construction built to courses with plain ashlar quoins. The outer face of the wall was squared and bedded in mortar, and the inner face was built up of coursed random rubble wall grouted up in lifts as the work progressed. The outer ring wall is 1200 mm thick at its base, and reduces to 850 mm above the main floor. The inner ring wall is 1500 mm thick below the main floor, and reduces to 1300 mm for the upper section. According to the original specifications, keystones were placed on a regular pattern to connect the face wythe to the rubble core. However, the investigation conducted by the design team could not clearly identify the keystones.

The area inside the inner ring wall is referred to as the Reading Room. Originally, it had only one basement level, with the reading room rising approximately 30 m to the base of the lantern, and up to 41 m at the lantern. The only floor slab had a brick arch support, with a concrete, gravel, sand and hydraulic lime mortar topping. The slab was carrying the multi-level wooden book stacks (Fig. 2), with eight radial projecting stacks, and access from the perimeter offices area. The stacks have a wrought iron framing, and include two levels of circulation galleries to provide access to the shelves and projecting stacks. During the renovatons of 1950’s, the reading room slab was removed and replaced with a 127 mm two way reinforced concrete slab supported on steel columns on a 2743 mm grid. At the same time, the single basement level was replaced with two levels, by slightly lowering the bedrock and reducing the clear height on each level. The steel columns, built up from angles and tee sections, were integrated with the mobile shelving.

Figure 2. Interior of Library of Parliament, photography by Williams J. Topley, c.1898 (NAC, PA-8375).
system. The shellacked pine book stacks, refurbished off-site, were reinstalled on the newly constructed slab.

The perimeter offices area provides office and service space, including four stairs on a diagonally opposite configuration. The northeast stair is the Stair Tower, which extends to the top of the inner ring wall, and provides the access to the roof and lantern. It contains a stone circular stair within a round stone masonry tower. All the perimeter offices slabs were reconstructed in 1953, with a 65 mm reinforced concrete floor slab, supported either by a reinforced concrete skin wall placed against the ring walls, or horizontal slots cut into the stone masonry walls.

The roof over the Reading Room is carried by a semi-circular wrought-iron truss system, which is composed of 16 long trusses alternating with 16 short trusses (Fig. 3). All the trusses are connected at the top to a wrought-iron ring compression truss, and are supported at their bases by the inner ring wall. The long trusses are the main structural elements as they align with the buttresses. The trusses bear on large crystalline limestone blocks set through the walls, between the Reading Room windows. The short trusses bear on the masonry just above the receiving arches of the windows, with additional steel bracing incorporated into the masonry (their presence remains unconfirmed) transferring their loads to the long trusses. In 1953, the original wooden strut and purlin system supporting the wood deck, was replaced by a mild-steel secondary framing and steel deck system. At the same time, the original timber lean-to roof over the perimeter offices was replaced with a steel framed roof and steel deck.

The original timber Lantern structure was completely replaced during the 1953 renovations. A new structural steel framing system was installed, springing from the compression ring truss. Its structure includes cranked steel columns, two levels of horizontal diaphragm framing, secondary steel framing, and the central pipe column for the wrought-iron weathervane.

The Library also includes a number of architectural features – pinnacles, stair tower, and chimney. Stability of these masonry elements was addressed by the structural team, and the designers provided the reinforcing details.

