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The seismic vulnerability assessment of Québec churches: considerations on territorial specificities

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ABSTRACT

Masonry churches have demonstrated to be vulnerable to earthquakes. The cause of such vulnerability is due to their intrinsic structural characteristics. Many examples of Italian churches could be cited to illustrate this structural vulnerability, based on the long seismic history which characterizes this territory. A series of systematic studies have been performed since the 1976 Friuli earthquake, providing methods for vulnerability assessment, identification of macro-elements and the relative kinematic mechanisms, and damage classification. In this context, the present paper focuses on some territorial aspects, such as materials and techniques of construction, common in Québec churches. They should be considered in the evaluation of the structural performance of the church building under seismic actions. The long Italian history of seismicity and damage experience provides a knowledge base useful also in another context, such as the Canadian one. In this paper, some of the most important Italian earthquakes (Friuli, 1976, Emilia-Lombardy, 2012, Central Italy, 2016) are recalled for specific aspects that were observed and that constitute an experience in the field. These aspects are useful for a preventive analysis of some churches on the Island of Montreal, in the Province of Québec, Canada. Starting from a previous seismic vulnerability study, a research is in progress aiming to identify and define regional macro-elements or mechanisms specific to those churches. An adaptation of the Italian methodology for assessing the seismic vulnerability of churches to a different context, with proper materials and techniques of construction, is proposed in this paper. This approach leads to a method for the seismic vulnerability assessment for churches, specifically related to the territory, keeping as reference the already consolidated procedure.

Keywords: architectural heritage, historic churches, unreinforced masonry, timber, seismic assessment

INTRODUCTION

Churches are part of the historical building stock that are landmarks in the history of a city. Within a territory, they are the physical proof of the evolution of construction knowledge over the centuries. In seismic prone areas, the presence of such old buildings means that they may have survived many earthquakes. This aspect provides an additional reason to value the investment in the preservation of this Cultural Heritage asset that could be considered as a critical issue in some cities. Around the world, unreinforced masonry churches have shown their structural vulnerability even during low intensity seismic events. The geometrical and constitutive characteristics of these building typologies, such as slender high walls, presence of thrust elements like vaults or arches, and absence of floor diaphragms, play a determinant role in their seismic behaviour.

Since the second half of the 20th century, many strong earthquakes have struck different areas of the Italian territory [1], causing damage to masonry churches but also stimulating a constant evolution of the knowledge in the field of seismic vulnerability assessment. The 1976 Friuli earthquake (Mw 6.5) has provided an opportunity to study how churches behave under seismic actions, as a large amount of data on observed damage have been collected. Seismic assessment methodologies that were developed for common masonry buildings could not be applied to church structures. Doglioni et al. used data collected from Friuli earthquake to develop a first methodology for church damage and vulnerability assessment [2]. It is based on considering independently the behaviour of each part of the church buildings (aisle, transept, nave, façade, etc.), or macro-elements, and the identification of recurring failure mechanisms or damage patterns for each macro-element [2]. Subsequent work lead to the definition of 28 kinematic mechanisms for churches, which have become the reference for damage recognition campaigns or, in a perspective of prevention, for vulnerability assessment [3, 4]. The literature provides several examples of applications of this methodology as a tool to study or assess damage, especially in consequence of the major seismic events of the last decades: L'Aquila (2009, Mw 6.3) [5, 6], Emilia-Lombardy (2012, Mw 5.9) [7], and Central Italy (2016, Mw 6.2) [8, 9].

