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Development of an Inventory Modelling Framework for Seismic Risk Assessment of Residential Buildings in Eastern Canada

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ABSTRACT

Seismic risk assessment for residential buildings is a priority in Eastern Canada, given its densely populated cities and history of earthquake activity. A crucial component of this assessment is the development of an accurate and practical inventory model, which relies on comprehensive investigations and the collection of reliable data on residential buildings. A simple yet reliable inventory framework is essential to streamline the process of building inventory while reducing costs and time. Moreover, there is a need for more refined and standardized classifications of the structural systems of residential buildings. This study proposes a new inventory modelling framework for residential buildings, applied to Montreal as a case study, with a focus on the number of residential units. The two main objectives of this study are: (1) to conduct a historical review of residential construction practices in the city, defining common materials and structural systems; and (2) to determine their distribution across administrative areas, including both independent municipalities and boroughs within the City of Montreal. To achieve these objectives, previous studies and various pertinent resources were evaluated to trace the evolution of residential construction, and two open-access databases were employed and integrated to derive results. The analysis covers over 900,000 residential units, revealing that approximately 30% and 22% are associated with buildings constructed using wood light frames and concrete shear walls, respectively, while 48% correspond to buildings with mixed wood–masonry structural systems as well as masonry buildings. This inventory model offers practical insights into the distribution of residential units by structural systems, improving future simulations to estimate uninhabitable unit rates, population displacement, and shelter needs, which will support and strengthen community resilience.

1 | Introduction

Over the past century, various intense earthquakes with magnitudes ranging from 5.0 to 7.0 have occurred in Eastern Canada, particularly in the St. Lawrence and Ottawa river valleys, as well as the Charlevoix and Saguenay regions. Most of these past events occurred during periods of comparatively low population density. Nevertheless, the occurrence of similar events in the current urban context would likely result in amplified consequences due to substantial growth in population, building inventory, and infrastructure development [1, 2]. This seismic zone includes densely populated cities such as Montreal (agglomeration of Montreal), Ottawa, and Quebec City. Notably, Montreal ranks second in seismic risk in Canada due to both its history of earthquake activity and its large population. It is located within the Western Quebec seismic zone, a region of notable seismic activity where earthquakes are recorded frequently. The region has experienced several major seismic events, including the 1732 Montreal earthquake (magnitude 5.8), the 1935 Temiscaming earthquake (magnitude 6.2), and the 1944 Cornwall–Massena earthquake (magnitude 5.6) [3, 4]. According to the National Building Code of Canada (NBCC), Montreal is exposed to a peak ground acceleration of 0.46 g with a 2% probability of exceedance in 50 years and it can be defined as moderately high seismic zone according to the Semi-quantitative Seismic Risk Screening Tool for existing buildings developed by the National Research Council of Canada (NRC-SQST) [2, 4–7]. This level of seismic hazard raises concerns for residential buildings since they constitute the majority of buildings in the city [8]. Additionally, given the high population density, prioritizing seismic risk assessment of these buildings is vital for developing earthquake preparedness plans, mitigating the consequences of seismic hazards, and implementing effective emergency response measures. These evaluations are essential, as similar events in other countries worldwide have resulted in significant loss of property and life [9–12].

A seismic risk assessment of buildings typically consists of three main steps: seismic hazard analysis, inventory modelling (or exposure modelling in some literature references), and consequence analysis [13]. The first step involves estimating probable seismic intensities, and the last step involves predicting various forms of seismic losses. The second step, inventory modelling, focuses on building structural characterization and statistical analysis of the number of buildings or units. Building inventory is a region-specific activity that involves collecting data sets based on distinct features such as height or number of storeys, years of construction, structural systems (lateral load-resisting systems), number of units and residents. A comprehensive building inventory serves as the basis for robust seismic vulnerability assessment and improving preparedness, which in turn can support the development of mitigation strategies. Importantly, it also strengthens urban resilience, defined as a system's ability to withstand major disturbances such as earthquakes and recover efficiently from their impacts. Equally important is understanding the condition of buildings before an earthquake. Reliable data on the existing building stock is essential for identifying vulnerable structures and guiding the implementation of preventive measures. A detailed inventory further supports accurate estimation of seismic losses such as uninhabitable units and displaced populations, which are critical to enhancing post-earthquake resilience [14–17].

Several studies have been conducted in the domain of building inventory modelling. In the following, a selection of these investigations is reviewed, highlighting variations and considerations in their methods and approaches. Inel et al. conducted an inventory of a group of buildings in a selected area of Denizli in Turkey, using a field survey performed by trained observers. In this investigation, information on structural systems, years of construction, building irregularities, and building quality was collected and used for seismic loss estimation [18]. In another study, a sidewalk survey of mid-rise reinforced concrete residential buildings in six locations in Istanbul was conducted by a group of trained surveyors over 5 years, as described by Yakut et al. The number of concrete buildings and the number of storeys, along with the population, were gathered, and the safety score for each building was calculated [19]. Yepes-Estrada et al. generated an inventory model as part of the Global Earthquake Model for residential buildings in South America. They considered several factors to capture the model, including construction materials, structural systems, number of storeys, building area, costs, number of dwellers, number of units, and number of buildings. Their methodology was based on dwelling statistics, national population statistics, and expert opinions [20]. Calderon and Silva performed a seismic risk assessment for residential buildings in Costa Rica, proposing a new inventory model based on housing census data, open-access statistics, and private construction information. Their classification system considers factors such as material, structural system, ductility, building height, and year of construction. For instance, regarding years of construction, they selected specific periods and investigated construction trends during those times; or, for building height, they classified buildings based on their area and expert judgment [21]. Ana et al. conducted a seismic risk assessment for three large cities in Colombia. To this end, they developed inventory models categorized by factors such as area, building types, number of buildings, number of units, and inhabitants. They incorporated survey data and expert judgment in their models [22]. Torres et al. presented a comprehensive review of past studies regarding the development of inventory models using remote sensing data and created an exposure model for Haiti based on specific remote sensing techniques. In their study, they concluded that remote sensing techniques can save both cost and time by validating their results with available data sets [23]. These models serve as inputs to simulate and estimate potential losses from natural hazards. Based on previous studies, the most commonly employed methods for conducting building inventories in regional-scale seismic risk assessments include sidewalk surveys, using open-access and private statistics (such as national census data and tax roll information), expert judgment, and remote sensing techniques. While sidewalk surveying and remote sensing techniques may be constrained by time and funding limitations, the application of open-access data sets (when available for a given region) can provide a practical solution and expedite the process.

For developing an accurate inventory model, different aspects can be considered for grouping buildings, which may depend on region-specific characteristics and local construction practices. In Montreal, conducting inventory and collecting residential building information for regional-scale seismic risk assessment is particularly challenging due to the city's unique building characteristics compared to other cities in Canada. Research in this domain remains limited for Montreal. While existing studies have considered factors such as geographic location, year of construction, and number of storeys to infer building characteristics, a widely accepted and standardized framework, designed to enable consistent and practical estimation of structural system distributions across residential units, has yet to be established. Moreover, these studies often rely on small-scale surveys or consultations of structural documents, which typically represent only a limited portion of the city's residential building stock [24–27]. In addition, previous efforts have largely focused on the number of residential buildings. However, in densely populated cities such as Montreal, the number of residential units offers a more meaningful metric. Nearly 70% of the city's units are located in apartment buildings, which are generally more susceptible to evacuation in the event of earthquake damage compared to single-family homes. Therefore, emphasizing residential units rather than buildings is essential for more accurately estimating uninhabitable units, potential population displacement, and emergency shelter needs, as these factors are critical to enhancing the city's post-earthquake resilience [28, 29].