1.3 Structural challenges for building upgrade

The current conservation, rehabilitation and upgrade project scope-of-work listed a number of requirements set up by the Client. The most challenging tasks from the structural engineering point of view included: (1) conservation of the building for a minimum lifespan of 50 years; (2) upgrading of the building to current code requirements (National Building Code of Canada 1995), including seismic resistance upgrades; (3) construction of an underground link to the existing House of Commons loading docks and material handling facility; and finally, (4) construction of a dedicated mechanical room to provide all the air handling and stringent environmental control for the Library, all independent from the Centre Block systems. Of course,
all the work would have to be in conformance with the established heritage conservation principles in order to preserve the historic character of the building. The rehabilitation and conservation of the masonry walls, ring walls and buttresses, resulted in extensive investigation and research. Despite minor evidence of distress (localized cracking), there was evidence of major water infiltration problem within rubble core. Previous investigations had expressed concern regarding cavitations and the disintegration of the hydraulic lime mortar core, which was possibly effecting the stability of the exterior stone wythes. Considering that the deterioration was produced by the freezing and thawing of the infiltration water, and further aggravated by contamination with de-icing chemicals (silt), the research focused on a practical method of cleaning the interior cavities of the wall of silt, and the design of an injectable grout with improved resistance to freeze-thaw cycling and chlorides. With no available space for the required mechanical room, the another major challenge for the team was to excavate into the bedrock below the building and to create a large mechanical room. While maintaining the Reading Room floor slab in place, including the historical and fragile book stacks, a 21.5 m diameter and 8.9 m deep volume was excavated (Fig. 3). The number of support columns was reduced by replacing the 2743 mm grid with a 8230 mm grid. This work was integrated with the construction of an underground link to the House of Commons loading dock, extension of the elevator to serve the link and mechanical room level, as well as extension of another stair to serve as a second emergency egress route from the new lower level. The mechanical duct work distribution system was routed through sloped holes drilled into the rock, to bring the ducts from the mechanical room to locations below the vertical air shafts distributed throughout the building.

2 REHABILITATION AND CONSERVATION OF STONE MASONRY

2.1 Condition of masonry

The ring walls are founded on a massive coursed rubble crystalline bluish limestone foundation laid directly over the leveled limestone bedrock and forms an underground level base approximately 2 m in height. The foundation wall blocks are quite large, approximately 600 mm in bed depth and about 1200 mm long. The inner and outer foundation ring walls are approximately 1200 mm and 1500 mm in thickness. The blocks were apparently laid using imported English Portland cement mortar. The wall was constructed slightly oversize in plan to accommodate final layout adjustments to the main walls above, and this created an irregular ledge about 100–300 mm in width around the perimeter once the accurately laid-out upper walls were constructed. The joints between the blocks have been severely eroded by the flow of water down through the wall and were re-grouted in 1953 using a proprietary Portland cement grout. A metallic cementitious waterproofing render was applied to the inner face of the outer wall at the same time. The foundation walls were initially thought to be in relatively good condition but extensive voiding was later found to exist between the blocks where the bedding mortar was reduced to a sandy consistency.

The outer ring wall is constructed of an inner rubble shale facing, a concrete core of hydraulic lime mortar and limestone rubble, and an outer facing of coursed rubble cream-coloured Nepean quartzite sandstone trimmed with moulded light brown Ohio sandstone and red Potsdam sandstone. The core mortar consisted of a mixture of two-parts hydraulic lime and five parts sand.

The exterior joints have been repointed in a variety of cement-based mortars. In 1953 extensive Portland cement pressure grouting of the buttresses and foundation walls was undertaken to fill voids. The rubble facing of Nepean sandstone was originally pointed with a dense mixture of equal parts of brown hydraulic lime, forge ashes and iron scale to provide a black jointing treatment. Water overflow from the eaves resulted in frost action repeatedly forcing out the jointing in the first few years after pointing. The original pointing was replaced with a succession of mixes leading up to a recently installed lime-rich Portland cement mix. The joints around the mouldings were pointed with a matching colour mortar. At our initial inspections in 1989 the jointing on the lower walls and buttresses was found to be cracked, loose, missing, moss-filled, damp, delaminating and unsound. There also were large upper areas of tight, dense, hard Portland cement pointing that was tightly adhered to the stone blocks but obviously stressing the adjacent masonry and causing fracturing of arisises. The Ohio sandstone masonry window trim was found to be in good condition at the upper levels but was in progressively poorer condition at the lower levels, especially at the main doors and to each side of the stair gables where rain water dripped down from the roof and caused serious damage to the masonry.

Behind the pointing mortars of the lower walls the bedding mortar was found to be seriously damaged with a zone approximately 200 mm deep where the mortar had been reduced to sand in several locations. The walling around several window surrounds was found to be hollow and sand filled. We determined that water infiltration from roof leakage and open wall joints was percolating down through the walls and dissolving and carrying away the lime binder leaving a sandy residue and allowing the outer core of the wall to settle slightly and thus compress the outer face of the
masonry. During winter conditions the saturated walls and buttresses freeze resulting in the formation of ice-lenses in the wall and cracking of the outer joints. The exterior joints go through some one hundred freeze-thaw cycles each year which progressively cracks and deteriorates the mortar joints within a 100 mm space from the face of the walling. When the ice lenses melt in the spring the voids fill with silt and sand from the deteriorated mortar above within the wall, thus progressively weakening the assembly and slowly jacking the walls outward in places.

