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SAFEGUARDING EASTERN CANADA'S OLD UNREINFORCED MASONRY BUILDINGS FROM THE SEISMIC THREAT: A STATE-OF-THE ART REVIEW

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Abstract: The impact of a damaging earthquake striking Eastern Canada's medium-to-high seismicity cities would be catastrophic. This is largely due to the predominant presence in populous urban centres of highly vulnerable old (or pre-code) unreinforced masonry (URM) buildings – a relevant share of schools, fire stations, power plants and heritage (or historic) constructions also at the national level – posing a serious threat to our safety, cultural values and economy. Past research, albeit informative, has not systematically nor coherently addressed this key issue yet, mainly focussing on individual case studies. Similarly, and despite the undergoing work of various building code committees and responsible governmental agencies on this front, dedicated national guidelines and standards are either incomplete or obsolete, leaving engineering professionals without clear guidance. In this paper, an effort is made to unify and critically review previous fragmented applications through the lens of the ISCARSAH Principles, a globally accepted framework for the classification, characterization and evaluation of URM structures only marginally adopted in Canada, enabling us to identify in a structured manner knowledge gaps, challenges and future research opportunities in Eastern Canada and beyond. This investigative state-of-the-art review will also provide researchers and practitioners with a high-level report on best practices and relevant examples from other seismic-prone countries, where ad-hoc guidelines for old URM buildings have been developed decades ago, while substantiating the current efforts of the newly formed CSCE Existing Structures Committee.

1 INTRODUCTION

A lower magnitude earthquake that strikes in vulnerable areas, such as densely populated urban centers in Eastern Canada, can still be catastrophic. This is particularly true for existing buildings made of unreinforced masonry (URM), which are highly vulnerable to even low-magnitude ground shakings and identified as the leading cause of seismic fatalities and economic losses globally (So and Spence 2013). Seismic events such as the 1988 Saguenay earthquake, occurred in Québec with a moment magnitude M_w=5.9, that have been recorded in recent years (Bruneau and Lamontagne 1994) pose a threat to Eastern Canadian cities' economic, cultural and structural integrity. The overall risk associated with these seismic events remains low in Eastern Canada for most modern buildings. However, old (or pre-code, erected before the first 1941 National Building Code of Canada, NBC) non-engineered constructions are predominant in many of Eastern Canada's major cities and pose a serious, yet overlooked, threat to the safety of our communities. In old Montréal alone, where 44% of buildings are old URM structures (Antunez et al. 2015), recent studies (Rosset et al. 2019) determined that the impact of a damaging earthquake would resemble that of the 2011 Christchurch (New Zealand) M_w=6.3 earthquake: 185 deaths, thousands of injured and $14 billion of direct cost (Potter et al. 2015). Further, 37% of hospitals, 25% of fire stations, 15% of power plants and 46% of schools in Eastern Canada are old URM buildings (McCaffrey et al. 2013) – this undermines disaster preparedness and recovery as well. Local old URM structures (see **Figure 1**) are also the majority of Canada's heritage buildings ("historic" hereinafter). Safeguarding historic assets is not only essential to preserve our cultural heritage and identity values, but also vital for protecting the national economy: heritage tourism generated $54 billion in 2019 (4% of domestic gross product), $38 billion in Québec/Ontario alone (Dept. of Canadian Heritage 2020). Preserving old URM buildings and thus allowing their reuse will also have a tangible environmental impact, avoiding demolition/reconstruction responsible for 20–50% of the annual municipal solid waste in Canada (Yeheyis et al. 2013). This is a goal strategically aligned with national (e.g., 2016-2027 Pan-Canadian Framework on Clean Growth and Climate Change, >$100 billion investment) and international commitments (e.g., 2020-2030 United Nation's Agenda of Sustainable Development). Despite past events confirming the seismic vulnerability of Eastern Canada's old URM buildings, and although preserving them contributes to the national economy and environmental stewardship responsibilities, their earthquake response currently requires a greater level of understanding.

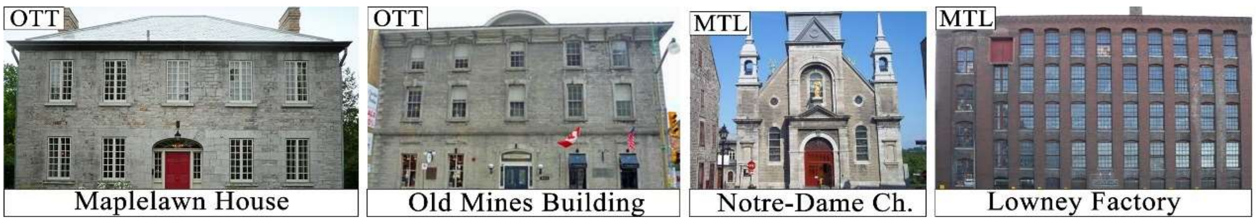


Figure 1: typical URM buildings in Montréal (MTL) - Ottawa (OTT), Canadian Register of Historic Places

Due to a lack of data from past earthquakes indeed (mostly isolated epicentres, see Lamontagne et al. 2008), the response of Eastern Canada's old URM buildings to local seismicity is largely unknown – the distinctive high-frequency shaking registered in recent events could e.g., trigger amplification phenomena and URM collapses even at low (M_w<4) shaking intensities (Meyer et al. 2019). The most recent major seismic event (M_w=5.9) in Eastern Canada, the 1988 Saguenay earthquake, pointed out the unpreparedness of the population as well as the vulnerability of the structures (Lamontagne 2010). Based on multiple site visits conducted by expert reconnaissance teams, particularly poor performance was noted for URM buildings, which suffered most of the observed damage. Diagonal shear cracking in-plane and one-way out-of-plane mechanisms characterized the URM response to the ground motion (Mitchell et al. 1989). To safeguard old URM buildings from the seismic threat, first the seismic risk must be quantified.

