Geometrical and material characterization of old industrial masonry buildings in Eastern Canada

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Abstract. The benefits of repurposing existing constructions are recognized by provincial legislation for their potential in achieving sustainable development goals. In recent years, adaptive reuse projects in Eastern Canada targeting seismically vulnerable old buildings, especially those once used by local industries and featuring unreinforced masonry members, have significantly increased. When major renovations are planned, however, the objectives set by the National Building Code of Canada require old buildings to achieve the same seismic performance of modern ones. As a result, and because of the lack of ad-hoc guidelines and the limited knowledge of traditional construction methods, local engineers are prompted to design overly invasive retrofits or demolish/reconstruct entire sub-structures. To avoid such unsustainable practices, preserve the integrity of Eastern Canada's built environment and enable its responsible reuse, this research aims to increase knowledge about the response of old unreinforced brick masonry industrial buildings. These results can aid in the classification of typical old industrial masonry buildings and uncover key structural characteristics and quantify their seismic performance, providing essential yet presently missing data to engineering professionals and researchers involved in seismic upgrading projects. First, archival resources are used to track the evolution of structural systems, architectural features and employed materials at the regional scale, enabling us to identify representative building assets at the municipal level. Targeted onsite surveys are thus conducted to evaluate structural conditions and material properties, as well as to create high-fidelity digital geometries, through visual assessment, non-destructive testing and 3D laser scanning. Informed seismic analyses can then performed via numerical modeling, providing insights on recurrent failure mechanisms, displacement and base shear capacities. In this paper, the proposed holistic methodology is applied to two case study buildings located in Montréal and preliminary results are presented. The results presented herein will allow for identification of more sustainable, less invasive but equally performing seismic retrofit measures, tailored to the unique characteristics of the local old industrial masonry structures.

Keywords: unreinforced masonry, non-destructive testing, seismic assessment, industrial buildings

1 Introduction

While the potential impact of a damaging earthquake in Eastern Canada is considerable, limited studies have been conducted on old unreinforced masonry (URM) buildings. These structures are highly vulnerable to earthquakes and their response to Eastern Canada's unique seismicity has largely not been characterized [1], [2]. Old URM buildings (*pre-code* or *low-code*, i.e. constructed prior to the release of robust seismic provisions [3]) are an integral part of the local existing building stock. However, existing codes and guidelines in Canada do not adequately address seismic evaluation procedures for existing URM structures. Limited applicable research has been completed for the seismic assessment of old URM buildings in Eastern Canada, mostly focused on isolated case studies [4]–[6]. Unlike most other earthquake-prone countries, updated technical standards on old URM buildings are presently missing in Canada. To add to the understanding of the seismic behaviour of Eastern Canada's old URM buildings, structural data and characteristics are necessary to continue to protect existing buildings. This information will also continue to make our built environment more sustainable and diminish barriers faced by practitioners and researchers when working with these structures. A 5-year research project is currently being conducted at McGill University to develop a baseline of information useful for the seismic assessment of old URM structures, including a comprehensive analysis of the properties and components of typical Eastern Canada's old URM building stock. This paper presents preliminary results of geometrical and material properties of two archetypical old industrial URM buildings in Montréal: the Craig Pumping Station (1887) and the Rue Saint Patrick's building (1915). These structures were chosen based on a recently conducted typological analysis of the evolution of industrial building structural typologies in Eastern Canada [7]. This paper also presents the archival resources utilized in analyzing Eastern Canada's industrial history and architectural trends, which informed the case study building selection included in this research.

At this early stage of the project, evaluation of the geometrical and material properties involves onsite non-destructive evaluation (NDE) as well as lab destructive testing on original samples (units, masonry prisms/cylinders or walls) extracted via minimally invasive (e.g. core drilling) or targeted demolition techniques (**Fig. 1**). We plan to use destructive test data of key materials to calibrate NDE tools as well as to better understand features of old units, mortar and URM in controlled conditions.