Large quantities of rock salt (sodium chloride) is used in the winter to melt snow on the service roads that run around the base of the building. The salt sprays onto the walls and is absorbed into the joints and masonry. The hygroscopic nature of the salt results in a state of continuous dampness in the outer walls and the salt crystallization cycling results in spalling and delamination of the surface of the weaker Ohio sandstone trim. The masonry trim around the main entrance has in fact been destroyed by salt action. The quartzite Nepean facing however is not seriously affected by the salt.

The masonry is lightly-soiled overall with some heavy accumulations under the sheltered cornices. Most of the soiling was a result of heavy atmospheric pollution from the pulp and paper mill that previously existed directly across the Ottawa River, which the Library overlooks. The sulphuric acid aerosols tend to penetrate the fissured surface of the masonry and react with the leached calcium carbonate from the lime mortar, forming gypsum crystals that disaggregate the crystal structure and subsequently cause deterioration of the stone. Pollution reacting with calcium carbonate has created over time a thin, relatively-insoluble gypsum crust on the surface, laden with black particulate matter. This insoluble gypsum crust seals the capillaries in the stone, retarding normal evaporation. This permits the fine capillaries to fill with water and subjects the stone to thermal stressing when heat is applied, eventually spalling off the crust and leaving a raw surface. Water comes from internal vapour and under-roof condensation, and from exterior joint cracks and roof overflow. Large areas of the Nepean stone have lightly exfoliated and appear clean. A relatively-harmless thin black crust covers most of the upper Ohio sandstone blocks, but the lower blocks and weatherings are all covered with a dense outer crust covering a powdery subsurface zone which is blistering-off through frost, heat and crystallization pressure.

The interior ring wall is composed of an inner, plastered brick lining, and a core of hydraulic lime and limestone rubble concrete, and a facing of Nepean quartzite sandstone rubble with Ohio sandstone window surrounds and decoration identical to the outer ring exterior face. The upper masonry is generally in better condition than the lower work with the exception of the rubblework above the cornice blocks, that has been found to be in seriously eroded condition due to water infiltration at the eaves. Upon removal of the leaded glass and inner wooden sash the areas of the Ohio sandstone window jambs concealed behind the glass were found to be in poor condition due to freeze-thaw damage.

2.2 Investigations

In order to understand the internal condition of the walls a series of investigations were carried out during the initial stages of the design work on the Library. A comprehensive set of Design Guidelines had been prepared by the Heritage Conservation Program staff in which a discussion of previous repairs and maintenance on the building and an outline of recommendations for work were presented. Of particular interest was the observation that the building had been repointed at least ten times and the buttresses had been cement-grouted once in 1953. And the repointing was done when the walls were in poor condition, meaning that the joints had been open for some time leading up to the repointing works and serious deterioration of the core of the walls was inevitable.

A one metre square section of outer ring wall masonry near grade was dismantled to review the condition of the core. The core rubble concrete was found to be quite sound but a zone of disintegrated mortar was found behind the smaller facing blocks. Most of the facing blocks were tenaciously bonded to the core.

Ten core samples were taken at a range of heights up the sides of two adjacent buttresses and wall. As we suspected that significant cavitation of the buttresses had occurred we recommended that the buttresses be partially grouted in the core areas before coring. This would stabilize the core where disaggregated and thus allow the removal of a solid core sample for review. The core locations were grouted with a proprietary cellulose stabilized hydraulic lime grout (Unilite B) and cured for seven days before coring. Inspection of the cores and video inspection of the core holes revealed that the walls were substantially sound but: (1) the zone behind the face and inner lining blocks was seriously disaggregated; (2) an extensive matrix of cavitation was present in many of the areas; (3) traces of the 1953 grouting campaign were found to be solid and well bonded but did not fill the smaller cavities; and (4) the core concrete consisted of large lumps of limestone rubble in lime mortar. An additional core was taken without pre-grouting in the upper inner wall. The conditions were found to be identical to the lower wall but it was noted that all the drill water disappeared into the core of the wall.

