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Seismic vulnerability of churches: the effect of context-related characteristics

Gessica Sferrazza Papa[a], Marie-José Nollet[b], Maria Adelaide Parisi[a]
[a] *Dipartimento di Architettura, Ingegneria delle Costruzioni e Ambiente Costruito, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy*
[b] *Department of Construction Engineering, École de Technologie Supérieure, Montréal, QC, Canada*

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ABSTRACT
In Italy, a systematic treatment of the vulnerability of churches and of the classification of their peculiar damage modes has been the object of extended studies. Starting from the definition of macro-elements that are the main components of a church structure, affected by specific and recurrent damage patterns, a series of the most frequent limit mechanisms has been defined and is currently adopted in practice in assessment procedures. This work investigates the possibility to apply these concepts and procedures to other regions with different church typologies and constructional traditions and to identify procedural modifications that may be necessary. The documentation of church damage, occurred in the region of Québec, and the seismic risk of the city of Montreal have motivated to set up a collaborative research program aimed at defining an approach suitable for assessing the vulnerability of historic churches in such territory. From a previously developed inventory, churches have been grouped according to their typology, pointing out the constructional characteristics of each group and the damage patterns that may or may not be applicable from the Italian mechanisms. A first prevision is made of other possible context-related damage modes. Structural analyses to confirm these assumptions are in progress.

1 INTRODUCTION

The long history of earthquakes that have affected Italy devastating its architectural heritage, together with the present higher awareness of the need to promote its conservation have motivated the development of methodologies to assess the seismic vulnerability of different masonry building typologies. Specific procedures have been developed for churches, affected by a high level of vulnerability, due to their structural characteristics (e.g. Lagomarsino and Podestà 2004a, 2004b). Earthquakes that occurred in different regions of the country in the last decades, have particularly stressed this weakness (e.g. Binda et al. 2010, Lagomarsino 2012, Sorrentino et al. 2014, Carbonari et al. 2017, Cescatti et al. 2017, Sferrazza Papa and Silva 2018, Penna et al. 2019). Since the 1976 Friuli earthquake, a systematic treatment of the vulnerability of churches and the classification of their peculiar damage modes has been carried out. Starting from the definition of macro-elements that are the main components of a church structure, affected by specific and recurring damage patterns, a series of the most frequent limit mechanisms has been defined.

On this basis, procedures for assessment of vulnerability and damage have been developed and, especially for damage assessment, have been widely applied during the last decades. These procedures rely on an extremely large base of observations of damage from Italian earthquakes, which to some extent relates to local construction characteristics. This work investigates the possibility to extend their use to other areas with significantly different constructional traditions pointing out the procedural modifications that may be required. The work is a first step of a collaborative project on the seismic protection of the religious architectural heritage of the Province of Québec, Canada. From a previously developed inventory, churches have been grouped according to their typology, pointing out their constructional characteristics and the damage patterns that may or may not be applicable from the Italian mechanisms. A first prevision is made of other possible context-related damage modes. Structural analyses to confirm these assumptions are in progress.

2 SEISMIC VULNERABILITY ASSESSMENT FOR CHURCHES

In the last decades, the Italian research on earthquake damage to masonry buildings - and particularly to churches - has brought to a systematization of the most frequent damage modes. Churches may be seen as an assembly of parts, or macro-elements, like the façade, the bell tower, the apse, etc. Since damage tends to occur in such elements in recurring patterns, the main macro-elements and the relevant damage typologies have been defined and classified, becoming a reference in two different operations:

1. the assessment of damage after an earthquake;

2. the rapid assessment of vulnerability, in which the presence of initial damage and other unfavourable conditions in the macro-elements may trigger damage or collapse in a seismic event.

These evaluations are usually performed by visual inspections, based on suitable reference scales. If the quality of the masonry is sufficient to avoid immediate disintegration, the damage, and eventually collapse, develops with the formation of compact blocks delimited by fracture lines and the limit situation of collapse may be represented by the formation of a kinematic chain mechanism. As a consequence, this scheme offers the possibility of estimating the limit capacity of the structure for that mechanism by means of limit equilibrium.

The first definition of church macro-elements was given as a mean for the interpretation of the damage developed in the 1976 Friuli earthquake (Doglioni et al., 1994). The experience acquired in subsequent earthquakes lead to the formulation of an abacus of 28 damage mechanisms that refer to the main macro-elements. For instance, the most frequently recurring mechanisms involving out-of-plane and/or in-plane behaviour of the façade macro-element are represented.