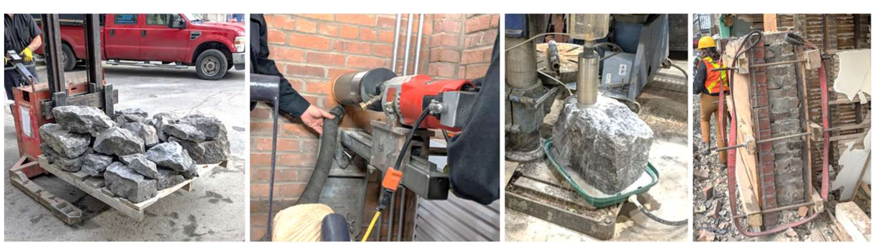


Fig. 1: Examples of specimens extracted onsite to be tested mechanically in the lab

NDE allows for the understanding of structural functioning and traditional construction techniques for properties of materials, building components and assemblies without causing damage, yet have not widely been applied in Canada for seismic evaluation purposes [9]. NDE including 3D laser scanning, Ultrasonic Pulse Velocity (UPV) and Schmidt Hammer Rebound (SHR) testing is used and discussed in this preliminary study. Accurate geometrical analysis of old structures is fundamental to corroborate onsite visual inspection and reduce epistemic uncertainties in seismic assessment. The geometrical assessments conducted in our research rely largely on terrestrial laser scans, resulting in high resolution point clouds to understand and map pre-existing damages as well as accurately measure complex building geometry for future use in numerical modelling. Terrestrial laser scanning is a remote sensing technology that uses high spatial sampling density to create point clouds, complimenting traditional survey methods and digital photogrammetry with the ability to interface in numerical models and computer methods. It is widely used internationally for structural health monitoring of URM structures [10]–[12], crack detection [13], [14] and surveying for seismic evaluation [15], [16]. In Canada, laser scanning has been applied to scattered case studies [9], [10], [17]. UPV tests are herein used to determine P-wave propagation velocities to be correlated with unit compressive strength f_c from destructive tests. UPV is widely used in the evaluation of old URM [18], [19] and reinforced concrete [20], [21] structures. Compressive strength of units is also correlated with R value inferred via SHR testing. As UPV, SHR is commonly used in URM [22], [23] and concrete [24] NDE. We aim to derive simple correlation equations, presently missing in Canada, to enable the quick NDE assessment of unit compressive strength onsite via UPV and/or SHR.

In this study, we present preliminary results from laser scanning for both Craig Pumping Station and Rue St. Patrick buildings, as well as first outcomes from destructive uniaxial compression tests, UPV and SHR measurements taken from the stone units of the walls of Craig Pumping Station. In what follows, a brief summary of how old industrial URM buildings in Eastern Canada have evolved through time is also presented. Results from this archival research, indeed, support the typological analysis and narrow the focus onto a small selection of buildings representative of larger architectural and structural trends – something we are leveraging on in our research [7]. The case study buildings are chosen to represent different periods of industrial history of Eastern Canada in which the structural and material characteristics are necessary to further contribute to the seismic assessment of old URM buildings.

2 Old industrial URM buildings typologies of Eastern Canada

The transformation of local industrial structures from saw and grist mills to large factories has played a significant role in shaping the architectural styles of old industrial buildings in Eastern Canada. Prior to the release of the first 1941 National Building Code of Canada (NBCC), many architects relied on thumb-rules and know-how to inform their designs [25]. The development of more complex structural systems including skeleton concrete and steel frames in the late 19^{th} century marked the beginning the structural engineering discipline in Canada [26]. This section draws on archival research using pattern books, architectural journals, building plans, and insurance maps as an examination of the evolution of architectural forms in response to important historical events and environmental actions, displayed in **Fig. 2**. Understanding recurrent typologies can inform seismic evaluation [27], providing valuable information that remains mostly unexplored for Eastern Canada's old industrial URM buildings.