Given that cavitation of the core of the buttresses had occurred it was recommended that the
compressive stress in the facing blocks be determined. Flat-jack testing (ASTM C-1196) was carried out by a testing agency at five locations and it was found that the stress levels ranged from 1.8–3.3 MPa. The calculated theoretical stress levels should have ranged from 0.16–0.20 MPa. It was determined that significantly high compressive stresses were occurring in the outer facings and (1) the buttresses were not carrying a properly distributed load; (2) loadings on opposite sides of the buttresses were not evenly balanced; and (3) any dismantling of buttress facings should be done with extreme caution.

Further evaluation of the core of the walls using ground penetrating radar was attempted but this method was unable to provide useful information given the relatively complex matrix of materials within the walls.

It was obvious that a method of consolidating the masonry using a lime-mortar-compatible grout and providing the exterior wall joints with a vapour-permeable yet frost-resistant mortar was required to stabilize the masonry and prevent further deterioration.

2.3 Grout research program

Investigation into the condition of the masonry walls of the Library resulted in the conclusion that consolidation of the core of the walls was required to evenly distribute seismic loading, adhere the inner and outer faces to the core, consolidate the sandy residue within the walls and stabilize the lower walls to allow underpinning and rock removal operations under the foundations. Injection grouting of the core appeared to be a method of achieving these aims whilst minimizing intrusive rebuilding operations. A review of commercially available grouts indicated that achieving technical performance criteria matching that found in the existing masonry in a grout was not possible.

Significant bond strength development in the grout is not required, and the lateral forces on the walls are extremely low, but there is a need to adhere the delaminated inner and outer faces of the walls to the core. Conventional cement grouts tend to shrink and delaminate from weak core material such as lime mortars, the grout therefore should be slightly expansive to counteract shrinkage and possess a degree of tuckiness to adhere to the soft lime mortar during the initial curing process. Verification that adequate bond develops within a 90-day cure time was required. As the deteriorated interface failed primarily through the action of water flowing through the walls and frost action on the damp mortar, it was believed that it was essential that the grout has good frost resistance. Air-entainment of the grout was therefore thought to be essential. Verification of the degree of freeze-thaw resistance was required.

A test programme for the development of a suitable grout was developed by our in-house testing laboratory. Review of the literature indicated that research at ICCROM related to the re-attachment of mosaics to lime core walls suggested that a formulation using hydraulic lime and fine aggregates might be suitable. Several formulations using diatomaceous earth and a filler to control shrinkage when combined with suitable stabilizers and fluidisers appeared to be suitable for use on the Library. A comparison of polyvinyl acetate and silica fume modified hydraulic lime grout mixes identified in the report were chosen for evaluation. An outline of formulation development methodologies and a summary of procedures and tests was developed that could be used to verify the characteristics of these basic formulations to determine if the ICCROM formulations could be adapted and made compatible with the mortar core walls of the Library.

The initial formulations for the grout consisted of 4-parts hydraulic lime: 2-parts fine aggregate: 4.5-parts water. This would be tested with the following additive combinations: (1) plasticiser, PVA and expansive admixture, and (2) superplasticizer, silica fume and expansive admixture. St. Astier NHL 3.5 hydraulic lime was chosen for the initial evaluation, and Riverstone, Jura and Unilit hydraulic limes would be evaluated after a stable and suitable formulation was developed.

The initial performance criteria for the grouts were established as follows: (1) Flow (ASTM C-939) less than 25 seconds; (2) Bleed (ASTM C-940) nil; (3) Initial set (ASTM C-953) 48 hours; (4) Shrinkage (Quick Method) nil; (5) Sand Column Injectability (NF P-18-891) 360 mm in 60 seconds; (6) Compressive Strength (ASTM C-942) 1.5 MPa at 28-days; (7) Splitting Tensile Strength (ASTM D-3967) 0.15 MPa.