To address those limitations, this study aims to develop a new standardized and systematic inventory framework for classifying residential buildings and their units in Montreal. The new inventory framework has two objectives: (1) to focus on the number of residential units instead of the number of buildings, and (2) to identify common structural systems in residential buildings and classify their respective residential units accordingly. To achieve the objectives, a historical review of the evolution of residential construction practices in Montreal was conducted to define the materials and structural systems commonly used in different construction periods. Next, data from two different open-access databases were collected and integrated to determine the number of residential units and their distribution in each defined structural system, based on the number of storeys and years of construction. The developed inventory framework was then applied across all administrative areas, including independent municipalities and boroughs in Montreal.

2 | Residential Buildings in Eastern Canada

2.1 | Case Study: Montreal

Montreal, the case study region for this study, was founded in 1642 and has gradually transformed over the years into an important residential and business centre in Eastern Canada, with a population of nearly 2 million people [25, 28]. Montreal consists of different administrative areas, including the City of Montreal (CM) and 15 other independent municipalities, which are listed in Table 1 along with their names and abbreviations. It should be mentioned that these municipalities have experienced changes over time due to mergers and demergers in the areas. As an example, the CM consisted of nine boroughs before the 2002 merger, which are defined in the table, compared to its current condition with 19 boroughs [30].

2.2 | Characterization of Typical Residential Buildings in Montreal

The principal goal of collecting building structural information is to establish a practical inventory model for regional seismic risk assessment. Seismic capacity parameters and fragility functions are dependent on the structural system of the buildings and are prerequisites for vulnerability and consequences analysis. The Hazus Technical Manuals (and their supplementary reports), along with the NRC-SQST guidelines for existing buildings, are well-established resources that specify the requirements for seismic vulnerability analysis based on structural systems, building height, and seismic design code levels [2, 29, 31]. These resources are particularly useful for large-scale assessments; although they may offer approximate estimations, they provide a practical and time-efficient means of capturing the overall seismic vulnerability of a city [32, 33]. This is especially advantageous when numerical modelling, despite its precision, requires considerable time, parameter calibration, and result verification, which may limit its feasibility for broad regional applications [34]. To apply the recommendations of the Hazus-based documents for defining buildings' seismic capacity parameters and fragility in Montreal, it is essential to classify buildings according to the standard Hazus-based classification. This process demands reviewing the evolution of housing construction practices in Montreal to identify commonly used materials and structural systems, examining building design codes to understand differences in design requirements, and aligning common structural systems in the city with the default Hazus-based building types. Each of these aspects is investigated in the following subsections.

2.2.1 | A Review of the Evolution of Residential Building Construction

Understanding the evolution of residential building construction is an important step in developing an accurate inventory model for regional seismic risk assessment. Therefore, this section provides a historical review of residential buildings based on available architectural reports, historic documents, studies, and theses.

In Montreal, patterns of residential buildings vary across municipalities. Generally, the city consists of three main building

TABLE 1 | Name and abbreviation of municipalities and boroughs in the agglomeration of Montreal.

Municipalities	Administrative areas
City of Montreal (CM) boroughs	Ahuntsic-Cartierville* (AC), Anjou (AJ), Côte-des-Neiges-Notre-Dame-de-Grâce* (CN), Lachine (LC), LaSalle (LS), Plateau-Mont-Royal* (PM), L'Île-Bizard-Sainte-Geneviève (IS), Mercier-Hochelaga-Maisonneuve* (MH), Montréal-Nord (MN), Outremont (OM), Pierrefonds-Roxboro (PR), Rivière-des-Prairies-Pointe-aux-Trembles* (RP), Rosemont-La Petite-Patrie* (RO), Saint-Laurent (LR), Saint-Léonard (LN), Sud-Ouest* (SO), Verdun (VD), Ville-Marie* (VM), Villeray-Saint-Michel-Parc-Extension* (VS).
Independent municipalities	Baie-D'Urfé (BU), Beaconsfield (BF), Côte-Saint-Luc (CL), Dollard-des-Ormeaux (DO), Dorval (DV), Hampstead (HS), Kirkland (KL), L'Île-Dorval (ID), Montréal-Est (ME), Montréal-Ouest (MO), Mont-Royal (MR), Pointe-Claire (PC), Sainte-Anne-de-Bellevue (BV), Senneville (SV), Westmount (WM).

*Show boroughs included in CM, before the 2002 merger.

taxonomies: single-family houses and multi-family buildings, with the latter further divided into plexes (i.e., superposed flats such as duplexes, triplexes, and up to sixplexes) and apartment buildings, as shown in Figure 1 [35, 36].

In the central core, multi-family dwellings like triplexes and duplexes are prevalent, and downtown areas are dominated by mid-rise to high-rise apartment buildings. Conversely, the suburban areas feature a higher concentration of single-family houses. While Montreal is characterized by its unique residential construction patterns and distinctive architectural features, its buildings also share similarities in construction materials with other cities in Canada. Like other large cities in Canada, Montreal's residential buildings have utilized four primary material groups: wood, masonry, concrete, and steel [2, 37].

Wood has been the most-used material in Canadian housing, both for single-family and multi-family buildings, from the past to the present [38]. The widespread use of wood is because of its benefits, including abundant availability, cost-effectiveness, and environmental advantages. The construction of wooden buildings initially began in rural areas using heavy timbers and logs, followed by a traditional French method known as Piece-on-Piece, which involved assembling horizontal squared timbers between vertical squared wooden posts. These early techniques can be collectively referred to as traditional wood construction methods. Over time, during the mid-to-late 1800s, the mass production of connection elements and power-sawn lumber led to the replacement of traditional methods by the balloon framing technique. In this technique, continuous vertical studs extend from the foundation to the roofline, creating uninterrupted vertical elements throughout the building. This shift brought advantages such as the use of lighter wood elements and increased construction speed [39]. In addition to wood, masonry is another widely used material in the Canadian building construction industry, classified into reinforced and unreinforced masonry bearing wall buildings. Unreinforced masonry bearing wall buildings were more common in residential buildings in Eastern Canada [40]. These buildings could consist of stone masonry, using stone blocks, or brick masonry, made from concrete, clay, or sand-lime bricks, or mixed structural systems that combine wood with unreinforced masonry bearing walls [41].