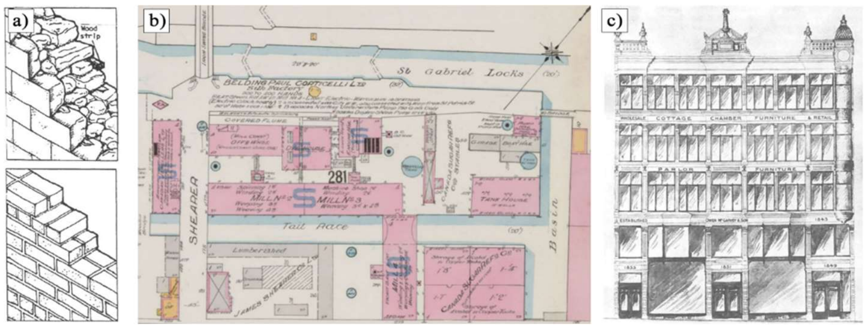


Fig. 2 Examples of archival resources a) URM walls construction example sections [28] b) fire insurance map, 1914 [29] c) sketch of Owen McGarvey Store and Factory (Montréal), 1891 [30]

Early Eastern Canada's structures were a combination of timber and masonry, designed to protect against cold winters using local and readily available materials. The designs were refined by existing knowledge of skilled builders immigrating from Europe. Rubble stone masonry walls were preferred by early settlers in New France to add thermal mass in addition to improved durability and fire resistance [31]. Stone continues as a popular construction material for all building types in Canada's growing cities throughout the 18th and 19th centuries [32]. However, brick buildings started to become more common as new domestic manufacturing technologies were developed in the Second Industrial Revolution (1860s-1950s) [33]. A decrease in unit-prices with increased manufacturing complimented by fire-proofing restrictions in city centers led to the increase in the production of brick structures in the mid 19th century [28], [34]. Brick buildings were first seen in Montréal in 1813 and Québec in 1830-39, yet until the middle of the 19th century clay bricks were primarily used for chimneys and fireplaces [34]. Loadbearing brick walls became common of industrial buildings in Eastern Canada due to the low unit cost and accessibility and remained a common structural system until the advent of the metal skeleton frame structure at the end of the late 19th century.

Typical loadbearing brick buildings utilized brick, wood, cast iron, wrought iron or a combination for the interior structure [35], [36]. Cast iron, a material known for its relatively low melting temperature and high compressive strength compared to other alloys, was introduced as a building material in Great Britain during the Second Industrial Revolution. Catalogues from the 19th and early 20th century show the transition of cast iron from ornamental [37] to structural uses [38]. Cast iron framing were typically composed of wrought iron beam and cast iron column systems, a combination that provided superior structural performance, albeit at a higher cost [26]. **Fig. 3** shows examples of the combined use of cast iron and wood in interior frames in connection to loadbearing exterior masonry walls.

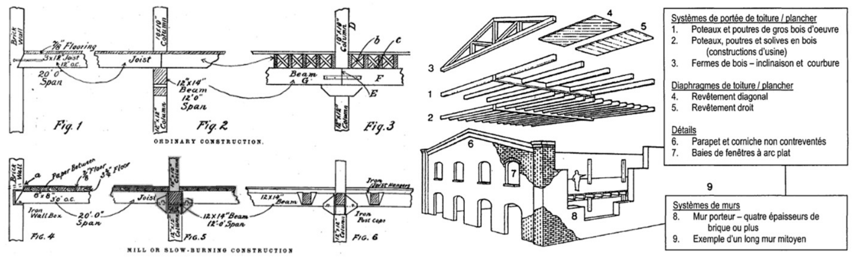


Fig. 3 Cross sections of typical industrial building construction using cast iron, wood and brick masonry (left) [39] and example of pre-1940 industrial URM building typology (right) [40]