To this end, various types of seismic risk assessment have been applied in Eastern Canada, typically on a citywide, or local (building) scale, despite the absence of ad-hoc standards and guidelines. Tools such as HAZUS (acronym of "Hazards United States"), a geographic information system-based analysis tool developed in 1997 and freely distributed by the US Federal Emergency Management Agency (FEMA) to calculate multi-hazard loss estimates on a regional basis in the United States, and other GIS based software were often used by local researchers (Hosseinpour et al. 2021) and engineering professionals (McCaffrey et al. 2013), making it possible to understand the potential impacts an earthquake can wreak on an area. Potential seismic losses have been investigated for some Canadian cities such as in Vancouver (Onur et al. 2011), Ottawa (Ploeger et al. 2010) and Montréal (Deng et al. 2016; Tamima and Chouinard 2016). However, reliable estimates require a large amount of initial data regarding the geological conditions, building conditions, ground motion characteristics and region demographics, most of which are presently missing. While various numerically based risk assessment methods have also been used across Canada, the large amount of data required (e.g. material properties, dimensions, etc.) allows for only small scale, high cost, analyses to be run (e.g., Abo-El-Ezz et al. 2013; Crowley et al. 2017; Fathi-Fazl et al. 2020; Goda and Tesfamariam 2015; Ploeger et al. 2010; Siqueira et al. 2014). To estimate and reduce future earthquake losses, regional seismic risk models and mitigation strategies tailored to the unique characteristics of Eastern Canada's old URM buildings are needed, but not yet available. This is largely due to the scattered nature of previous building inventories, limited knowledge of their structural properties, and unknown effects of local high-frequency seismicity. Another potential reason is that, unlike in most other seismic-prone countries, updated technical standards on old URM buildings are presently missing in Canada. Indications provided in NBC commentaries (NBC Commentary-L 2015) are very limited, leaving engineering professionals and researchers without clear guidance. The latest (yet now obsolete) official national guidelines on old URM buildings were published in the 1990s by National Resources Canada (NRC) and focused on seismic screening (NRC 1993a), evaluation (NRC 1993b) and upgrading (NRC 1995) approaches. At the international level, subsequent developments led by the International Scientific Committee on the Analysis and Restoration of Structures of Architectural Heritage (ISCARSAH) resulted into the creation of what is now an accepted general conceptual framework for studying old and historic constructions from a structural engineering perspective, i.e., the Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage (ISCARSAH Principles hereinafter), based on three knowledge-based consecutive steps: typological classification, characterization and evaluation. This holistic methodology, despite being widely adopted globally (Cruz et al. 2015; Lagomarsino and Cattari 2015; Lourenço 2006; Roca 2021) and implemented into several building codes at various levels (ASCE/SEI-41-13; NZSEE 2017; PCM 2011), has never been applied systematically in Canada as far as the authors are aware of, with most of past research targeting isolated case studies.

In this paper, a state-of-the-art review of previous studies on old URM structures typical of Eastern Canada is proposed for identifying potential research gaps, challenges and future opportunities through the lens of the ISCARSAH Principles, by referring explicitly to *typological classification* (i.e., informed selection of recurrent building types, or assets, and identification of relevant structural categories, vital to ensure local representativeness of seismic analysis results), *structural characterization* (i.e., determination of the physical properties and integrity of key materials in old buildings) and *seismic evaluation* (i.e., quantitative estimation of the seismic response of selected assets) approaches. Through the critical investigation proposed herein, also complemented by the description of relevant applications from abroad, we investigate the feasibility of adopting such a framework in Canada, while providing local practitioners and researchers with a comprehensive overview and a unified repository of past national research efforts on the topic. This research also aims to substantiate a larger community-based effort that recently led to the creation of a new CSCE Existing Structures Committee, whose objectives include fostering best practices to safeguard the built environment and promoting a constructive interaction among researchers and engineers working on old buildings.

2 TYPOLOGICAL CLASSIFICATION

The ISCARSAH Principles provide an analysis framework designed to overcome the rigid constraints of applying modern codes to ensure safe intervention design without sacrificing authenticity or cultural value (Roca 2021) of old buildings. To adopt such a framework in Canada on a large-scale begins with the classification of building stock and typological analyses. This section proposes use of a unified building inventory to carry out a typological analysis, defined here as a domain-specific categorization of buildings by shared physical shape and organizational characteristics (Stouffs and Tunçer 2015). Such information can be utilized to provide building information e.g., structural features and other key information useful for seismic engineering investigations, intended in the first phase of a holistic analysis framework.

Building stock classification used in large-scale analyses is completed using inventories created by various means including census data, pre- or post-disaster inventories, heritage building inventories, or site-specific inventories. Knowledge from building inventories is integral in determining disaster responses to be able to account for damage and designing potential retrofitting and upgrading interventions (Myers 2016). In Eastern Canada, detailed building inventories of representative districts in Montréal, Québec City (see **Figure 2**) and Ottawa were done by e.g., Abo-El-Ezz et al. (2019), Nollet et al. (2013b) and Sawada et al. (2014), respectively. This methodology, however, is extremely time consuming and hardly applicable at the regional scale. A complementary option is using existing building inventories focused on historic URM structures. Classified heritage buildings are better documented than other similar unclassified structures, due to the presence of archival sources that refer to its history and design details as well as accessibility to visitors and the possible location in clustered districts. Historic structures can indeed be considered in Canada (unlike e.g., European countries whose historic structures date to centuries ago) as a typological subset of old buildings with heritage value (Humphreys and Sykes 1980). Classification can be completed with analogous features and period of construction and applied to structures of a similar typology.