The order of application between wood and masonry changed over time. Before the 1840s, Montreal mainly consisted of wooden single-family houses. According to past investigations and census data, nearly two-thirds of the houses were constructed from wood, while the remaining houses were masonry buildings, with a higher proportion of stone compared to brick. However, this changed following the great fires of the 1850s in Montreal, which destroyed one-fifth of the houses. In response, the Canadian Parliament enacted new construction regulations that required newly constructed wooden buildings to incorporate fire separation measures, using elements with noncombustible material such as firewalls made of stone or brick. The masonry firewalls were designed to either separate neighboring buildings or subdivide a building to slow the spread of fire from one part of the structure to another [35, 42]. Although the firewalls enhanced safety, they also increased the costs associated with new construction. To mitigate these additional expenses, mixed structural systems began to emerge in Montreal. Such systems represented the legal fireproofing systems for housing at that time, and they rapidly became popular in the city. According to Gendron et al., two prevalent types of mixed structural systems can be found in Montreal [37]. One type consists of interior wooden frames combined with unreinforced masonry external bearing walls, typically used for two-storey single-family houses. Another type emerged between the 1860s and 1940s in the form of plexes with firewalls, driven by significant population growth, the introduction of flat roofs, and a further reduction in brick costs [36]. In the latter type of mixed structural systems, the horizontal wooden elements made of timber planks are arranged between the vertical wood posts as infills and are interlocked at the corners along with a brick veneer to protect the wooden elements from humidity [43]. Most plexes with mixed structural systems were constructed as two-storey buildings (i.e., duplexes) until the 1890s, after which the number of three-storey buildings (i.e., triplexes) gradually increased. These types of housing offered more living space compared to single-family houses and were more financially accessible, leading to a gradual replacement of the earlier type [25, 39, 43, 44].

FIGURE 1 | Example of (A) single-family houses, and multi-family houses including (B) plexes, and (C) apartment buildings in Montreal (photos were taken by the authors).

With advancements in building techniques and upgrading regulations, the mixed structural systems gradually diminished in 1950 due to their extensive labor requirements and the need for additional space to accommodate thermal insulation. Consequently, wood construction regained popularity with the adoption of another modern wood light framing technique named platform framing [39, 45]. In contrast to balloon framing, platform framing involves constructing each storey as a separate and distinct unit, with the floor framing of each level resting on top of the walls of the storey below. In addition to balloon and platform framing techniques, wood post-and-beam construction is another method that uses large rectangular timber columns combined with wooden beams or trusses. This construction method is mainly utilized for industrial and commercial constructions and is rarely used in residential buildings in Canada [2].

Other common materials used in residential buildings in Montreal include concrete and steel. These materials became increasingly prominent in mid-rise and high-rise apartment buildings, starting in the 1950s and 1960s, respectively [24]. The popularity of mid-rise and high-rise apartment buildings is attributed to their ability to provide more dwellings in response to the high cost of land and increased demand for rental accommodations following the Second World War. Also, constructing apartment buildings in the city centre helped reduce transportation difficulties between suburban areas and downtown. To the best of the authors' knowledge, there are no certain statistics to show the total number of concrete-based and steel-based residential buildings in Montreal. Nevertheless, according to past studies, concrete-based systems are more prevalent than steel-based systems in residential buildings across Canada [39, 46]. Similarly, in Montreal, although steel-based buildings are present, they are used less frequently than concrete-based buildings. Instead, they are typically employed for commercial and industrial buildings, as well as a few skyscrapers in downtown [2, 25, 47]. The dominance of concrete-based construction is attributed to several reasons, including the familiarity and experience of developers in working with concrete, the lack of need for clear open-span spaces in apartment design, the ease of installation, and labor preferences. These reasons also align with the architectural characteristics observed in the development of apartment buildings in this city. Point block and slab-type systems were two common configurations used in the construction of residential high-rise apartment buildings in Montreal, with symmetrical plans in square, circular, and hexagonal shapes, and a central core designated for stairs or elevators. The common structural systems for these configurations involve concrete-based elements, especially the application of concrete shear walls located at the core of the building plan [48–50]. In addition, several high-rise residential-commercial apartment buildings built before 1975 were investigated by Raina [49]. This investigation presented examples of high-rise apartment layouts, along with relevant details regarding occupancy and locations. The layouts revealed that the majority of the examples utilized concrete for their key structural elements such as columns and lateral load-resisting systems. Therefore, these indicators highlight the predominance of concrete-based systems over steel-based ones.

In conclusion, the historical review of residential building construction demonstrates that wood, masonry, and concrete are the common materials used in Montreal. Therefore, it is reasonable to base our inventory framework on the structural systems associated with these materials, which are discussed in the following sections.

2.2.2 | Building Design Codes

Another criterion for developing an inventory model is the consideration of the impact of building seismic design codes, which results in the appropriate selection of seismic capacity parameters and fragility function. In Canada, residential buildings may be designed according to two approaches: code-based non-engineered construction guidelines or engineered construction guidelines. The difference between these two approaches results in varying seismic performances in buildings. Thus, accurately incorporating the specific seismic capacity parameters of each approach is essential for conducting effective seismic vulnerability analysis.

The NBCC provides distinct guidelines for different construction conditions and purposes [5]. Specifically, NBCC Part 4 outlines structural and seismic design guidelines while Part 9 addresses guidelines for housing and small buildings, which are categorized as non-engineered construction guidelines. The selection of the guidelines for a building design depends on parameters such as the building area and its height. Buildings with an area of less than 600 m^2 or up to three storeys high should follow NBCC Part 9, which did not include any seismic provisions until 2010 [51]. In contrast, buildings that exceed these limits must be designed under NBCC Part 4, which outlines requirements for engineered construction and incorporates additional relevant standards, such as CSA 086 and CSA A23.3 [52, 53]. As the NBCC Part 4 editions have evolved, changes in the code have influenced the strength and ductility of buildings. These changes can be titled seismic design code levels, which assist in seismic risk assessment by offering close estimates of key seismic parameters of building capacities, including seismic coefficients, modal characteristics, and system ductility. Standard risk assessment tools categorize seismic design code levels into high-code, moderate-code, low-code, and pre-code. The pre-code level refers to buildings constructed before seismic design criteria were established, while the other levels, ranging from low to high seismic design, correspond to modern codes. In Eastern Canada, threshold construction years for engineered buildings have been established to distinguish between various seismic design code levels as follows: buildings constructed before 1970 are assumed to be pre-code, buildings constructed between 1970 and 1990 are assumed to be low-code, buildings constructed between 1990 and 2005 are assumed to be moderate-code and buildings constructed after 2005 are assumed to be high-code. More information regarding seismic design code levels, their relation to years of construction, and the justifications behind them can be found in the cited references [27, 54].

2.2.3 | Alignment With Hazus-Based Building Structural Systems

In this section, structural systems are defined based on the common materials, categorized into wood, masonry, and concrete, as discussed in Section 2.2.1, and then classified into Hazus-based building types.

To define wooden structural systems in Montreal, two groups of buildings should be considered: traditional and modern wood light frame buildings. The closest Hazus-based structural system for both groups is wood light frames, although they may differ in terms of height, area, and seismic design characteristics. The non-engineered single-family or small multi-family houses built with wood light frames, not exceeding three storeys or having an area of less than 600 m^2, should be classified as W1 [2, 29]. Also, engineered wood light frame buildings exceeding three storeys or 600 m^2 area may be classified as W1A, which represents multi-storey multi-unit wood light frame buildings [36, 37, 55]. Note that this type of building is known as W2 in the Hazus Technical Manual [29]; however, the Rapid Visual Screening of Buildings for Potential Seismic Hazards: FEMA P-154 document separates the W2 definition for industrial and commercial occupancy and uses W1A for buildings with residential occupancy. Thus, the updated classification has also been employed in this study [56].