At the end of the 19th century, steel and reinforced concrete became popular materials to work with in the United States as steel skeleton framing was used to build taller [26]. Steel in skeleton framing was popular in industrial buildings, able to span further than cast iron and wood, ideal for heavy industry sections which required large open spaces for manufacturing equipment [41]. Reinforced concrete was able to produce similar wide spans, and demand for these structures increased in the 20th century: in 1916 over 90% of new factories were built with reinforced concrete [42]. Through the course of Eastern Canada's history, industrial buildings transitioned from stone or brick masonry as primary structural materials to a more modern age of steel and concrete framing systems. This transition is observed in archival resources and is informing our selection of representative industrial URM building typologies in Eastern Canada.

3 Historical review of selected case study buildings

The Craig Pumping Station was constructed in 1887. The building is located in the southwest Montréal neighbourhood of Ville Marie, at the foot of the Sainte-Marie stream on Rue Notre Dame. Today, Rue Notre Dame is a highly trafficked road running beneath the Jacques-Cartier Bridge. The bridge was constructed in 1930 and resulted in the demolition of some of the buildings surrounding the pumping station around the bases of the bridge, leaving it isolated between traffic directions (**Fig. 4**) [43].

Fig. 4: Craig Station on Rue Notre Dame (left: 1921 [43], center: 1921 [44], right: 2020 [44])

The building is constructed of a three wythe masonry loadbearing walls with a face of ashlar limestone on the exterior façade, rubble masonry core and clay brick inside. The roof is made of a wood frame and additional steel beams and cast-iron columns are used for support of the roof and mechanical systems [44]. The Craig Pumping Station was part of a then-new sewage network of water lines in Montréal, designed to mitigate the impact of Montréal's regular spring floods, after a series of major floods in the 19th century which would leave neighborhoods underwater [45]. Major renovations by Montréal and Québec City to control the formation of ice jams and reduce spring flooding in the 1950s involved the construction of dams and the St. Lawrence Seaway. Shortly after, in the 1980s the Montréal Urban Community (MUC) modern sewer system was constructed. The diversion of sewage to a wastewater treatment plant instead of direct flow into the river as well as the controlled flooding, left the Craig Pumping Station obsolete [46]. The station sat abandoned for over 40 years until the fall of 2022 when demolition (for partial reconstruction somewhere else) began. The Craig Pumping Station was one of Montréal's oldest industrial URM buildings, built in one of the more prominent sectors of Montréal, as the Centre Sud-Ouest neighborhood attracted many growing industrial enterprises including the Molson Brewery and Canadian Rubber Company. Another prominent area for industrialization in Montréal is along the Lachine Canal, as the canal was constructed in 1824 during the First Industrial Revolution (1780-1850) in Canada. Emerging industries were commonly located along the canal to generate hydro-electric power and have access to shipping across North America and internationally [47], [48]. Due to the ability to connect people and goods across distant places, the area along the Lachine Canal was a hub for industry. By the end of the First Industrial Revolution, the majority of the new structures were built with clay brick masonry or wood structures, as industry was rapidly expanding and new buildings for manufacturing and storage were in high demand [33], [49]. Rue St. Patrick's building, located along the Lachine Canal is a clay brick URM structure with diaphragm-supporting timber frames and cast-iron connection elements, typical of other structures in the area. **Fig. 5** shows the exterior of the structure along with interior detailing.

Fig. 5: Rue St. Patrick's building exterior (North facing) and interior timber frame/URM details

4 Geometrical properties of selected case study buildings

Geometrical evaluation in this research was completed separately for both case studies. The point cloud data and Building Integrated Model (BIM) presented below (**Fig. 7**) for the Craig Pumping Station was commissioned by the City of Montréal to specialists and kindly shared with us to inform further analysis and our ongoing/future works.