Typological analyses have been used as guides to understand historical architecture (Stouffs and Tunçer 2015) as well as for modelling purposes (García-Gago et al. 2014) and seismic analyses (Lagomarsino and Giovinazzi 2006; Zuccaro and Cacace 2015). The combination of data from detailed district-based and larger historic building inventories would be useful in the classification of Canada's building stock, a possibility currently being investigated.

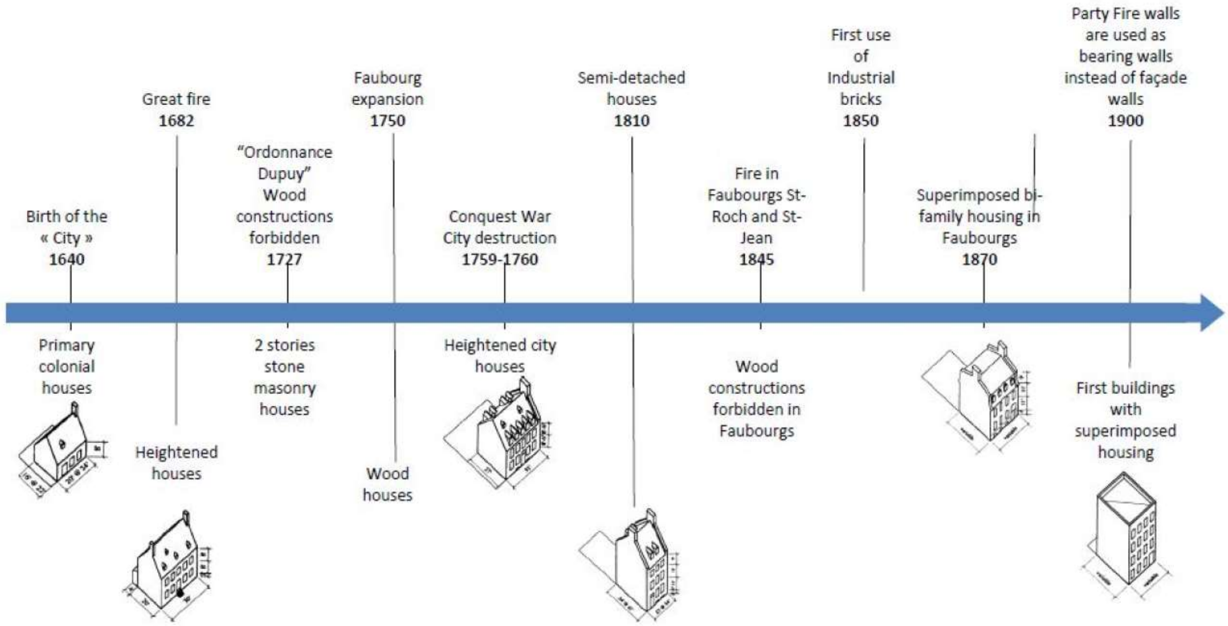


Figure 2: Typological classification and Evolution of traditional stone masonry residential buildings in Québec City (adapted from (Nollet et al. 2013b))

Consolidation of relevant structural data from existing heritage building databases is the study of a current research project at McGill University. The database created by this project, henceforth referred to as the unified heritage building database (UHBD), aims to combine municipal, provincial and federal inventories into a unified, accessible database. Heritage building databases are already robust in Canada yet remain scattered and lack structural parameters necessary for a seismic evaluation. For example, Canadian Inventory of Historic Buildings was established in 1970 and created what is now known as the Canada Register of Historic Places (CRHP). This heritage inventory combines approximately 12,500 federal, provincial and territorial structures that have been heritage designated (Cameron 1986). While the CRHP provides adequate information about these structures, it is no longer kept to date with newly classified buildings, leaving heritage inventories the responsibility of the government these buildings are locally classified under. The CRHP also lacks data from municipal inventories, and thus buildings classified as heritage according to their respective city governance. In addition, heritage inventories in Canada focus on character-defining elements as well as cultural and historical importance. While these are important factors in heritage conservation, not all included data can be applied for architectural or engineering purposes when designing a conservation plan or seismic interventions. Structural data integral to these designs is often lacking in heritage inventories. Relevant parameters for seismic analysis which can possibly be integrated are available via e.g., Statistics Canada (Statistics Canada 2019) (e.g., storeys, footprints), as well as in the detailed inventories mentioned earlier. As in Western regions (British Columbia Heritage Branch) and abroad (US National Park Service), these inventories contain valuable, complementary, non-protected yet hardly accessible data. Typological analyses were conducted in e.g., Québec, albeit only for specific types of stone URM houses (Abo-El-Ezz et al. 2013) or churches (Carrier et al. 2020). Research is needed to rectify the scattered nature of the existing building inventories as well as limited amount structural data for old URM buildings in Eastern Canada. To date, the UHBD includes information from over 2,500 buildings including federally recognized properties, properties recognized by Québec as well as buildings on the municipal building inventories of Montréal and Québec City. The database is currently expanding to include recognized properties from Ontario and major metropolitan areas throughout these providences—including Toronto, Ottawa and Kingston, among others, summarizing these inventories in **Figure 3.**