On the other hand, buildings with solid stone or brick masonry bearing walls can be classified as unreinforced masonry bearing wall buildings, URM (either URML for low-rise URM buildings or URMM for mid-rise URM buildings).

Between wood and masonry buildings, there are mixed structural systems. The lateral load resistance of these systems is influenced by wood frames or timber plank walls, leading to different lateral performance compared to W1 and URM buildings. These mixed structural systems exhibit characteristics specific to the region and are not adequately captured by the Hazus-based building types. Therefore, separate categories, designated as URML-W and URMM-W, have been used for these buildings [43].

Furthermore, as detailed in Section 2.2.1, concrete-based buildings are more prevalent in Canada than steel-based ones in residential apartment buildings. According to the NRC-SQST document, typical concrete-based structural systems are concrete moment frames, concrete shear walls, and concrete frames with infill masonry shear walls, which are classified as C1, C2, and C3, identified in both mid-rise and high-rise according to Hazus, respectively. For mid-rise buildings, these systems are referred to as C1M, C2M, and C3M, whereas in high-rise buildings, they are labelled C1H, C2H, and C3H. Other systems, such as precast concrete walls and frames, are also available but they are less commonly used and usually found in office and industrial buildings [2, 29, 57].

3 | Methodology

3.1 | Available Open-Access Databases

This study employs governmental open-access databases to collect information on residential units and buildings. For Montreal, two open-access databases are available: Statistics Canada and Montreal Property Assessment Units (PAU) [8, 28]. The data from these two databases are integrated with the historical evolution of residential construction practices in Montreal (discussed in Section 2.2.1) to establish a new inventory framework.

3.1.1 | Overview and Limitations of Statistics Canada and Montreal PAU Data Sets

Statistics Canada is the primary statistical agency in Canada and provides information on society, economy, and environment. In the households and dwellings characterization section of Statistics Canada, the data sets present the distribution of dwelling types, categorizing them into single-detached houses, semi-detached houses, row houses, apartments or flats in a duplex, apartments in buildings with fewer than five storeys, apartments in buildings with five or more storeys, and movable dwellings [28]. In terms of limitations, the data sets lack details such as years of construction, number of storeys, and structural systems. Additionally, the statistics are only available for independent municipalities and for the entire CM municipality as a single entity.

On the other hand, the *Montreal PAU* database provides two types of data sets—attribute and spatial—which include information on the number of units and their unique addresses, building categories (i.e., Regular and Condominium), the number of storeys in buildings associated with these units (available only for the Regular category), years of construction, and building areas [8]. The spatial data sets detail geographic forms and locations suitable for geographic information system software, while the attribute data sets are available in Comma-Separated Values (CSV) format. Unlike Statistics Canada, which does not necessarily provide separate data for all boroughs within the CM municipality, the Montreal PAU database does offer this level of detail. However, it does not contain any information on structural systems. The CSV files contain data for 456,646 unique addresses. Some records, particularly within the Condominium category, lack data on either the number of storeys or the year of construction. After excluding these incomplete records, the final sample represents 63% of all residential addresses in Montreal. It is important to acknowledge that this partial coverage may introduce sampling bias. This refined data set is used to estimate the distribution of residential units by structural system across each borough in the CM and the independent municipalities. Table 2 provides a comparative summary of the availability of key data attributes such as the number of units, dwelling type, number of storeys, and year of construction, from both Statistics Canada and the Montreal PAU database.

3.1.2 | Application of the Available Data Sets

As discussed, neither database provides detailed information on building structural systems, which is a key requirement for regional seismic risk assessment. To address this gap, the following inventory framework was developed by integrating both open-access databases through a complementary approach:

- *Statistics Canada* is employed to obtain the total actual number of residential units for all independent municipalities, and the entire CM as a single entity.

TABLE 2 | Availability of key residential building attributes across open-access data sets (as of the time of this study).

Data attribute	Open-access databases	For each independent municipality	For the City of Montreal (CM)	
			Aggregate*	For each borough
Number of units	Statistics Canada	Yes	Yes	No
	Montreal PAU	Yes	Yes	Yes
Dwelling types	Statistics Canada	Yes	Yes	No
	Montreal PAU	No	No	No
Number of storeys	Statistics Canada	No	No	No
	Montreal PAU	Partial	Partial	Partial
Year of construction	Statistics Canada	No	No	No
	Montreal PAU	Partial	Partial	Partial
Structural systems	Statistics Canada	No	No	No
	Montreal PAU	No	No	No

*"Aggregate" refers to data availability for the entire CM as a single entity.

TABLE 3 | Correlation between Statistics Canada's dwelling types and the number of building storeys.

Statistics Canada's classifications	Typical number of storeys
Single-detached, semi-detached, row houses, and apartments or flats in duplexes	1 or 2
Apartments fewer than five-storey	3 or 4
Apartment with five storeys or more	5 or more

 Montreal PAU is used as a sampled data set in two ways for obtaining:

1. *The proportion of residential units in each borough:* The Montreal PAU data set is first used to determine the proportion of residential units within each borough of the CM. These proportions are then applied to the total number of units for the entire CM obtained from Statistics Canada, allowing the estimate of the actual number of units in each borough.
2. *The distribution of structural systems:* The Montreal PAU data set, combined with the historical context of residential building development, is also used to derive the distribution of structural systems based on building material, number of storeys, and year of construction across all administrative areas in Montreal, including both the CM and the independent municipalities.

Note that while both sources include data on the number of residential units, Statistics Canada's standardized dwelling type classifications allow for a more consistent estimation of the number of storeys by linking each type to typical building heights. Since the Montreal PAU data, particularly for condominiums, provides partial information in terms of the number of storeys, Statistics Canada's categories offer a more stable foundation for estimating vertical distribution. Additionally, using two independent data sets strengthens the analysis by allowing cross-verification and improving the overall reliability of the results.

3.2 | Inventory Framework for Residential Units

A standardized and systematic inventory framework is presented to address the limited information on structural systems of residential buildings and their corresponding units in Montreal. The first step involves obtaining the total number of residential units for each independent municipality and the entire CM, based on data provided by Statistics Canada. Given the significance of storey-based differentiation in seismic vulnerability analysis, the existing dwelling type classifications by Statistics Canada should be further detailed. Therefore, units can be divided into three subgroups: one- and two-storey buildings, three- and four-storey buildings, and buildings with five-storey or more [32]. This can be achieved using Table 3, which illustrates the correlations between Statistics Canada's dwelling types and the number of storeys in buildings associated with them.

To estimate the proportion of residential units in each borough, the Montreal PAU sampled data set is used, following the classifications outlined in Table 3. By determining the proportion of units for each borough based on the Montreal PAU samples and the total number of units provided by Statistics Canada for the entire CM, the actual number of units in each borough can be separately estimated.

After determining the residential unit counts for each administrative area, including boroughs and independent municipalities, the next step is to analyze the distribution of units based on materials, the number of storeys in buildings associated with those units, and key years of construction. For this analysis, again, the Montreal PAU sampled data set is employed. The analysis aims to evaluate the distribution of common structural systems based on both the number of storeys and years of construction. According to Section 2.2.3, the most common structural systems for residential buildings in Montreal include wood (W1, W1A), masonry buildings (solid masonry, i.e., URML, URMM; and mixed structural systems, i.e., URML-W, URMM-W) as well as concrete-based buildings (C1, C2, or C3). The next step is to identify the default key years of construction for those common structural systems and allocate the residential units accordingly. Analysis of the Montreal PAU sampled data set indicates that fewer than 0.1% of residential units were constructed before 1850, representing a negligible portion of the total building stock. As a result, the inventory framework focuses on buildings constructed after 1850. In the following, the classification related to each subgroup in Table 3 is discussed.