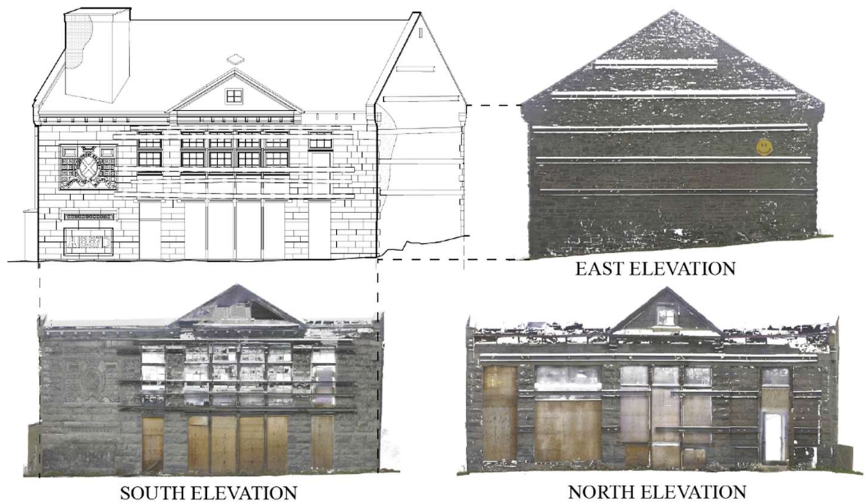


Fig. 6: BIM model and post-processed point cloud data – courtesy of the City of Montréal

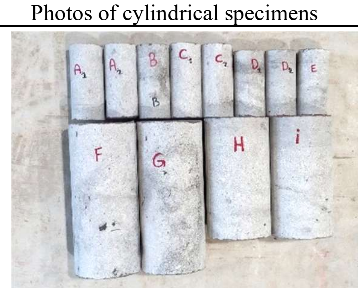
In the geometrical survey of the Rue St. Patrick's building, a laser scan of the structure was completed using our Leica RTC360. Laser scans were registered with scan-to-scan recognition and links to create a geometric network. The medium-density point could from the laser scan was post-processed to create an accurate geometrical model of the structure. **Fig. 7** depicts the setup of the Leica RTC360 and the resulting point cloud. The resulting precision of the point cloud is about ± 0.006 m. Further processing of these point clouds will inform accurate geometrical models for seismic evaluation.

Fig. 7: Laser scan setup (left) and point cloud results (right) of Rue St. Patrick's building

5 Material properties of Craig Pumping Station

In this section, the material properties of the stone units from the Craig Pumping Station are discussed. For Rue St. Patrick's building, tests are ongoing. The pumping station was built using a combination of limestone, brick and wood structural components. The wall sections were composed of an exterior stone wythe, rubble stone infill and interior clay bricks. The ashlar stone along the exterior façades are composed of fossiliferous crystalline limestone and the interior wythe is composed of fossiliferous crystalline limestone plus clayey limestone. Stones retrieved from the demolition of the structure were cored in the laboratory in cylinders of two diameters, 50mm and 100mm, in directions either parallel (‖) or perpendicular (⊥) to visible bedding planes. Cores were machined in the laboratory to various lengths to achieve an aspect ratio (length L : diameter D) of 2.0-2.4 (**Table 1**). Tests on rubble infills and clay bricks are ongoing.

Table 1. Cored cylinder dimensions, bedding direction and specimens' photos

ID	#	‖/⊥	D [mm]	L (mm)	Photos of cylindrical specimens
A	2	‖	49.8	120.8	
B	1	‖	50.1	120.7	
C	2	‖	49.5	121.6	
D	2	⊥	49.6	110.0	
E	1	⊥	49.9	110.0	
F	1	‖	99.8	241.0	
G	1	‖	99.8	241.7	
H	1	⊥	99.9	195.3	
I	1	⊥	98.7	197.6	