FEDERAL		PROVINCIAL		MUNICIPAL	
Directory of Federal Heritage Designations (DFHB)	- 2,500	Répertoire du patrimoine du Québec	- 42,000	Montréal	- 1,300
Canada Register of Historic Places (CRHP)	-12,500	Ontario Heritage Trust	- 7,000	Québec City	- 150
		Lieux de culte du Québec	- 2,700	Toronto	- 16,000
				Kingston	- 1,500
				⋮	

Figure 3: List of some heritage inventories and their approximate count of registered buildings

The methodology of the UHBD processes a given listing according to a set of characteristics that can be applied to conservation interventions as well as seismic retrofits. To list a structure or monument with a level of national importance requires a level of cultural and historical significance that is valuable to the fabric of Canada. In this case, a specific set of guidelines and criteria apply to determine whether the listing meets general guidelines set in 1988 that classify its national importance (Historic Sites and Monuments Board of Canada 2017). For buildings, this includes consent of the property owner, boundaries of the site, components of the property, site condition and additional documentation. Provincial and municipal building inventories each have their own governing criteria for listing a site. Among these criteria and listing characteristics, reasonable data categories were chosen based on their prevalence within listing descriptions as well as the application for structural assessments. General identification data such as building name location, current and historic use type, date of construction and occupancy are required for each entry. Additional characteristics relevant to structural evaluation includes number of storeys, floor area and materials of the structure, veneer and foundation, useful in large-scale analyses such as Aguado et al. 2018, Allen and Rainer 1995 and D'Ayala and Speranza 2003. Preliminary results from the UHBD show a corridor of heritage designated buildings within an extensive range across Ontario and Québec (see **Figure 4**), with a focus of structures in Montréal and Québec City, where much of the listings have been recorded.

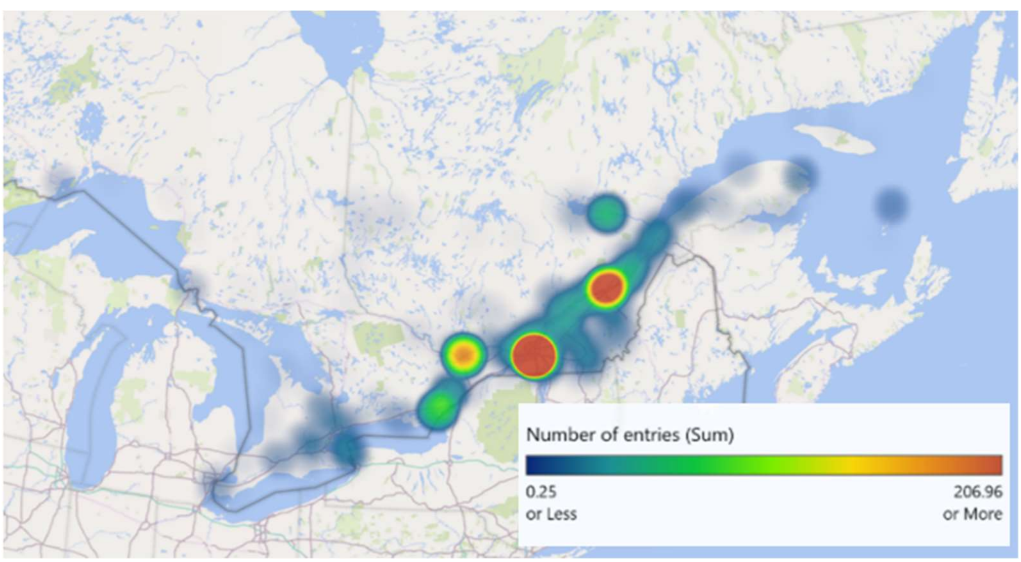


Figure 4: Density of heritage buildings from the UHBD along the Québec City—Windsor corridor

Based on preliminary results from the UHBD, over 70% of heritage designated buildings within Eastern Canada are composed of some type of masonry, see **Figure 5.** Masonry buildings in Eastern Canada have developed from types used by some of the first European settlers and evolved with local material availability including an abundance of wood and many local stone quarries (Kalman 1995). Studies have followed the architectural evolution within Eastern Canada, especially in Québec-the advancement from rubble masonry walls and the creation of fire walls, to the use of cast iron and wrought iron in multi-level commercial and industrial structures-following the use and creation of architectural pattern books to the building code used today (Kalman 1995). Identifying structural evolution within a designated use type, as can be identified in building inventories such as the UHBD (see **Figure 6**), can serve as a basis of typological classification. Already, structural classification of common typologies is seen minimally through specific types of residential (Kraiem et al. 2019) and religious (García-Gago et al. 2014) buildings in Québec and by looking critically at the structures in old Montréal (Nollet et al. 2004). The UHBD and similar inventories can serve as the basis for conducting a thorough typological analysis of old URM buildings in Eastern Canada, constituting the foundation on which to implement informed regional seismic risk analysis frameworks inspired by the ISCARSAH Principles.