The abacus of mechanisms is reported as reference in the official survey form A-DC (MiBAC, 2006) that is adopted for damage recognition campaigns in Italy. Church damage surveys after the earthquakes of L'Aquila in 2009, of Pianura Padana Emiliana in 2012, and of Centro Italia in 2016 have been performed according to this form.

3 THE SEISMICITY OF QUEBEC AND HISTORICAL DAMAGE IN THE AREA

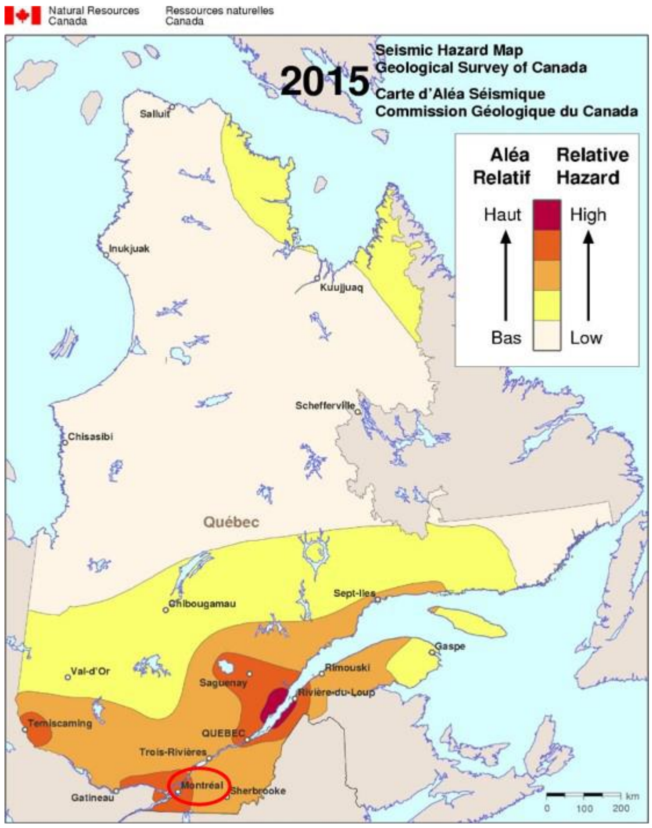


Figure 1. The Seismic hazard map of Québec from the Canadian Building Code (CNBC 2015). The city of Montreal is pointed out with a red circle.

The Pacific coast of Western Canada, as a segment of the Ring of fire, is exposed to a high seismic hazard, while in Eastern Canada, seismic hazard is generally moderate. Figure 1 shows the relative seismicity of the Québec province. The most populated cities, such as Québec City and Montreal, are located in the south of the province. Due to the density of its population Montreal is the second largest city at risk in Canada, after the greater Vancouver (Adams 2010). The seismic risk is further increased in old sectors of the city with a high concentration of unreinforced masonry, URM, buildings. The URM churches are highly vulnerable; additionally, the cultural value of such building stock, with the oldest assets dating back to the 17th century, increases the associated seismic risk.

A characteristic of the geology and soil in Québec is the low attenuation of seismic waves. During the seismic event of Saguenay in 1988, with a magnitude M_w5.9, damage occurred in the city of Montreal at a distance of 350 km from the epicenter (Nollet et al. 2013).

The major earthquakes, which struck the province of Québec from the 17th to the 21st century, are listed in Table 1, together with a summary of the damage reported for churches and unreinforced masonry. The most damaging earthquakes occurred in the Charlevoix region in 1701, 1860, 1870, and 1925. In Figure 1 this area is indicated with the darkest color. The damage reported in Table 1 has to be read bearing in mind that before the end of the XVII century most buildings were built in timber. It is only after major fires which occurred in 1682 and in 1720, respectively in Québec and in Montreal, that masonry construction was enforced inside the fortification walls of the cities by Intendant Dupuy of Nouvelle France.

Table 1. Major earthquakes and reported damage in the province of Québec (Nollet et al. 2013).