After selection of a final mix for testing the following additional performance criteria were tested: (8) Water Retention (ASTM C-941) 20 minutes; (9) Compressive Strength (ASTM C-942) 5 MPa at 90-days; (10) Splitting Tensile Strength (ASTM D-3967) 3 MPa at 90-days; (11) Vapour Permeability (ASTM E-96) greater than 5.3 gm/m²/day; (12) Shrinkage (ASTM C-531) less than 2%; (13) Rubble Column Injectability (NF P-18-891) 360 mm in 60 seconds; (14) Air-void Content (ASTM C-457) paste-to-air factor 4–10, specific surface 24–43 mm⁻¹, and spacing factor 0.1–0.2 mm; and (15) Bond Wrench Strength (ASTM C-1072) 0.5 MPa.

Grouts were mixed in five litre batches using a laboratory high-shear mixer at greater than 8000 rpm for six minutes then transferred to a low speed mixer at 150 rpm until use. Samples were to be damp cured for seven days in a 98% relative humidity environment then burlap-covered and damp-cured at 50% RH for 28-days.
The laboratory testing was carried out by an independent testing laboratory. The initial testing process identified the following problems with the initial material selection and mixing methodology: (1) air-entrainment caused serious foaming problems and was eliminated; (2) PVA emulsions created clumping and retarded set problems and was eliminated; (3) naphthalene sulfonate-based superplasticisers retarded set and were replaced with a polycarboxylate type that provided suitable results; (4) shrinkage reducing admixtures were found to be unnecessary with a stable grout and were eliminated; (5) silica fume required very high speed mixing (15000 rpm) to achieve mix segregation and stability; and (6) short mixing time is required to control mix temperature.

Some forty mixes were eventually tested to achieve a stable and properly performing mix. The slightest change to the formulation would lead to extreme variation in performance. The final formulation was based on the following criteria: water to binding-agent ratio 0.9; water to fines ratio 0.8; Binding agent to aggregate ratio 7.6; silica fume 1% by weight; superplasticizer 2.3% by weight. The components were Hydraulic Lime NHL3.5; Dicalite UF; Force 10000 silica fume; and Grace Adva 100. Two formulations were tested, one with entrained air in the hydraulic lime and one without. The entrained air mix was about 20% weaker in compressive and tensile strength but both passed the performance criteria. Questions were brought forward related to the acceptability of the air-entrainment matrix which appeared to be not stable when compared to standard concrete evaluation criteria, but this did not take into consideration that the grout would be mixed with sand residues in service. The bond results were excellent with the breaks occurring in the grout and not at the stone to grout interface.

Similar mixes were evaluated using Riverton and Unilit hydraulic limes with acceptable preliminary results. The grout was not tested at this time for freeze-thaw resistance. The tendered grouting package contained this formulation and required the successful grouting contractor to verify and modify the formulation using site equipment to achieve a workable mix.

2.4 Mortar Research Program

The Joint Venture Architects recommended to Public Works and Government Service Canada that an hydraulic lime based mortar be used for all rebuilding and repointing work on the Library of Parliament. This recommendation was based upon historic precedent, site investigation findings and contemporary technical performance requirements. Due to the specific nature of the colored mortars required for the Library it was found necessary to verify by testing that the proposed mortar mixes met all the performance and aesthetic requirements.

The high porosity of the original hydraulic lime core mortar indicated that the pointing mortars should have similar or higher porosity to allow the migration of water-vapour to the exterior. The Nepean quartzite wall facing is relatively impervious and directs most water vapour out through the joints and adjacent Ohio sandstone mouldings. The Ohio sandstone is however quite permeable and tends to wick water-vapour out through the face of the stone. The molded face increases the surface area significantly. Where the joints are impervious, this tends to drive all the water-vapour out through the moulded window trim, and this has resulted in extensive failure of the faces of this relatively weak stone.

A programme of mortar testing was developed by a Masonry Group committee consisting of members of the consultant team and technical staff from PWGSC, the Heritage Conservation Program and the National Research Council of Canada. A testing agency was retained to carry out verification testing of the following 8–10% air-entrained mortar mixes: (1) NHL3.5/ Buff granitic-aggregate 1:3 ratio; (2) NHL3.5/ Black granitic-aggregate 1:3 ratio; (3) NHL3.5/ Red crushed-brick aggregate 1:3 ratio; and (4) White Portland Cement/Lime Putty/Buff granitic-aggregate 1:2:7 ratio. These mixes represented the best-best formulations for each required mortar type and a control mix of conventional cement-gauged mortar.