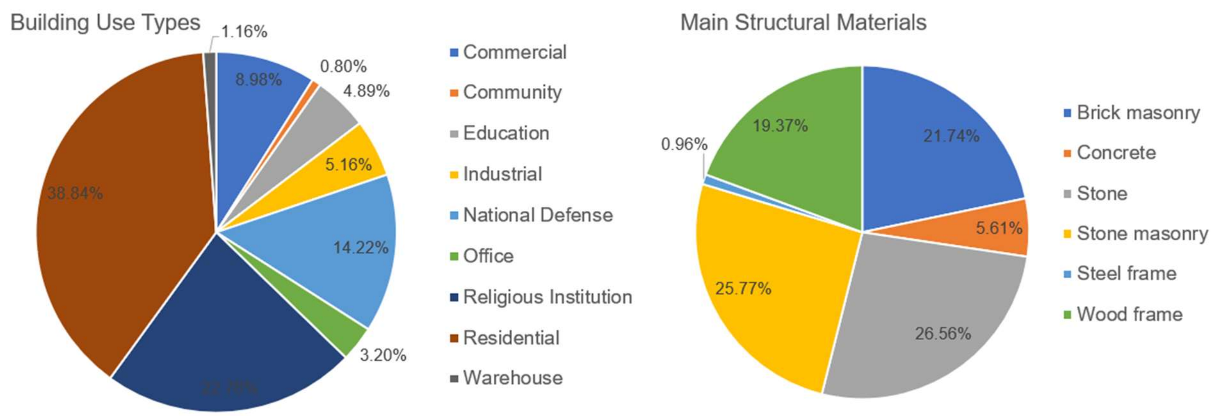


Figure 5: Building use types (left) and main structural materials of buildings (right) in Eastern Canada according to the UHBD

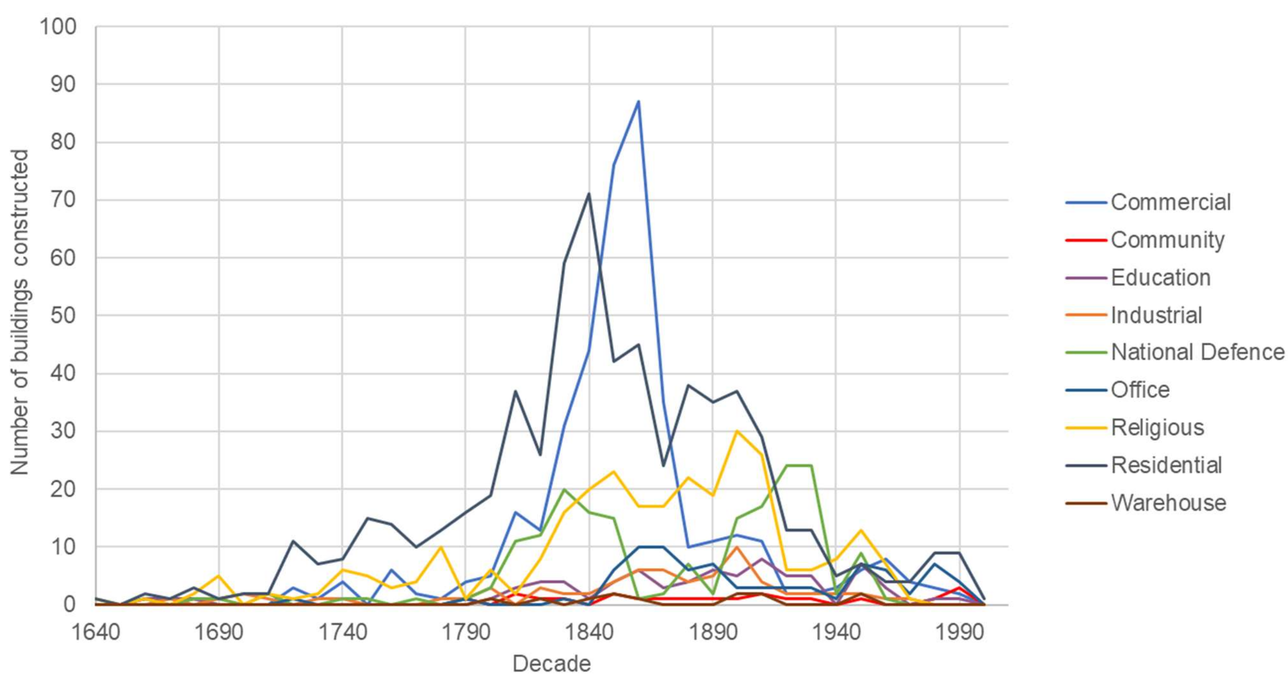


Figure 6: Main building typology vs. decade built in Eastern Canada according to the UHBD

Consolidated, accessible structural properties are necessary to complete the typological classifications proposed in the initial phase of study, as suggested by the ISCARAH Principles, is difficult to carry out in Canada due to lack of information and scattered nature of existing building inventories. Case studies outside of Canada support the methodology proposed here. Typological classification and earthquake vulnerability analysis based on inventories have been evaluated on a citywide scale in Italy (Polese et al. 2019; Da Porto et al. 2013a; Rota et al. 2008) and across Central and South Asian countries Tajikistan, Kyrgyzstan, Pakistan, Afghanistan and India (Lang et al. 2018). These case studies provide data regarding the damage characteristics and failure mechanisms that contribute to the vulnerability of a defined typology as well as potential intervention methods. Results from each case study provide much needed data regarding vulnerability in seismic risk scenarios. Applying such a typological classification strategy based on building inventory to Eastern Canada, such as the UHBD, has the potential to bridge the knowledge gap on structural vulnerability characteristics on a regional level.