Year	Mw (*Estimate)	Region	Reported damage to churches and unreinforced masonry elements
1663	7*	Charlevoix-Kamouraska	Nonstructural damage to churches / Collapse of chimneys
1732	5.8*	Montréal	Bending of bell towers / Light damage to houses / Failure of chimneys
1791	6*	Charlevoix-Kamouraska	Damage to 3 churches
1860	6*	Charlevoix-Kamouraska	Failure of one bell tower and wall cracking
1870	6.5*	Charlevoix-Kamouraska	Severe damage 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 damage 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	Damage 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 façade) / Cracking of foundation masonry blocks / Damage to chimneys
2010	5.0	Val des Bois	Damage to chimneys and out of plane failure of a church gable

4 THE CHURCHES OF MONTREAL

As a first step in the conservation of architectural and historical heritage, an inventory of 108 churches of the Montreal island has been elaborated (Youance 2010), describing the main characteristics in terms of geometry, materials and typology and giving a first synthetic vulnerability assessment.

Starting from this collection, a group of churches was recently selected for further studies. The selection was based on the occurrence of characteristic elements, like the façade type, the presence and location of the bell tower, the plan configuration, in order to assemble a set sufficiently representative of the churches in the territory.

Figure 2 indicates the set of churches further investigated. Each church has been inspected, with the aim at pointing out the local construction characteristics that were expected to affect the seismic structural behaviour. Based on the Italian experience, the presence of elements inducing vulnerability for these structures was checked. The sample was composed of several church typologies. This aspect has pointed out the necessity of observing more specifically the vulnerability for each of them. In fact, working by categories has allowed to observe more in detail the territorial specificities (Sferrazza Papa et al. 2019).

Figure 2. The Seismic hazard map od Québec from the Canadian Building Code (CNBC 2015).

4.1 Principal church typologies

From the sample of the selected churches four principal church typologies were identified. The principal criterion used for the organization into different groups was the façade configuration. The reason is the high vulnerability demonstrated by this macro-element in previous earthquakes. In the Italian experience, many studies focused on the structural response and the corresponding vulnerability of the church façade (e.g. Casolo et al. 2000, Casolo and Uva 2013). Walking down the urban streets, the majority of the churches of the Diocesis of Montreal can be easily brought back to these principal typologies: the Baillargé (1790-1820), the Conefroy (from 1800), the Néo-Roman (1880-1930), and the Italian baroque (second half of 1800). Figure 3 shows the most common church façades.

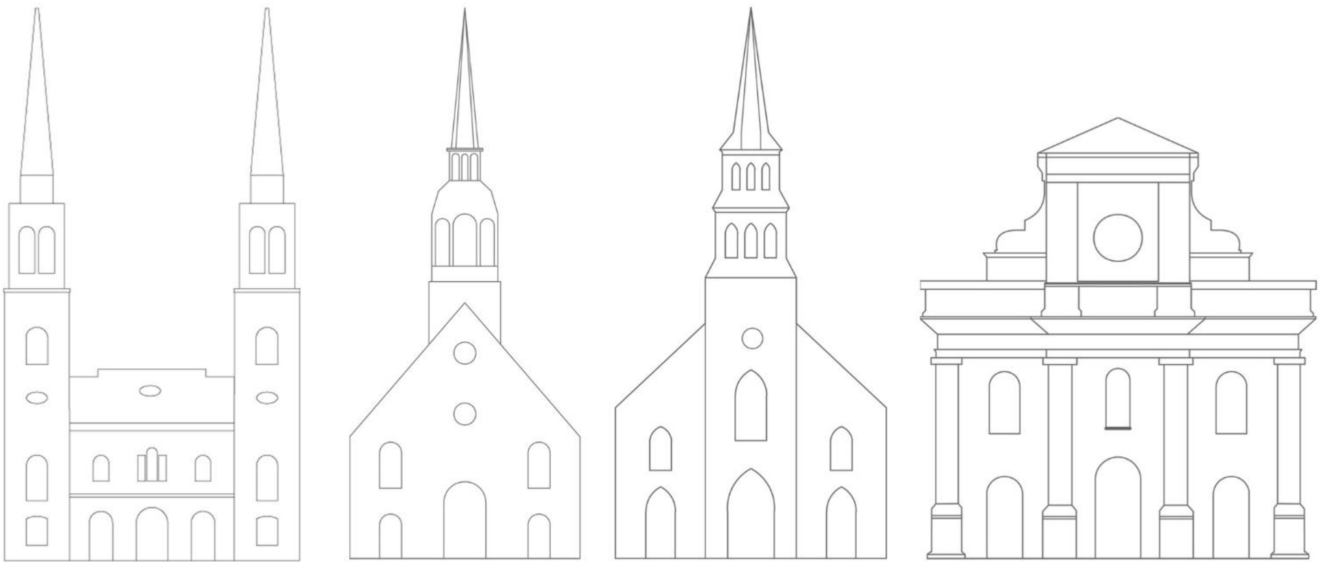


Figure 3. The principal church façades: Baillairgé, Conefroy, Néo-Roman, and Italian Baroque (from left to right).