All aggregates were coarse well-graded materials. Hydraulic lime was St. Astier NHL3.5 with a factory-blended aliphatic hydrocarbon insoluble (Vinsol) resin. Lime putty was made from a Type SA (Special/Air-entrained) dolomitic hydrated lime.

All mixes were prepared in the laboratory and tested in a plastic state to the following standards and criteria: (1) Flow (ASTM C-230) 50%; (2) Consistency (ASTM C-780) 20–25 mm; (3) Water Retention (ASTM C-230) 80–90%; (4) Wet Air Content (ASTM C-231) 10–12%; Samples were then prepared and damp cured and tested in a hardened state to the following standards and criteria: (5) Compressive Strength (ASTM C-109) 28-day 1.5 MPa and 60-days 3.5 MPa; (6) Air Void (ASTM C-457) 10–12%; (7) Flexural Bond (ASTM C-1329) 0.3 MPa; (8) Drying Shrinkage (ASTM C-1148) less than 1%; (9) Water Vapour Permeability (ASTM E-96) 5.34 gm/m²/day; and (10) Freeze-thaw Resistance (prEN 772-22) intact after 100 cycles.

Testing indicated that while most criteria were met an wet air-content over 9% could not be achieved and the dry air-content was in fact only 5%. Flexural bond was also very low (0.02 MPa) on all mixes. And freeze-thaw resistance was poor with all samples failing the 100 cycle test. The cement-gauged mix performed well and achieved the promised 12% air-entrainment.
A second series of tests was undertaken using NHL5 hydraulic lime and additional air-entrainment to provide 12–15% air-content. A wet air-content of 15% was achieved on all mixes but it was found that the black granite aggregate mix only achieved a dry air-content of 6%. All the mixes passed the freeze-thaw test with no surface erosion. The bond strength improved marginally (0.1 MPa) but still was poor. It was later found that the freeze–thaw specimens were intimately bonded after testing at 90-days and required a chisel and hammer to break the joints.

We determined that: (1) significantly higher levels (15%) of wet air-entrainment are required to produce frost-resistant mortars; (2) higher flow and consistency (25–30 mm) values are required to achieve good initial bond; (3) prolonged damp curing (50–70% RH) curing is required to develop carbonization and hardening of the lime; (4) significantly lower dry air-content values are found in mortars that have been worked; (5) compressive strengths after one year are approximately three-times the 28-day result; (6) prolonged damp curing of hydraulic lime mortars is essential to limit shrinkage and develop bond; (7) good permeability values are achieved with hydraulic lime mortars; (8) ASTM bond testing methods are too aggressive for new HL mortars; (9) air-entrainment values of over 12% are required to ensure good initial freeze-thaw resistance; and (10) NHL5 hydraulic lime is required to provide frost resistance after a 60-day laboratory cure.

Testing indicated that high permeability and moderate strength could be achieved through the use of either a Portland cement/Lime Putty/Aggregate mix in the ratio of 1:2:7 or an Hydraulic Lime/Aggregate mix in the ratio of 1:3 while still maintaining adequate technical performance including excellent freeze–thaw resistance and low compressive strength. The recommendation was made to use an hydraulic lime-based mix primarily on the aesthetic basis that hydraulic lime mortars age more gracefully than Portland cement-gauged mortars and also are historically appropriate.

2.5 Conclusions

Although the initial site evaluation testing of the walls indicated that the core of the walls was in good condition, further investigation indicated that serious voiding and dissaggregation of the core of the walls had occurred. Field work subsequently revealed that the cavitation problem was systematic throughout the walls and the voiding was in excess of 8% by volume, almost three times the pre-construction estimate, and has required over 180 tonnes of grout to consolidate. Consolidation of the masonry was essential as the seismic analysis had found the stability of the structure to be marginal while assuming a masonry wall of solid construction.

Field verification testing of the grout mix design proved to be difficult as the grouting contractor had no experience with hydraulic lime grout. A suitable mix was developed after five sessions of multiple tests. The following issues were noted: (1) high speed (3000 rpm) high-shear equipment with a large mixing rotor (300 mm) and a ten minute mixing time was required to disperse the silica fume and produce a stable mix; (2) finding a stable mix that will penetrate a sand column was difficult as variations in any component will create major changes in characteristics; (3) different types of hydraulic lime performed differently; (4) factory blending of the final mix was essential to provide consistency of mix in the field; and (5) air-entrainment of a grout with good penetration qualities is not possible. The final test results using Riverton NHL2 were as follows: (1) Flow: 12 seconds; (2) Expansion and bleed: nil; (3) Set time: 4 days; (4) Linear Shrinkage: 0.2%; (5) Unit Weight: 1557 Kg/m³; (6) Compressive Strength: 7-days 1.6 MPa, 60-days 8.7 MPa; (7) Air Content wet 0.7%, dry 2.4%.