3 STRUCTURAL CHARACTERIZATION

The second component attributed to the ISCARSAH Principles considered herein corresponds to the inspection and diagnosis of building characteristics, registering material and geometrical characteristics used to evaluate a structure and design a good intervention (ISCARSAH 2003). One of the largest hurdles to overcome within the accurate evaluation of old buildings—heritage designated or not—is the lack of information regarding geometry, material properties and integrity. For the sake of simplicity, structural characterizations for use in seismic evaluations are discussed below referring three distinct categories—geometrical, material and dynamic—which this section details for commonly employed methods in Canada or other seismic prone areas.

Geometrical characterization using photogrammetry and laser scanning to inform the structural and seismic analysis of old URM buildings are well documented in technical literature (Loverdos et al. 2021; Napolitano et al. 2019; Sánchez-Aparicio et al. 2014) and recently also used in combination with advanced numerical modelling (Castellazzi et al. 2017; Kassotakis et al. 2020). Surveying techniques and their applications are a vital part of the geometrical characterization of old buildings, and innovations within these aid in streamlining the modelling process and decreasing the cost of the structural evaluation. Canadian researchers also employed these tools albeit mostly outside the country (Gutland et al. 2021) and for building conservation purposes (Ide et al. 2020).

To characterize masonry materials, a limited number of experimental testing campaigns have been conducted in Eastern Canada targeting different construction types and in various states of conservation, most notably by Sorour et al. (2011) using lateral load testing of stone masonry walls, as part of a larger campaign to restore the Ottawa West Block of Parliament (Elmenshawi et al. 2010a; b), see **Figure 7**. These walls, however, were re-created in the lab using modern materials, not necessarily representative of the characteristics of the original ones. In-situ tests on stone masonry elements were performed by Isfeld and Shrive (2015a) in the framework of a larger research on the impact of climate change on the durability of the Prince of Wales Fort (Churchill, Manitoba). With respect to brick masonry, material testing campaigns using various destructive testing methods on brick masonry wallets have been completed by Nollet et al. (2019) to determine mechanical properties of historic unreinforced brick masonry. Availability of tests data on load-bearing URM walls in Canada is limited, with one example studying the out-of-plane strengthening from Ontario (Ghobarah and El Mandooh Galal 2004). Other testing campaigns of typical old building systems of Canada have focused on reinforced concrete and concrete masonry units. Concrete beams can be scanned to find subsurface flaws or cracks (Rathod and Gupta 2019). Additionally, non-destructive testing methods such as stress-waves (Sajid et al. 2018), ultrasonic pulse velocity (Saint-Pierre et al. 2016) or ground penetrating radar (GPR) (Rathod et al. 2019) were used to determine concrete compressive strength, the coefficient of thermal expansion, deterioration levels and rebar information. The potentialities of these non-destructive techniques, which have also been applied to URM structures abroad (Da Porto et al. 2013b; Vasanelli et al. 2015) yet not fully exploited in Eastern Canada, represent a possible future research direction for Eastern Canada’s structural engineering research and may help creating much needed material data repositories.

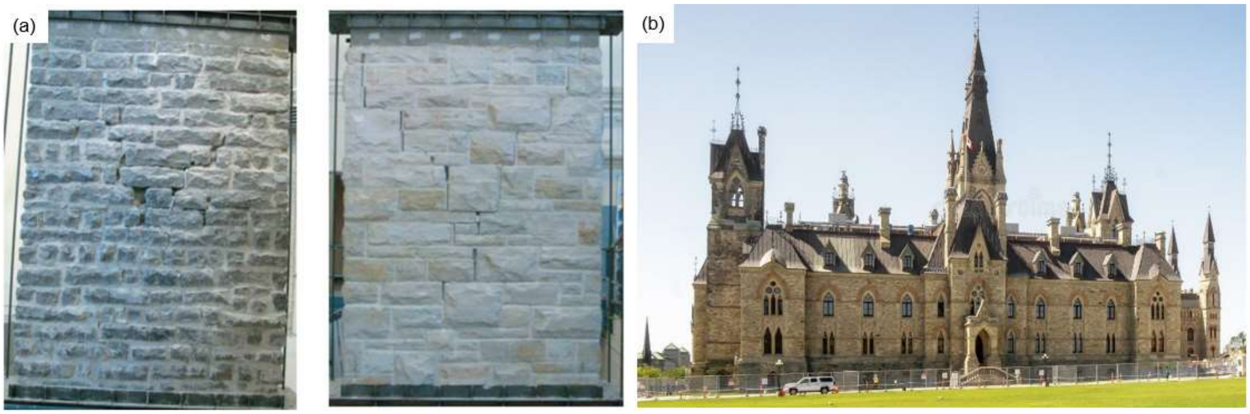


Figure 7: (a) Stepped cracks in stone masonry wall, typical of (b) West Block of Parliament, Ottawa (Elmenshawi et al. 2010a)

Dynamic or seismic testing, such as shake table tests, have also been performed in Canada especially on recurrent brick masonry wall typologies with ground motions seen on the West Coast (Meisl et al. 2007; Penner and Elwood 2016), while only one example exists for Eastern Canada’s building typologies (Krstevska et al. 2010). Elsewhere in Canada, tests on assemblies (Touraille et al. 2019), components (Meisl et al. 2007) and building prototypes (Paquette et al. 2004) using specimens built with new materials produce results which are not necessarily representative of old URM. Groups abroad overcame this issue with destructive in-situ testing (Walsh et al. 2015), typically not allowed in Canada for protected buildings. Further research needs to be done to fill the information gap regarding the geometrical and material characteristics of Canada’s old URM buildings. To infer the dynamic properties of old URM and estimate damping characteristics, data from ambient vibration measurements (AVM), such as the study done by the University of British Columbia on school URM buildings (Turek et al. 2006; Ventura et al. 2012) can begin to fill this gap. In Eastern Canada, however, only limited studies on this front have been conducted so far (Asgarian and McClure 2014; Hafeez et al. 2018; Kolaj and Adams 2021). To provide a complete and holistic seismic evaluation of old URM structures, the ISCARSAH principles require detailed structural and material identifications, vital for understanding the structure’s conditions as well as potential cause of decay or deterioration (ISCARSAH 2003). The methods discussed in this section using in-situ or laboratory testing and various surveying and monitoring techniques to characterize a structure summarizes the main approaches used in Canada and identify the lack of research completed on old URM structures to be able to apply the ISCARSAH principles in a large-scale fashion. Further research, using rigorous typological analysis approaches to organize the large amount of data, is certainly needed.