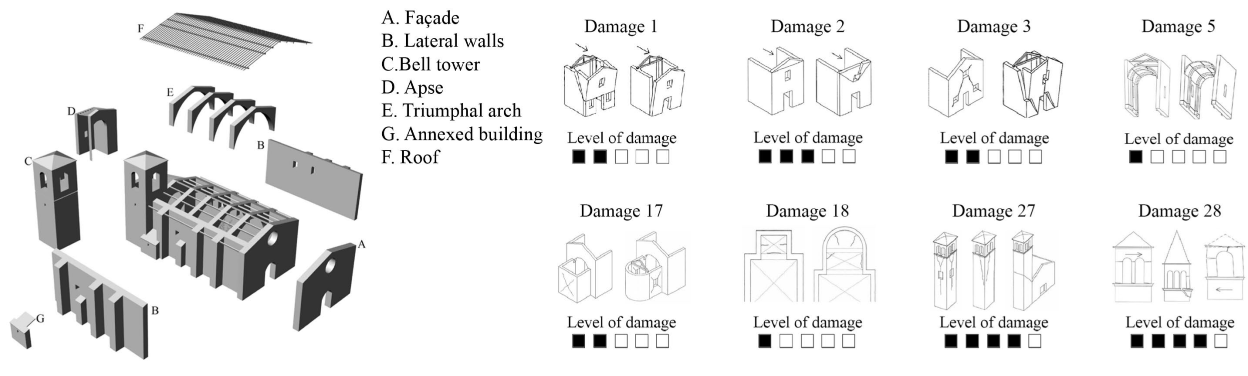
Another important moment in the field was the 1997 Umbria-Marche earthquake (Mw, 6.0). This seismic event presented the opportunity to observe the effectiveness of the strengthening and repairing interventions applied through the years preceding the earthquake [10, 11]. Heavy damage to masonry was observed in churches where previous strengthening and repairing interventions increased significantly local mass and stiffness, such as thick reinforced concrete slabs, rigid localized concrete walls and ring beams. Several churches with such elements performed poorly during the seismic event, demonstrating the inefficiency or an inappropriate realization of these intervention techniques. In 2000, the Regional Authority of Marche published some guidelines in support to professionals, with indications for reconstruction and repairing interventions [12]. In the same years, other manuals of practice were written in other geographical areas, understanding the necessity to act with a territorial vision [13-17]. The positive aspects of this approach are evident as demonstrated by the response of some structural interventions to the 2016 earthquake in Central Italy [18]. Indeed, interventions were executed in some churches after the 1997 Umbria-Marche earthquake following the recommendations collected in the manuals of practice and the response of these buildings to the 2016 earthquake was mostly satisfactory.

In the history of the Italian seismicity, the 2012 Emilia-Lombardy earthquake represents a recent example of area that was classified only recently as seismic. Observed damage on historical buildings and especially on church buildings stresses the importance of working in a preventive approach to reduce their seismic vulnerability in territory with low and moderate seismicity. In the province of Québec, the urban area of Montreal Island, constituting one axis of the seismic Western Quebec zone, is considered to have a moderate seismicity but with a relatively high seismic risk level due to the high density of buildings and the presence of several unreinforced masonry churches (URM). From the information gathered in a previous inventory of 109 churches, these churches present some similarities with the Italian ones [19]. For this reason, a collaborative research project between Politecnico di Milano and École de technologie supérieure in Montreal was initiated to test the applicability of the Italian seismic vulnerability assessment methodology to the churches in Québec.

The objective of this paper is to present some initial results of the application of the Italian methodology to some churches on the Island of Montreal. The attention is focused on the Montreal "territorial specificities" which is based on the identification of typical materials and construction practices for a predominant church typology, the néo-Roman architecture. With such an approach, the vulnerability assessment procedure goes more in detail in the process of knowledge of the building, in relation with the territory where the church is located and with the local construction tradition. The identification of specific kinematic mechanisms is hence facilitated. After a short introduction, the methodology is explained and some initial considerations are formulated for application of this approach to case studies on the Island of Montreal.

THEORETICAL BACKGROUND

Churches are a building typology that, by its characteristics, is vulnerable to earthquakes. In Italy, since the second half of the 20th century, post-earthquake damage surveys have provided abundant material to investigate the structural response of this building typology during an earthquake. The 1976 Friuli earthquake constitutes the starting point of all the following studies. The severity of this seismic event affected a large number of churches [2]. The observation of the way churches reacted to the earthquake led to the formulation of the concepts of *macro-element* and *mechanism*. The structure of a church appears as an assembly of parts, macro-elements, which under seismic actions show a typical kinematic response, the mechanism. Figure 1 is an exemplification of a church, seen as an *ensemble* of macro-elements with the associated kinematic mechanisms and the assessed level of damage caused by the 2016 Central Italy earthquake.