Field verification of the mortar mixes by the contractor resulted in the following modifications: (1) factory-blended pre-bagged air-entrained hydraulic lime and aggregate mixes was used for quality control; (2) hand-held high speed mixers were used to prepare 20 litre batches of mortar on the scaffold as required.

3 STRUCTURAL ASPECTS OF THE UPGRADING

3.1 Underground mechanical room

Construction of a mechanical room below the Reading Room slab required excavation of a large volume of rock, and a significant reduction in the number of columns supporting the ground floor slab. It was determined at an early stage that the Reading Room slab must be retained in place to avoid removal of the fragile book stacks, and also to allow conservation and rehabilitation work to proceed above this level during the construction of the Mechanical Room below. It was also decided to increase the head room in the two basement levels of the building in order to meet current code requirements and allow a more efficient use of the space.

The first design decision was to increase the column grid from 2743 mm to 8230 mm, this way reducing the number of columns from 76 to 12. A new steel beam grid was specified below the slab on a 2743 mm grid, allowing this way to maintain the same support points for the concrete two way slab, and retaining the slab as found. The new columns were placed at the locations of the existing columns, which created some additional temporary shoring challenges, but allowed maintenance of a regular grid. Eight of the new columns (the perimeter columns) were placed close to the inner ring wall, on a rock ledge just below Level 0 slab (approximately 2000 mm below the underside of the ring
of the base plate to allow placing of the concrete into the caisson. Concrete was placed only after the final alignment of the column, and included both the caisson and the interior of the steel pipe column. A lean concrete mix was placed between the steel column and the rock, in order to provide lateral stability for the column during the following phase of construction.

The following phase of construction was the installation of the Reading Room slab support grid, spanning between the 12 new columns. Some of the new steel beams were cambered to compensate for the calculated deflection. All the beams were installed with temporary shoring of the slab. Support plates were installed between the beams and the underside of the existing slab exactly where the cast-in steel plates were left behind after removal of the original columns. The loading was transferred from the temporary shoring to the new steel grid by jacking at pre-determined locations until the calculated deflection was induced into the new beams. The slab movements and book stacks above the slab were monitored at all times. This operation was followed by the demolition of Level I slab, and installation of temporary lateral braces for the four central columns, from a location just above the top of the rock (above the future Level 0 slab) to the new steel grid below the Reading Room slab. During this time, book stack woodwork conservation activity continued above in the Reading Room in an air conditioned space, with plaster and stone conservation activities continuing within the dome space above.

The next phase was the excavation of the new Mechanical Room (Fig. 6), a circular space of approximately 21.5 m diameter and 8.9 m deep. This excavation was part of a long list of similar items which included the loading dock link, elevator extension, new stair access, and mechanical distribution shafts. The excavation, rock stabilization and monitoring was designed by the geotechnical consultant. All the excavation was by mechanical means: drilling, rock splitting, hoe-ramming. The rock faces, the Library
and the adjacent historical buildings were monitored at all times for movement and vibration levels. Monitoring equipment included extensometers, jointmeters, strain gauges, convergence monitors, inclinometers, tilt beams, piezometers. For the Mechanical Room, the excavation proceeded in 2 m deep concentric lifts. It was coordinated with local underpinning of the inner ring wall, and other excavation items. Finally, the inclined distribution shafts were drilled, by the raise bore technique, for the mechanical distribution system.

The final construction phase included construction of the reinforced concrete walls of the Mechanical Room, placing of a reinforced concrete jacket around the columns, and construction of Level 0 and Level 1 reinforced concrete slabs. The temporary lateral braces of the central columns were removed after the placing of Level 0 slab.