4 SEISMIC EVALUATION

Seismic evaluation for existing structures can be broadly defined as the assessment of their performance under a considered seismic hazard level, to meet an acceptable level of life safety, serviceability and remaining structural integrity. For structures with the least amount of inherent seismic resistance, standard (e.g., ASCE/SEI-41-13 2014) recommend a systematic evaluation procedure to assure adequate performance, completed with advanced structural analysis tools such as linear or nonlinear numerical modelling approaches. Seismic analysis via numerical modelling is also the reference URM evaluation approach (Lourenço 2002), as recognized by ISCARSAH principles. However, numerical modelling requires an in-depth knowledge of structural functioning and material characteristics, precisely where national research falls short. Informed numerical models tailored to the unique features of Eastern Canada’s old URM buildings and seismicity are essential for predicting their seismic capacities and failure modes. The missing data is crucial for defining proper damage limit states correlating to key performance levels on which to devise, before a catastrophic earthquake happens, regional seismic risk and mitigation strategies.

Numerical seismic analysis of old URM structures is popular in e.g., Europe, South America, Oceania (Lourenço and Silva 2020), where dedicated guidelines (ASCE/SEI-41-13 2014) and codes (NZSEE 2017) are available, yet unsuited to the unique features (e.g., stack bond walls, irregular openings, tall fire gables) of local old URM systems. Application of the ASCE/SEI-41 standard in Canada has been minimally used on steel structures (Balazadeh-Minouei et al. 2017; Mottier et al. 2018) but remains difficult to implement due to differences in seismicity and material characteristics. Minimal investigation of local URM systems has been completed (Abo-El-Ezz et al. 2013), mainly using simplified numerical models. Canada's URM structural evaluation standards are obsolete (NRC 1993b) and neglect numerical modelling (Commentary-L 2015) which leads engineers to inappropriately rely on steel/reinforced concrete analysis techniques, unsuitable for the analysis of URM structures. Application and creation of guidelines in Canada for the use of numerical modelling techniques would aid in the proper implementation of ISCARSAH Principles.

Three levels of detail (see **Figure 8**) are used for URM numerical seismic analysis (Lourenço 2002), at the *macro*, *meso* and *micro* scales, requiring diverse competencies, efforts, analysis times. Macro-scale models characterized by practitioner use, low-cost of in-plane capacity, estimated and basic knowledge of *component-level* damage while typically neglecting out-of-plane actions. Meso-scale models can be used by specialized engineers, providing data on the in-plane/out-of-plane actions as well as an accurate representation of *masonry-level* failures. Micro-scale models are the most cost intensive but provide the most information with modelling of the *joint-level* damage mechanisms and in-plane and out-of-plane damage, used by researchers. Respectively, the level of user competency decreases with each scale of analysis while computational effort and analysis times increase. Their adequacy depends on the governing seismic response (e.g., in-plane vs. out-of-plane), which remains unknown for Eastern Canada's old URM buildings. Macro (El-Dakhakhni et al. 2006), meso (Shieh-Beygi and Pietruszczak 2008), micro (Isfeld and Shrive 2015b) models of Eastern Canada's URM were used in seismic studies (see **Figure 9**) on residential (Kraiem et al. 2019), religious (Carrier et al. 2020), industrial (Karbassi and Nollet 2013) and institutional (Krisanova et al. 2013) buildings, but the unknown effect of uncertainties on predictions, the absence of comparisons among numerical strategies and the lack of informed idealizations of construction details prevent modelling-based recommendations from being considered by decision and policy-makers (e.g., National Research Council Canada, Parks Canada, Canadian Commission on Building and Fire Codes).

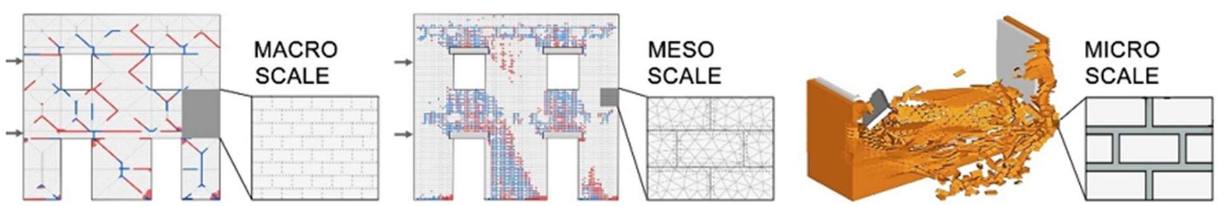
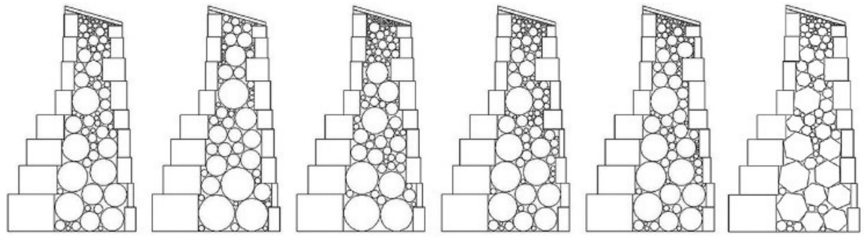