(a) (b)

Figure 1. Example of a church: (a) 3D view of the macro-elements that constitute the church, (b) associated kinematic mechanisms with the level of damage after the 2016 Central Italy earthquake [22].

In 2006, the official version of the damage survey form to be used in Italy for churches was issued [20]. After an earthquake, teams of experts from MiBAC, the Italian Ministry of Cultural Heritage, and from ReLUIS, a consortium of Italian universities, fill this survey form to provide the Italian Civil Protection Department, founded in 1982, with an overview of the damage observed in the affected territory. In this damage assessment procedure, the experts go through the 28 kinematic mechanisms to evaluate the level of damage from 0 (absence) to 5 (collapse), referring to the damage classification defined in the European Macroseismic Scale, EMS-98 [21].

A similar procedure is also available for a preventive analysis to assess the seismic vulnerability of churches. To this purpose, in 2011 MiBAC elaborated guidelines for assessing and implementing the seismic safety of cultural heritage assets [23] that recognize the importance of preventing the damage to churches. This procedure includes the evaluation of the vulnerability of each single macro-element, as well as the verification of the presence or absence of seismic devices that could avoid or facilitate the development of a specific mechanism [24]. The assessment leads to the attribution of certain coefficients to express the vulnerability of each single macro-element. However, this effective and powerful method has some limitations, as pointed out in [25] and is mostly suitable for rapid surveys. The necessity to look in detail at specific aspects of the building as well as in the local construction tradition is fundamental for an accurate analysis, even more from one seismic territory to another. The seismic hazard of the province of Québec is moderate, with the exception of Charlevoix region the most seismically active region of Eastern Canada. Montreal is located in Western Québec Seismic Zone enclosing the Ottawa Valley from Montreal to Temiscaming, as well as the Laurentians and the Eastern Ontario. The seismic hazard combined with the vulnerability of the churches makes evident the importance of a preventive seismic vulnerability analysis of this building typology. Table 1 provides an overview of the historical seismicity of the province. Major earthquakes, which struck the province of Québec from the 17^{th} to the 21^{st} century, are listed in the table together with the damage reported to churches and unreinforced masonry elements.

Table 1. Major earthquakes and reported damage in the province of Québec [26].

Year	Magnitude Mw (*Estimate)	Region	Reported damages to churches and unreinforced masonry elements
1663	7*	Charlevoix-Kamouraska	Nonstructural damages to churches / Collapse of chimneys
1732	5.8*	Montréal	Bending of bell towers / Light damages to houses / Failure of chimneys
1791	6*	Charlevoix-Kamouraska	Damages to 3 churches
1860	6*	Charlevoix-Kamouraska	Failure of one bell tower and wall cracking
1870	6.5*	Charlevoix-Kamouraska	Severe damages to 2 churches: Collapse of the portal and part of the vault, cracking of walls
1925	6.2	Charlevoix-Kamouraska	Collapse of one church (out of plane failure of lateral walls and roof collapse) / Severe damages to 2 churches: Falling of blocks of bell tower, out of plane failure of unreinforced walls, shear cracking, / Collapse of chimneys / Severe damages to masonry houses
1935	6.1	Témiscamingue	Damages to 80% of chimneys and masonry walls
1988	5.9	Saguenay	In plane shear failure of unreinforced masonry walls an infill and cracking at opening corners / Out of plane failure of unattached partition walls and masonry claddings / Damage to churches (out of plane failure of facade) / Cracking of foundation masonry blocks / Damage to chimneys
2010	5.0	Val des Bois	Damages to chimneys and out of plane failure of a church gable

In Québec, the path towards the seismic vulnerability assessment of churches with the application of the Italian methodology started in 2009, with an exhaustive structural inventory of 109 churches built on the Island of Montreal before 1945 [19]. A significant portion of these churches has a heritage value or a confirmed interest. The response of the façade and the bell tower, known as the most vulnerable macro-element and frequently studied in the Italian research field, see for example [27, 28], were studied. Moreover, the quality of the masonry and the presence of wood truss framing in the churches and some recurrent plan and façade church typologies were pointed out, tracing the path for the following investigation that aims to preserve this Cultural Heritage asset.