5.1 Ultrasonic pulse velocity results

UPV tests were performed prior to destructive compression testing, to be able to correlate UPV test results with strength properties. UPV testing was completed according to the ASTM D2845 standard with the TICO equipment by Proceq. Direct transmission testing was performed along the longitudinal axis of the cylinder and the average of five measurements was recorded. Direct transmission tests require the placement of two 54 kHz P-wave piezometric sensors on either end, where one sensor releases electric pulses and the other measures the time to receive them. A water-based lubricant was applied to the sensors to improve wave transmission. Results are displayed in **Fig. 8.**

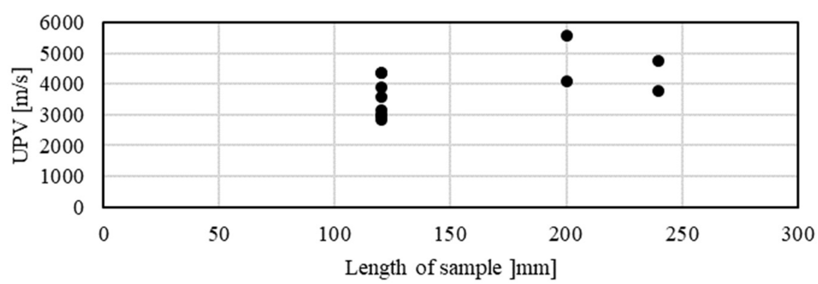


Fig. 8: UPV results versus sample length for stone cores of the Craig Pumping Station

In UPV measurements the parameters including ultrasonic pulse velocity, minimum length of specimen, frequency of the transducers and the grain size of the rock are interrelated. To obtain accurate measurements, the following equation (**Eqn. 1**) should be satisfied where D is the minimum lateral dimension of the sample, v is the ultrasonic pulse velocity and f is the transducer frequency [50].

$$D \geq 5(\frac{v}{f}) \geq 5d \tag{1}$$

The sample sizes of greater than 100 mm and transducers of 54 kHz satisfy this relationship. Results from the UPV tests display good correlation between sample lengths, and correlation values (c.o.v.) are less than 5% for all samples in terms of results in time and ultrasonic pulse velocity, despite varying degrees of anisotropy between samples cored parallel and perpendicular to the bedding plane.

5.2 Schmidt rebound hammer results

SRH tests were completed on each stone specimen, prior to destructive compression testing as for the UPV ones, where the average of five tests of the rebound (R-) value were recorded. The Schmidt original hammer Type L with an impact energy of 0.735 Nm, suitable for a compressive strength between 10 MPa and 70 MPa was used to test each stone specimen. R-values were recorded from the top face of each specimen, where index values were carried out at least 2 cm from the exterior face of the specimen. This test was completed according to the ASTM D5873. Results are depicted in **Fig. 9.**

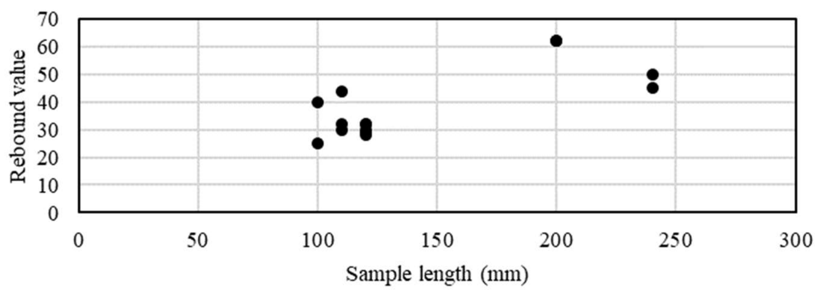


Fig. 9: Schmidt rebound hammer results on stone specimens of the Craig Pumping Station

The SRH results of each specimen display a variability that is inherent in the test. R-values recorded in specimens at each length varied between 1% and 33% difference. This recorded variation could be due to dissimilarities in the surface roughness and/or to the variability of stone toughness in the two selected coring directions.