Figure 8: Commonly employed numerical modelling strategies and conceptual differences

Additional proposed research involves expansion of numerical modelling techniques on Eastern Canadian structures by assessing buildings from important building typologies with characterization data identified in the previous stages addressed in this paper. The most common modelling strategies include limit analysis techniques, finite element modelling (FEM) or discrete element modelling (DEM) strategies. Each of these modelling strategies brings a various simplicity of implementation, computational cost as well as the level of accuracy, of which recent research dives into the optimization of the outputs using simplified analysis methods (D'Altri et al. 2020; Giordano et al. 2002; Roca et al. 2010).

(a) 

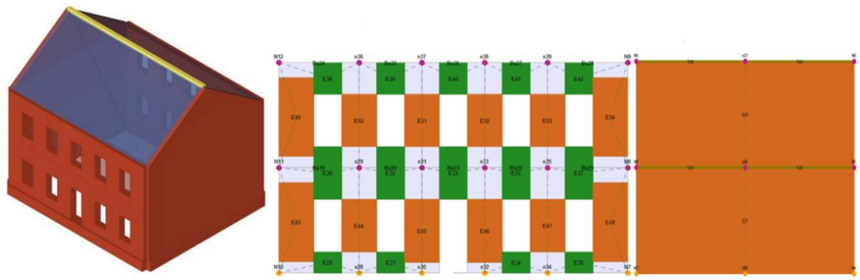
(b) 

Figure 9: Example of (a) discrete element micro-model of Prince of Wales Fort (Isfeld and Shrive 2015b) (b) macro-model discretization of Québec residential building (Kraiem et al. 2019)

To expand knowledge of structural performance of Eastern Canada’s old URM buildings, further research is suggested. Codes and algorithms created to aid in model creation (Funari et al. 2020; García-Gago et al. 2014) are methods to simplify input, while DEM macro- (Malomo and DeJong 2021) or meso- (Pulatsu et al. 2020) scale strategies can be applied to model in-plane and out-of-plane failure mechanisms in a reasonable timeframe. Following the ISCARSAH Principles, the evaluation phase considers seismic risk mitigation strategies including parametric analysis of applicable intervention strategies. Potential intervention strategies to model include steel ties or grouting to diminish delamination of masonry wythes, improved connections to horizontal diaphragms, or addition of shear walls. Retrofit design guided by the ISCARSAH Principles require minimal intervention, reversibility, compatibility between existing materials and those applied, as well as care for the maintenance and future of the structure (ISCARSAH 2003). Interpretation of the results requires special attention to the safety of the public, the preservation of the integrity and authenticity of old structures, their contents and cultural value (Roca 2021). Seismic structural evaluations, such as the numerical modelling strategies previously mentioned, can be used to verify acceptable levels of damage in current or rehabilitated condition, examples which could be applied to any building of the similar typology. Evaluation of the structural typologies commonly seen in Eastern Canada would allow practitioners and experts in the field to better understand their building stock and make informed decisions regarding the conservation, maintenance and designing effective intervention strategies.

5 CONCLUSIONS

Eastern Canada’s cities located in moderate seismic zones remain vulnerable to earthquakes due to a high population density and a high density of vulnerable unreinforced masonry (URM) structures. Increasing public awareness and resiliency of the building stock to respond to future seismic actions can save lives, protect economic losses and protect cultural values. The steps presented in the ISCARSAH Principles as a framework for the analysis of old buildings of - typological classification, characterization and evaluation - are accepted globally and included within codes in many seismic-prone countries, including New Zealand, Italy and the United States, yet remain unapplied in Canada. This paper presents an investigative state-of-the-art review of large-scale structural evaluation of URM structures completed in Canada through the lens of the ISCARSAH Principles, identifying relevant examples, best practices as well as knowledge gaps to continue to guide engineering professionals, whose main outcomes are summarized below:

- Past seismic risk studies targeting old structures at the regional scale, vital for devising proper seismic upgrading and other intervention strategies, rely on international and/or generic data in terms of material properties and structural features, potentially leading to inaccurate predictions
- Although district-scale building inventories represent an invaluable source of information to support seismic risk studies, they are time consuming to carry out and not applicable at a regional level
- Compilation of a unified building inventory in Canada from which to conduct a typological analysis applicable on a regional level is recommended
- Existing data regarding the geometrical, material and dynamic characteristics of old URM buildings, especially in Eastern Canada, is extremely limited, potentially leading to inaccurate estimates of key structural properties
- Numerical modelling is the recommended approach for advanced structural analysis on URM buildings, yet no guidelines exist in Canada regarding procedures and techniques
- Further research using a rigorous typological analysis approach is recommended to provide structural characteristic data as well as critical numerical evaluation examples

Relevant results from such evaluations, as presented, can be utilized within seismic hazard management on a large-scale, providing accurate inputs for loss estimation models with easier access to building inventories and data. Future research is necessary to implement such a framework as presented by the ISCARSAH Principles into guidelines for old URM structures applicable in Eastern Canada and beyond.

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