3.2.1 | One- and Two-Storey Residential Buildings

As shown in Table 3, single-detached, semi-detached, and row houses plus apartments in duplexes fall under the category of one- and two-storey buildings. The use of construction materials for these buildings has evolved due to changes in zoning regulations. Historically, one- and two-storey residential buildings were constructed with wood and masonry classified as W1, followed by URML; however, by the mid-19th century, wood became the predominant material [39]. Following the great fires of the 1850s and the subsequent ban on new wooden construction, there was a notable shift towards URML and URML-W buildings. Most URML buildings were constructed before the 1880s, while URML-W buildings began appearing after the 1850s and gradually became more prevalent, driven by the rising costs of solid masonry construction in Montreal at that period. Fire regulations remained in effect in boroughs within the CM until the 1970s (see *boroughs in Table 1) and in other administrative areas until the 1950s. Given that URML-W system continued to be used until the late 1950s (or the 1970s within the central municipalities) and was employed over a much wider period compared to URML buildings, which offered greater accommodation in response to population growth, it can be concluded that URML-W buildings were the dominant type of one- and two-storey residential buildings between 1850 and 1950 [2, 58, 59]. With advancements in fire-resistant methods, the prevalence of mixed structural systems diminished due to improvements in design codes and construction practices [2, 58]. Consequently, innovations in wood construction led to a revival in wood light frame construction for low-rise and mid-rise residential buildings after the mid-1940s, a trend that has persisted to the present day [39]. Based on this information, an inventory framework for one- and two-storey buildings is outlined in Figure 2. As shown, residential buildings with one or two storeys constructed between 1850 and 1950 may be classified as URML-W, while those built after 1950 are classified as W1.

3.2.2 | Three- and Four-Storey Residential Buildings

Another subgroup for the inventory framework is residential buildings with three or four storeys, which may belong to apartments with fewer than five storeys in accordance with Table 3 [28]. A similar approach for one- and two-storey buildings can be applied to three- and four-storey buildings, with some modifications. For the ones constructed between 1850 and 1950 (or 1970), the classification includes URMM-W for three-storey buildings, since the majority of mixed structural

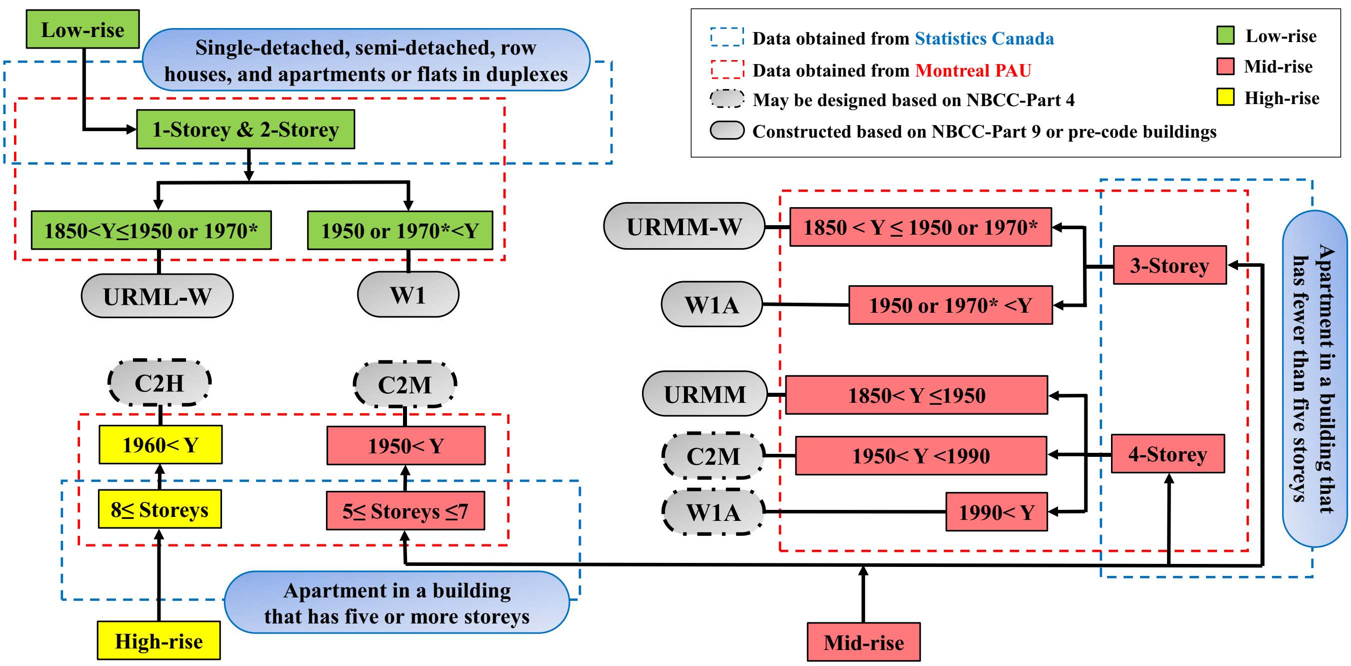

FIGURE 2 | Inventory framework for Montreal based on building types, number of storeys, and key years (Y). *The years 1950 and 1970 should be considered respectively for residential units located in independent municipalities, excluding the City of Montreal (CM), and for boroughs within CM before the 2002 merger.

systems were typically constructed up to three storeys, and URMM for four-storey buildings [37, 43]. For the buildings built after the year 1950 (or 1970), W1A is used for wood light frame residential buildings instead of W1, as most of them are multi-storey and accommodate multiple units. Also, the three-storey and four-storey residential buildings need to be separated due to a critical change in the 1990 NBCC regulation, which increased the maximum allowable storeys for wooden buildings from three to four [60]. Thus, four-storey residential buildings constructed after year 1950s should be divided into periods before and after 1990. Following this adjustment, four-storey apartment buildings constructed after 1990 can be classified as wood light frame construction, or W1A; in contrast, buildings constructed before 1990 (i.e., between 1950 and 1990) are likely to employ different structural systems, as mid-rise apartment buildings became more common starting in the 1950s—most notably concrete-based systems (i.e., C1, C2, or C3), as discussed in Sections 2.2.1 and 2.2.3. To simplify the inventory, only C2 is selected as the dominant structural system for four-storey buildings during that period. C2 buildings dominate apartment construction in Canada, and many studies focus on the use of concrete shear walls, identifying them as a common lateral load-resisting system in the country [2, 39, 40, 48, 49, 61–64]. On the other hand, C3 buildings have typically been used for commercial and industrial structures in Canada. Most of these can be classified as pre-code buildings, as they were generally constructed between 1915 and 1960 [2, 40].