THE METHODOLOGY

The methodology, presented in this work, is intended for the seismic vulnerability assessment of churches. In this preventive phase analysis, the acquisition of knowledge on the investigated church is facilitated by the time available to correctly use different sources of information. The complex process of knowledge acquisition on the building in a territory includes several stages. For this reason, it is important to study the vulnerability of a church from two perspectives, on one side considering the building in the territory, and on the other considering the specific aspects of the building itself. They are not necessarily addressed in chronological order, as the constant shifting from one vision to the other is required for a better comprehension of the building.

The building in the territory.

The church is located in the territory and put in relation with the seismicity of the site, the local soil condition and the history of seismicity of the territory. This last aspect is fundamental to understand traces of interventions or to explain some changes that the building could have undergone. The history of seismicity is also a guideline to look for information in the different archives of the parish, the diocese or the municipality. In this way, the research can focus on specific aspects relevant to the building and for the goal of the investigation. In [22], the history of seismicity of the site, put in relation with the building, facilitates the comparison between two states of post-earthquake damage and it helps understanding possible correlations between interventions and damage.

The building.

This stage refers to the proper aspects that characterize the building. Simple questions guide the process of knowledge acquisition on the building:

What is the plan and elevation configuration of the church? What is the structural configuration of the building? How do the different structural units interfere one with the other? What is the construction building material of the structure? Is the box-like behaviour guaranteed? What is the type of roof system (vault, truss, etc.)? Are there any thrust elements? What are the principal macro-elements of the church? Are there any aspects difficult to be described through the 28-kinematic mechanisms procedure? Are there any known interventions, or visible ones? Are there any cracks? Are there any common or recurrent aspects of construction in the considered territory?

All the information that derives from the above steps of analysis aims to assess the vulnerability of the church. The original mechanism-based procedure was developed for rapid investigations. In a less time-constrained condition, the seismic vulnerability assessment can be performed at different levels of detail depending on the specific situation. In some cases, architectural and numerical models can be developed to understand the structure of the building and its seismic behaviour as a basis for identifying the damage mechanisms most likely to develop. When common typologies or conditions are identified, considerations from a previously studied case can be extended to another, contributing to the process of knowledge acquisition on other churches. In other cases, the observation of damage in other contexts with similar conditions and the consultation of the literature becomes crucial to include all relevant aspects in the vulnerability assessment procedure: for example, structural interventions that were executed in a certain way and have shown to be ineffective or otherwise helpful to improve the seismic performance of the structure. Other experiences of post-earthquake damage events are useful to observe possible weakness of the building in cases where no intervention has been done.

THE APPLICATION OF THE METHODOLOGY TO SOME CHURCHES IN MONTREAL, QC

The proposed methodology was applied to a certain number of churches located on the Island of Montreal and selected from a previous inventory of 109 churches (figure 2), identified as representative of the traditional religious architecture and studied with the aim of evaluating their seismic vulnerability [29].

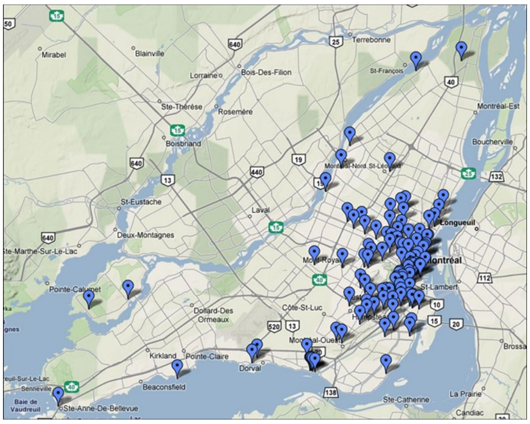
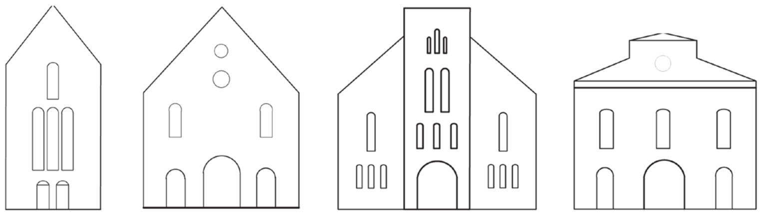


Figure 2. Inventory of the 109 churches on the Island of Montreal [29].