3.2 Mechanical distribution system

Finding appropriate routes for the mechanical distribution system was a major challenge for the entire team. The building contains four climatic control zones, each with strict temperature and humidity requirements, plus the complication of getting air to optimum locations within the Reading Room open space. Level 0 and Level 1 over the Mechanical Room are fed directly by a standard vertical mechanical shaft. The Reading Room is supplied by a large number of flat ducts located in the narrow space available between the book stacks and the inner ring wall, bringing air to the top of the stacks, with the return system located in the slab, and built into the furniture.

The most challenging system was for the perimeter office space. Seven diagonal shafts drilled into the rock (diameter between 800 and 1200 mm) together with seven vertical shafts (1500 mm diameter) provide the connection between the Mechanical Room and the perimeter offices space. They host ductwork, sprinklers, plumbing, and other mechanical and electrical systems. The diagonal shafts were drilled from outside the building using raise-bore equipment, up to the meeting point with the vertical shafts. From this location, the ductwork is placed on the rock, in a crawl space below the lowest floor level (the lowest floor level is a structural suspended slab). With no headroom for a horizontal distribution duct work system, the vertical supply risers are distributed uniformly throughout the floor plan – with one semi-recessed shaft behind every buttress, in the tension zone of the buttress. The majority of the shafts are recessed only in the concrete liner placed in 1953, therefore with minimal impact on the stone masonry walls. The buttresses were pressure-grouted before cutting any slots. The return air ducts were partially recessed in the brick masonry walls, at each side of the four stair shafts.

Increasing the number of mechanical risers significantly reduced their size, and good overall coordination within the design team limited the impact on both the heritage structure and on the space functionality.

3.3 Underpinning of stone masonry walls

New floor levels were constructed below the Reading Room (Level 0 and Level 1), while the floor levels of the perimeter offices were retained. Used as book storage, these two new levels required leveled access to the elevator. Therefore, the slab in one quadrant of the perimeter office space, on Level 0 and Level 1, was lowered to match the new interior space. While reconstruction of Level 1 slab at the new elevation did not result in any structural complications, the new elevation of Level 0 slab was below the underside of the inner and outer ring walls. In addition, the crawl space for the mechanical distribution system had to be maintained. This required an overall excavation of up to 2 m below the bearing level of the masonry walls. The condition of the rock was found to be weakened by a large number of joints, and significant fragmentation. Therefore, it was concluded that the inner ring wall, with excavation of both faces must be underpinned, while the rock below the outer ring wall could be stabilized with pre-reinforcing dowels and tie back rods.

A 1-2-3 underpinning sequence was specified (Fig. 7). A trench was excavated in the middle section.
along the perimeter office, while the inside area was lowered as part of the Mechanical Room excavation. Trenches perpendicular to the inner ring wall were extended to the face of the wall on both sides, not exceeding 1200 mm width. Needle beams at 400 mm centers were installed in cores drilled into rock just below the underside of the walls, and hung from the underside of a steel beam bearing each side of the trench. Considering significant deterioration of the wall rubble core, it was a concern that pre-grouting would not be sufficient to ensure the integrity of the wall and sections of wall might fall into the excavation. After the installation of the needle beams, the rock below the wall section was removed and replaced with unreinforced concrete. The joint between the top of the concrete and underside of the wall was dry-packed a few days after placing of the concrete, in order to allow for the initial shrinkage. The procedure was repeated for the stage 2 and 3 sections.

3.4 Conclusions
Remodeling and upgrading of heritage buildings to meet modern code and functional requirements is possible. It requires a team approach within the design team, as well as continuous supervision and collaboration during the construction phase. Architects, conservators and engineers of different specialties must work together, understanding each other requirements, and search for innovative ideas in order to satisfy the Client’s needs. Design assumptions must be confirmed by further exploratory work and confirmation all the time during the construction phase, as a variety of site conditions are revealed.

The construction of the new Mechanical Room required extensive coordination, review and detailing of step by step construction activities, and on going quality control and supervision. Good communication with the General Contractor’s team, Fuller Construction (Ottawa), ensured a smooth implementation of the design.

Underpinning of large loadbearing masonry walls is possible only with a good understanding of actual soil conditions. The procedure must be tailored to such conditions, and must ensure full control of the wall, or sections of the wall, at all times. It is a good practice that any temporary support element be removed from the wall after the completion of the work.

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REFERENCE