3.2.3 | Five-Storey or More Residential Buildings

The last category refers to residential buildings with five or more storeys. The most common structural systems in this category are C2 and C3. Similar to four-storey buildings, most C3 buildings in Eastern Canada were constructed before 1960 [40]. As discussed in Section 2.2.1, the construction of mid-rise apartment buildings began in the 1950s in Canada, with high-rise apartment buildings following in the 1960s. According to the Montreal PAU sampled data set, 84% of mid-rise and 95% of high-rise apartment buildings were constructed after 1960, indicating a lower likelihood of using C3 in residential buildings. Furthermore, several studies highlight a strong preference for concrete shear walls as the lateral load-resisting system in mid-rise and high-rise residential buildings, especially in seismic zones in Canada [39, 48, 49, 61–64]. Given these factors and also considering that C3 buildings were typically used for commercial or industrial construction, C2 can be assumed the typical structural system for both mid-rise and high-rise residential buildings in Montreal [2, 39, 40, 48, 49, 61–64].

As outlined in Figure 2, the roadmap for determining common structural systems during key periods involves categorizing residential units based on factors such as material, number of storeys, and year of construction. To summarize the inventory framework, the following steps should be taken into account:

- *For independent municipalities:*

  Step 1. Obtain the actual number of residential units from Statistics Canada for each building subgroup listed in Table 3.

  Step 2. Classify the Montreal PAU sampled data set by the number of storeys and key years shown in Figure 2 to determine the distribution of common structural systems as percentages. Then, generalize these percentages to the actual number of units using the results from Step 1.

- *For boroughs within the CM:*

  Step 1a. Obtain the actual number of residential units from Statistics Canada for each building subgroup listed in Table 3 for the entire CM.

  Step 1b. Use the Montreal PAU sampled data set to determine the proportion of residential units as a percentage in each borough, following the classifications in Table 3. Then, apply these proportions to the total actual number of units in the CM (obtained in Step 1a) to estimate the actual number of units in each borough.

  Step 2. Utilize the Montreal PAU sampled data set again to classify the units by the number of storeys and key years shown in Figure 2. Determine the distribution of common structural systems as percentages, and then generalize these percentages to the actual number of units using the results from Step 1b.

To demonstrate the inventory methodology and the process of preparing results, two administrative areas have been selected as examples: Westmount (WM), an independent municipality, and Ville-Marie (VM), a borough within the CM. The discussion and related results can be found in Section 4.2.

4 | Results and Discussion

The results of using data from open-access databases and the outcomes of the proposed inventory framework are presented in the following sections based on the steps defined in the methodology for both independent municipalities and boroughs of the CM.

4.1 | Actual Number of Residential Units (Step 1)

The classified results from Step 1 of the methodology for independent municipalities and Steps 1a and 1b for boroughs within the CM are presented in Figure 3, utilizing Statistics Canada dwelling data sets and the classifications detailed in Table 3. Figure 3a displays the locations of independent municipalities in lighter gray and boroughs in bolder gray, along with their respective abbreviations. In Figure 3b, the actual count of residential units in independent municipalities and the entire CM area is illustrated. Since Statistics Canada does not provide the number of residential units separately for each borough within the CM, the total number of residential units for the CM has been distributed among the nineteen boroughs based on proportions derived from the sampled data set provided by Montreal PAU, as shown in Figure 3c.

Based on the results, Montreal has almost one million residential units, the majority of which are concentrated in the central part of the island. The statistics illustrate that 53% of the residential units are in buildings with fewer than five storeys,

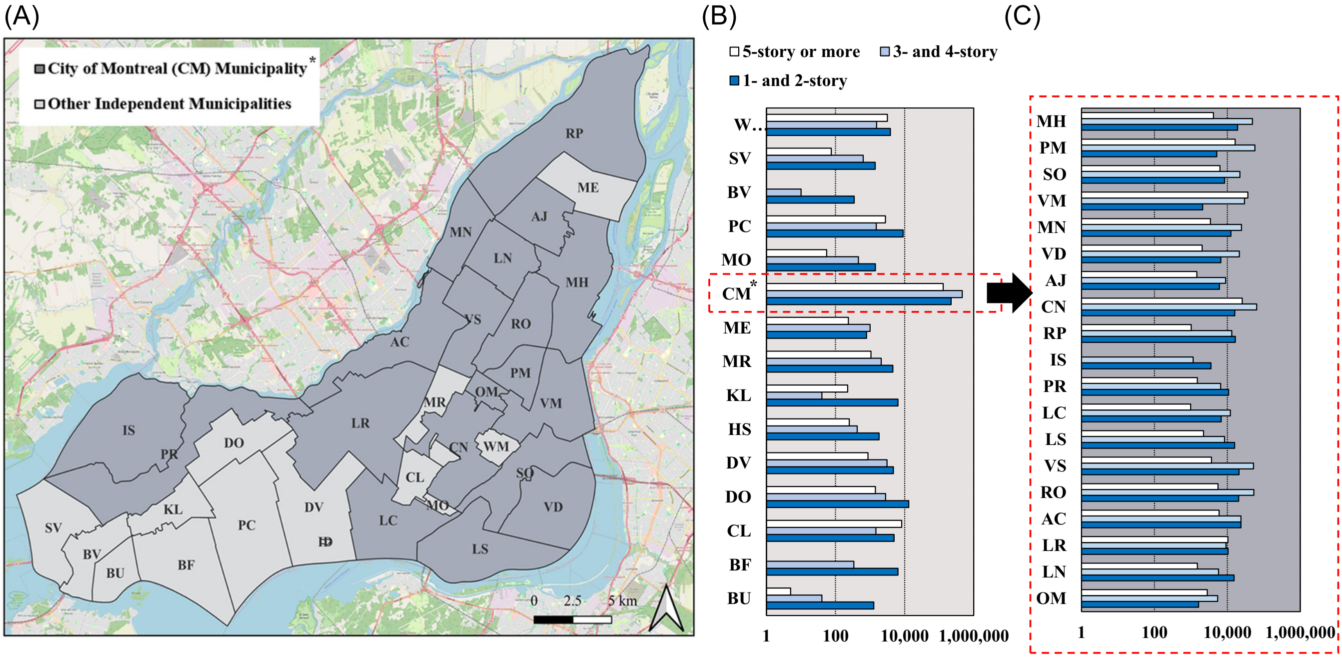

FIGURE 3 | (A) Location of administrative areas in Montreal, including independent municipalities and boroughs within the City of Montreal (CM), (B) number of residential units across all independent municipalities and the entire CM based on Statistics Canada data, and (C) distribution of residential units in the CM between its boroughs based on the proportion of sampled data sets Montreal PAU.

which are categorized as three- and four-storey buildings. Also, 31% of the units are in one- and two-storey buildings, while 16% of the units are located in buildings with five or more storeys.

Among the boroughs in the CM, Ville-Marie (VM), Côte-des-Neiges-Notre-Dame-de-Grâce (CN), and Ahuntsic-Cartierville (AC) exhibit higher densities of units in buildings of five storeys or more, three or four storeys, and one or two storeys, respectively. In independent municipalities, Côte-Saint-Luc (CL), Dorval (DV), and Dollard-des-Ormeaux (DO) have a greater number of units across the same building categories.