From the information gathered in the inventory, some churches present common features, such as the plan or the façade configuration or symptomatic structural problems. These were the rough and principal reasons that oriented the selection of the visited churches. Four principal church typologies are defined according to the façade configuration: Baillargé (1790-1820), Conefroy (from 1800), Néo-roman (1880-1930), and Italian baroque (second half of 1800) church typology (figure 3).

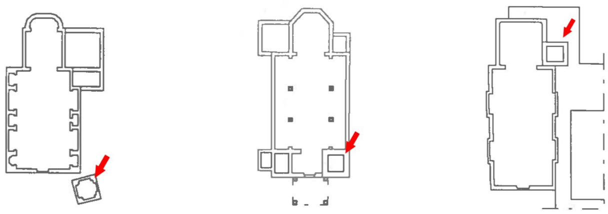


(a) (b) (c) (d)

Figure 3. Façade typologies of the churches in Montreal: (a) Baillargé, (b) Conefroy, (c) Néo-Roman, (d) Italian Baroque.

Some survey forms were prepared in advance in order to collect detailed and accurate information during the on-site visits. These visits include visual recognitions of the state of conservation and of existing cracks, materials and techniques of construction, and inspections of the roof and foundations. Moreover, some dimensions were taken to draw plans and elevations with the aim at identifying some common or interesting aspects that could require an in-depth study. The on-site visit is a crucial stage of the procedure to confirm the state of conservation of the building and at the same time to validate some hypothesis. During the on-site phase, the building was observed from the perspective of the local construction tradition to suggest the most appropriate interpretations. One of the first elements of interest was the different use of the construction material compared to the Italian churches. In the churches visited in Montreal, stone masonry is used for the external structural walls while, when present, the internal bearing colonnade system is made of wood, the roof system is composed of large wood timber trusses and the bell tower is a mixed use of masonry and timber.

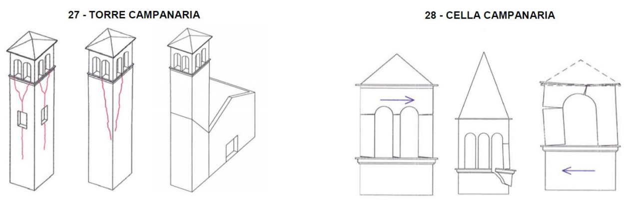
Another crucial phase of the survey was the identification of the existing macro-elements according to the Italian abacus of macro-elements. Immediately, this procedure pointed out a difficulty in the identification of some macro-elements and the corresponding possible kinematic mechanisms. In the néo-roman typology the position of the bell tower differs from the typical conditions notable on the Italian territory. Figure 4 shows some examples of the usual position of this architectural element in the Italian churches.



(a) (b) (c)

Figure 4. Typical position of the bell tower in the Italian church typologies: (a) independent from the rest of the church, (b) on one corner of the façade, (c) on the backside of the church included in the structure of the church.

According to the Italian kinematic mechanisms, two kinematic mechanisms are associated to the bell tower macro-element: mechanism of the bell tower along the height (Mechanism 27, figure 5a) and mechanism of the upper portion of the bell tower (Mechanism 28, figure 5b).



(a) (b)

Figure 5. Bell tower mechanisms: (a) Mechanism 27, (b) Mechanism 28.

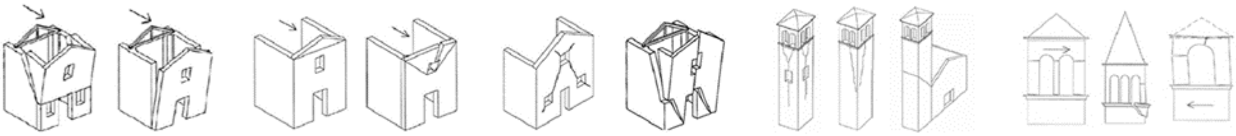
In the case of the néo-roman typology, the bell tower stands in the middle of the façade interrupting the continuity of the façade macro-element. Figure 6 shows three examples of néo-roman churches on the Island of Montreal.