5.3 Compression test results

Uniaxial compression testing was performed using a 1MN-capacity MTS Rock Machine, according to ASTM D2938. To reduce friction in testing, two 0.1mm Teflon sheets were placed between the actuator and the specimens, as suggested by Vasconcelos et al. (2009) [51]. An extensometer of 50 mm was attached to the 110 mm and 120 mm specimens, while a 100 mm extensometer was attached to the 200 mm and 240 mm specimens to measure axial displacement. Specimens were loaded in force control up to 30% of the expected compressive strength. First, four loading and unloading cycles were performed to measure the Young's Modulus. Then, after the attainment of the assumed target strength, a 0.002 mm/s velocity was applied in displacement control, to record the post-peak behaviour of each specimen. In **Fig. 10**, test setup and examples of damage patterns and force-displacement curves obtained (specimen B) are depicted.

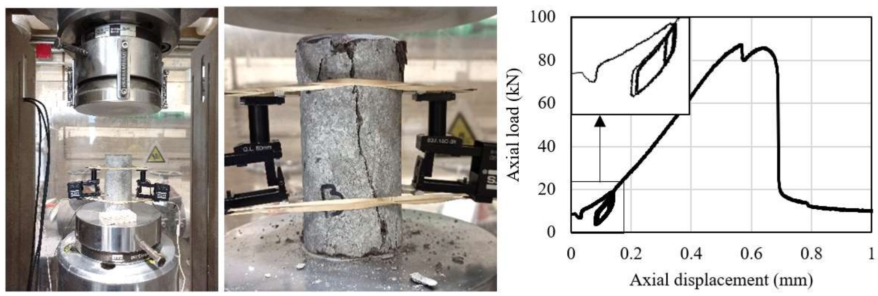


Fig. 10: From left to right: test setup, example of damage specimen and force-displacement curve

Specimens tested so far (diameter of 50 mm) exhibited vertical fractures and around 90 kN of peak compressive force, corresponding to a maximum of approximately 45 MPa. Current post-processing efforts will also reveal Young's modulus, Poisson ratio and fracture energy in compression of tested stone units. Further tests on other stone cylinders are ongoing and will be presented at the conference to inform professional and research communities. After these tests, we plan to correlate results with those inferred using UPV and SRH devices for creating a set of experimentally validated R-UPV-f_c graphs to support onsite NDE and future research.

6 Conclusions

Eastern Canada's industrial URM buildings are an important subset of the region's existing building stock. Despite the potential of low to medium magnitude earthquakes occurring in the area, existing building codes and guidelines do not adequately address the seismic characterization and adaptation procedures for old URM buildings. In this paper, preliminary results are presented as part of a research project designed to address the lack of robust seismic assessment guidelines, ongoing at McGill University. The results presented include geometrical characterization of two case study buildings typical of Eastern Canada's industrial buildings, according to a typological analysis completed by the authors. Geometrical data was extracted from terrestrial laser scans and the post-processing of high density point clouds completed for the creation of building elevations and future numerical models. Non-destructive UPV and SRH results are presented towards the stone material characterization of the Craig Pumping Station (1887) in Montréal. Additionally, monotonic compression results are presented, displaying preliminary results of an average 90kN peak-compressive force.

These results will allow for more sustainable and less invasive seismic retrofit measures to be identified and implemented. The geometrical and material characteristics allow for the unique characteristics of local old industrial structures to be explicitly accounted for in seismic assessment which in turn leads to tailored retrofit measures, which can save time and money in these projects. The results presented herein are a compilation of the preliminary measures accomplished as part of a robust research program which aims to continue to conduct non-destructive and destructive tests on masonry samples from archetypical buildings including stones, bricks, mortar and infill from old URM structures in-situ and in the laboratory. Future research will also include implementation of geometrical and material data compiled into numerical models to display seismic response and optimize seismic retrofit measures.

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