4.2 | Distribution of Residential Units Based on Structural Systems (Step 2)

The estimated percentages of seven defined building structural systems—W1, W1A, URML-W, URMM-W, URMM, C2M, and C2H—for residential units are presented as pie charts in Figure 4. The size of each pie chart is relatively scaled according to the total number of units in each administrative area. For example, in the central part of the island, the pie charts are larger than those in suburban areas, reflecting the higher concentration of residential units in those regions. Based on the assumptions and the proposed framework for inventory modelling, approximately 30%, 48%, and 22% of the residential units on the entire island are estimated to be wood (W1, W1A), mixed wood-masonry structural systems and masonry (URML-W, URMM-W, URMM), and concrete shear walls (C2M, C2H) buildings, respectively. For independent municipalities, the distribution is 59% wood, 13% mixed wood-masonry structural systems, and 28% concrete shear wall buildings. In contrast, for the CM, the distribution is 26% wood, 52% mixed wood-masonry structural systems plus masonry, and 22% concrete shear wall buildings. The results show that URML-W, URMM-W, and URMM residential buildings are considerably found in the central part of the island, while W1 and W1A are more common in independent municipalities, which are mostly located in suburban areas. Moreover, other structural systems, such as C2M and C2H residential buildings, are also found in both CM and independent municipalities.

To provide more details of the inventory procedure, two administrative areas have been selected for further discussion: Westmount (WM) as an independent municipality and Ville-Marie (VM) as a borough within the CM. Figures 5 and 6 present a summary of the inventory for WM and VM, respectively, based on the defined steps in Section 3.2. As shown in both figures, the initial step is unit classifications based on subgroups denoted in Table 3 and information provided by Statistics Canada. For independent municipalities like WM, the actual number of units for each subgroup is available in Statistics Canada. The residential units were categorized into three subgroups: one- and two-storey buildings, three- and four-storey buildings, and buildings with five or more storeys. These groups accounted for totals of 3885, 1540, and 3165 units, representing 45%, 18%, and 37% of the total, respectively. Afterward, the distribution of common structural systems can be defined using the inventory framework in Figure 2, based on the number of storeys and key years.

However, since Statistics Canada does not provide the actual number of units for each subgroup separately for all boroughs within the CM, but only for the entire CM, the values for each subgroup in Table 3 were initially based on the total data for the entire CM. As shown in Step 1a of Figure 6, the percentage of one- and two-storey buildings, three- and four-storey buildings, and buildings with five or more storeys for the entire CM area can be obtained based on Statistics Canada and Table 3, with

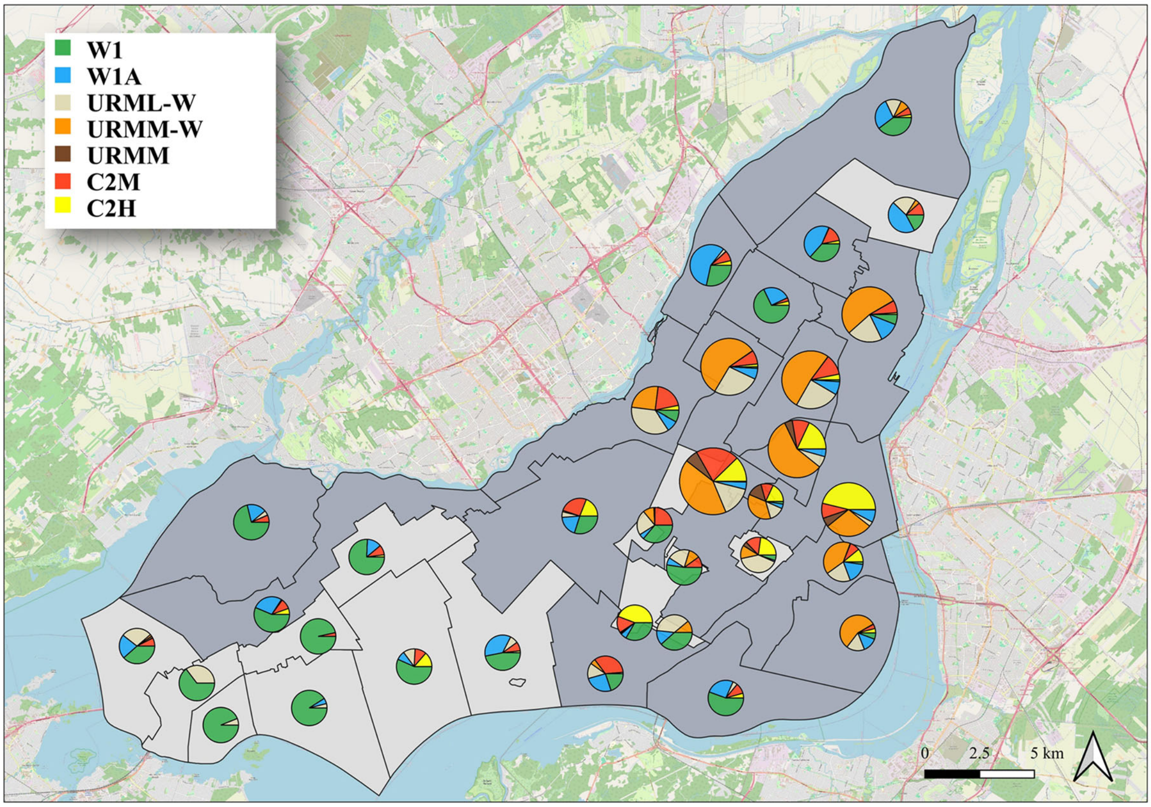

FIGURE 4 | Distribution of common structural systems for residential units based on the proposed inventory framework.

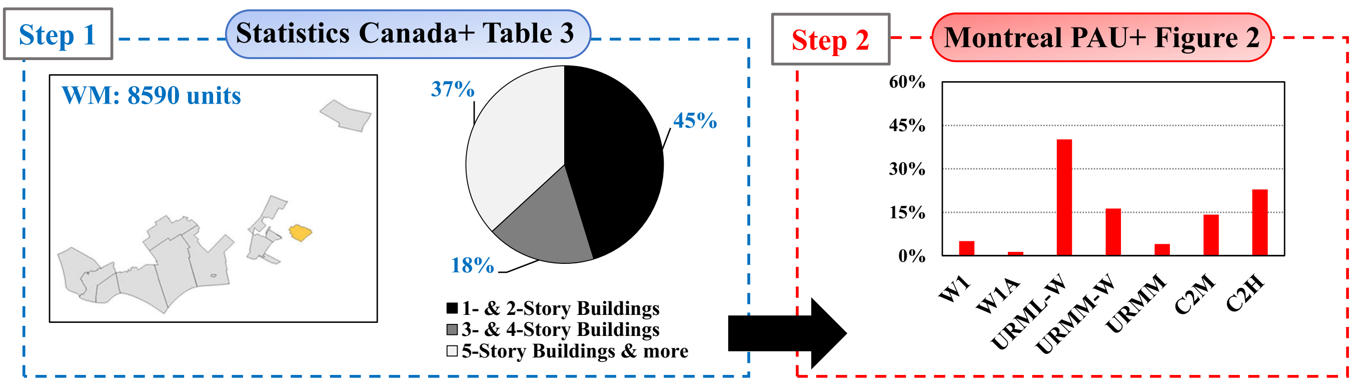

FIGURE 5 | The procedure of obtaining the distribution of common structural systems in Westmount (WM), as an example of independent municipalities.

totals of 220,895, 464,420, and 130,615 units, representing 27%, 57%, and 16%, respectively. Then, in Step 1b of the procedure, the sampled data set provided by Montreal PAU was used to determine the proportion of these units for each borough. From the sampled data, it was found that approximately 1%, 6%, and 28% of residential units in one- and two-storey buildings, three- and four-storey buildings, and buildings with five or more storeys are located in VM. This corresponds to 2097, 29,492, and 36,173 units out of the total 220,895, 464,420, and 130,615 units in the entire CM, respectively.