(a) (b) (c)

Figure 6. Examples of néo-Roman churches in Montreal:(a) Immaculée Conception, (b) Presentation de la Sainte Vierge, (c) Saint Joseph.

The position of the bell tower makes it difficult to perform a seismic vulnerability assessment only referring to the abacus of the 28 kinematic mechanisms of the Italian methodology. In this case, the involved macro-elements are the façade and the bell tower and the seismic vulnerability of the following mechanisms have to be evaluated [24]:

- Mechanism 1: overturning of the façade (figure 7a);
- Mechanism 2: mechanism of the upper part of the façade (figure 7b);
- Mechanism 3: in-plane mechanism of the façade (figure 7c);
- Mechanism 27: mechanism of the bell tower along the height (figure 7d);
- Mechanism 28: mechanism of the upper portion of the bell tower (figure7e).



(a) (b) (c) (d) (e)

Figure 7. Mechanisms related to the macro-element façade and bell tower: (a) Mechanism 1, (b) Mechanism 2, (c) Mechanism 3, (d) Mechanism 27, (e) Mechanism 28.

It is clear that it is necessary to go beyond the rapid 28-kinematic mechanisms procedure. The consideration of other aspects of these macro-elements, such as how they are constructed and what is the connection between the bell tower and the façade, becomes crucial. Visual inspections of the above church examples show that the structure of the bell tower is strictly tied to the façade, the “jubé” (church balcony or roof screen) and the lateral walls. Analysis of the construction materials visibly shows that the structure of the bell tower is made of wood while the supporting walls and façade are in stone masonry. Figure 8 shows the timber structure of the bell tower observed from the interior of some churches at the level of connection between the masonry of the façade and the timber of the bell tower.

(a) (b) (c)

Figure 8. Examples of the structure of the bell tower at the level of connection with the façade: (a) the timber structure of the bell tower is attached to the façade masonry wall, (b) the structure of the roof intersects with that of the bell tower, (c) the timber structure of the bell tower starts inside the masonry of the façade.

Another significant aspect related to the construction tradition of this territory is represented by the structures of the roof of these churches, as shown in figure 9. Often difficult to be inspected, this part of the building plays an important role in the box-like behaviour of the structure, a key element for a good seismic performance [30, 31].

(a) (b) (c)

Figure 9. Examples of roof structures of visited churches in Montreal Island: (a) Sainte-Famille, (b) Présentation de la Sainte Vierge, (c) Saint-Joseph.

A 3D model of a case study of the néo-roman typology is in progress to understand possible implications of these construction practices, frequently observed in this territory. Some ambient vibration measurements were also taken both on the ground and in the building to identify, respectively, the natural frequency and possible local amplification effects of the site and the natural frequency and vibration modes of the building. Moreover, the understanding of the behaviour of the bell tower is important because it helps to preserve this architectural element important both at the building and urban scale, considering that Montreal is known as the "The city of a hundred bell towers" as Mark Twain proclaimed during his first visit of the city in 1888 [32].

CONCLUSIONS

Masonry churches are among the most vulnerable buildings to seismic action. History of damage from past earthquakes in the region of Québec made it worth to study the seismic vulnerability of masonry churches from a preventive perspective. This paper focuses its attention on the applicability of the Italian 28-kinematic mechanisms methodology to some case studies on the Island of Montreal. Differences in local materials and techniques of construction, proper of this geographical area, motivate an investigation of the applicability of the methodology for its adaptation. Territorial specificities are aspects specific to a territory that are subjected to significant changes from one territory to another. A clear example refers to the Néo-roman church typology with the position of the bell tower in the middle of the façade and its material of construction made of timber elements and stone masonry. Ambient vibration measurements were taken on site to assess the possible amplification effects of the ground and of the modal shapes of the building. A 3D numerical model of a church case study, representative for the néo-roman typology, is in progress with the aim to identify possible mechanisms that could help to predict the structural behaviour in case of an earthquake.

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