With the actual number of units for each subgroup in VM, the common structural systems can be estimated based on the guidelines outlined in Figure 2 and again by using the Montreal PAU sampled data set. Based on the final step in both Figures 5 and 6, URML-W and C2H buildings have the highest number of residential units in WM, and URMM-W and C2H buildings have the greatest number of residential units in VM.

4.3 | Application of Inventory Data

4.3.1 | Vulnerability Assessment

The final step in regional seismic risk assessment is the evaluation of building vulnerability, which should be grounded in inventory data. To effectively bridge the gap between inventory and vulnerability analysis, several key elements need to be addressed such as the identification of structural systems, the number of residential units, population distribution, and the

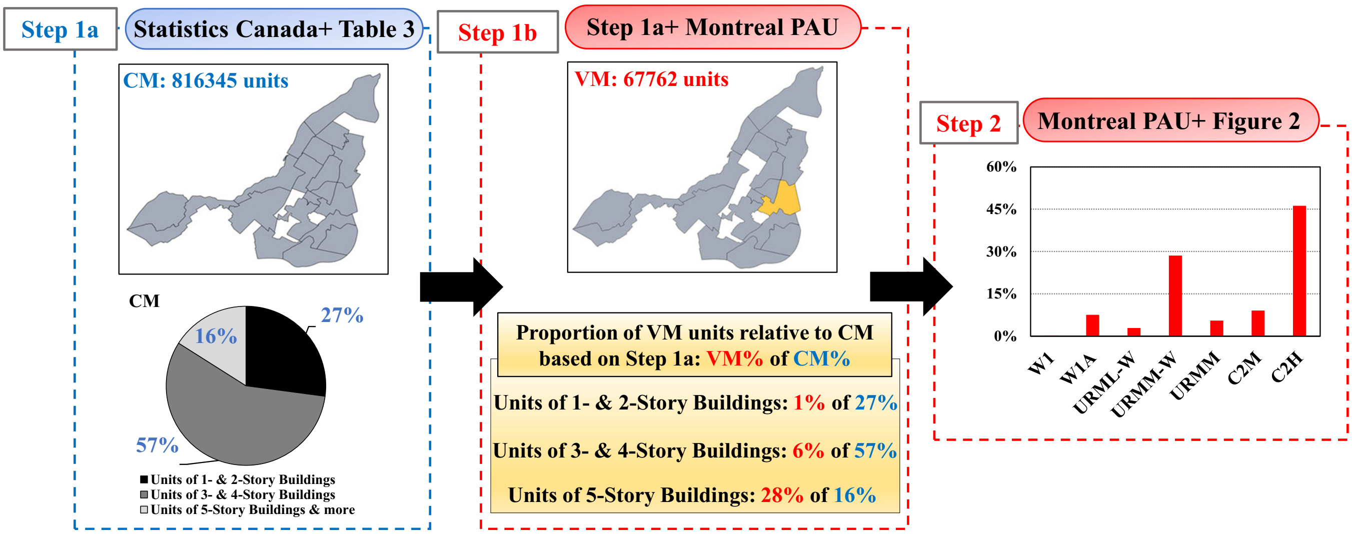

FIGURE 6 | The procedure of obtaining the distribution of common structural systems in Ville-Marie (VM), as an example of boroughs within the City of Montreal (CM).

socioeconomic characteristics of the area. This study aimed to develop a simple yet reliable inventory framework to clarify the structural typologies and unit counts in a complex urban context like Montreal. While the most accurate approach would involve detailed, building-by-building surveys conducted by trained engineers and inspectors, such efforts are time-consuming and resource-intensive. Instead, this framework leverages available open-access data sets and knowledge of historical construction trends to provide timely and practical estimates. These estimates can serve both as a foundation for immediate decision-making and as a baseline for more detailed future investigations. One of the key outcomes of a vulnerability assessment is estimating the proportion of uninhabitable units following an earthquake. This metric depends heavily on the number of units, their associated structural systems, building types, and the seismic design code level of the buildings they occupy. Having access to this information enables the estimation of outcomes based on different intensity measures across the city, offering critical insights into post-earthquake conditions and guiding emergency response planning.

4.3.2 | Regional Adaptation

Although this framework was developed using open-access data sets from Montreal, the underlying methodology is generalizable to other regions of Canada, particularly in the eastern regions. This is due to similarities in construction practices and shared historical patterns in residential development. While some structural systems, such as mixed structural systems, are unique to Montreal, other common types in this study are also found across Eastern Canada due to the evolution of building techniques and adherence to the NBCC. For example, solid masonry construction using brick or concrete block structural walls was widely used in Toronto as well, and the emergence of apartment buildings occurred around the same time in both Montreal and Toronto [39]. The framework relies on the integration of three key components: a review of local construction history, data from Statistics Canada, and city-level property information. The latter two components are typically accessible, as Statistics Canada provides standardized data sets across Canadian regions, and municipal property details can often be obtained through tax roll records or city-based property assessment databases. By combining these elements, a comparable inventory framework can be developed for other cities, facilitating the estimation of building exposure and supporting future seismic risk assessments.

It should be noted that this study necessarily relies on assumptions regarding materials and structural systems. While seismic vulnerability assessments are beyond the scope of this study, it is important to recognize that such assumptions may introduce uncertainties in future loss estimations. Variations in inventory assumptions could lead to different levels of estimated losses. Furthermore, the proposed framework is based on the currently available open-access data sets; however, it could be further refined either in terms of the number of units and incorporating more detailed building-specific information, or by integrating additional urban data sets in future research. Periodic updates using reliable sources would improve the accuracy of the inventory and strengthen its utility for long-term seismic risk and resilience assessments.

5 | Conclusions

This study proposes a new inventory modelling framework for residential units in Montreal, providing a simple yet reliable model that is essential for the assessment of regional-scale seismic vulnerability. The main objectives of the inventory framework are to identify common structural systems of residential buildings in this city and define their distribution in terms of units in each administrative area, including independent municipalities and boroughs within the CM. The framework integrates two open-access data sets from Statistics Canada and Montreal PAU, complemented by a thorough historical review of residential building construction practices in Montreal. The historical review reveals that wood, masonry, and concrete are prevalent materials in the city, with common structural systems for residential buildings including wood light frames (W1, W1A), mixed wood-masonry structural systems and masonry (URML-W, URMM-W, URMM), and concrete shear walls (C2M, C2H). Utilizing the proposed inventory framework, the distribution of each common structural system has been determined for each independent municipality and borough within the CM, and the actual number of units for each structural system has been estimated. The results of this study will fulfill the prerequisites for future studies on regional seismic risk assessment, contributing to the development of post-earthquake mitigation plans and providing insights for estimating different forms of earthquake-induced losses in Montreal.

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Conflicts of Interest

The authors declare no conflicts of interest.

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