A peculiar characteristic of these churches is the combined use of timber and masonry as construction materials. The timber is generally employed for the structure of the bell towers, the roof system, and the colonnade of the nave. On the contrary, the use of masonry is relegated to the external walls. The curtain walls are made of local stone blocks that can be roughly square or square cut, depending on the church. They are laid with a regular pattern with, in some cases, transversally laid stone elements to interlock the different leaves. In absence of Non-Destructive Tests (NDT), the hypothesis of a double leaf wall was formulated for what was possible to observe at the roof level. The exterior of the church clearly shows the use of stone for the masonry walls, while the interior walls are covered with timber planks and plaster. Another distinguishing aspect found in this territory is the use of timber that is skilfully employed, concealing the decoration and the structure in the interior of the churches. Other specific characteristics, pointed out during the visit of the different churches, are reported here and organized by typology.

Figure 4. Baillairgé typology: two examples of churches.

The *Baillargé typology* has a façade enclosed by two bell towers (Figure 4). The façade has a symmetrical layout. At the ground floor, it generally presents a principal entrance door in the middle of the façade, and openings or niches on both sides of the entrance. At the second order of the façade, a large central opening, on top of the entrance, and other openings or niches, organized symmetrically, characterize the front. In this typology, the façade and the two bell towers create a sort of diaphragm that separates the exterior from the interior of the nave with an atrium, constituting a massive structure annexed to the rest of the structure of the church. The bell towers are made of masonry up to the first level of the belfry that is higher than the cornice of the gable, while the rest of the structure, that continues above, is made of timber, sometimes painted and other times covered with laminates. The Baillargé churches have typically three naves.

Figure 5. Conefroy typology: two examples of churches.

The *Conefroy typology* is characterized by a bell tower located in the middle of the façade, set back from the façade plan (Figure 5). The façade is frequently characterized by a symmetrical shape in axis with the bell tower and the entrance door, which gives directly access to the nave of the church. Two rose windows, one under the other, are aligned along the axis of symmetry of the façade. One such opening is close to the cornice, at the level of the roof, and one gives light to the nave. Moreover, two large windows are located in the left and right portion of the façade. In some cases, two doors are also present, aligned with the windows, to provide additional access to the church. The pillars of the bell tower are well visible inside the church at the beginning of the nave. Four pillars support the entire structure of the bell tower. They generally describe a square shape, corresponding to the upper part of the bell tower, and they constitute a distinguishing element in this church typology. In the interior of the church, the pillars are arranged in two pairs, one pair is close to the façade and the other penetrates the jubé level, the inner tribune over the main entrance, ending at the ground level of the church. Conefroy churches have a single nave.

Figure 6. Néo-Roman typology: two examples of churches.

The *néo-Roman typology* is characterized by the position of the bell tower that, occupying the central position, interrupts the continuity of the façade and provides the distinguishing configuration visible in Figure 6. The detailed inspection of this typology was fundamental for the comprehension of the structural system that involves the façade and the bell tower. Visiting also the roof and bell tower, the mixed use between timber and masonry was observed. This complex structural configuration makes this typology particularly interesting and worth being more deeply investigated. Néo-Roman churches have typically three naves.

Figure 7. Example of an Italian baroque typology.

The *Italian baroque typology* is characterized by the high slender and lofty façade with pilasters. These regulate the design of the façade and the volutes embellish the gable at each side.

This church typology is composed of three naves that repeat the exterior rhythm of the façade. Most churches of this building typology have unfortunately been destroyed. Figure 7 shows one example of Italian baroque church. In consequence of some renovation works, the interior was transformed from the original state, keeping the three nave distribution, but replacing the vault and arch system, typical of a baroque church, with a flat non-structural slab. Consequently, the structural concept was deeply modified.

4.2 The vulnerability assessment

A seismic vulnerability assessment for Québec churches is necessary. The reasons are: the seismicity of the area, the quantity of churches, 108 inventoried just for the Catholic Diocesis of Montreal in Montreal Island, for which cultural heritage value is recognized, and a new trend in designing rehabilitation projects inside these historical buildings, that tends to underestimate their seismic vulnerability. Motivated by these reasons, the recommendations proposed in the Italian guidelines of Cultural Heritage for the seismic vulnerability assessment of churches (MiBACT 2011) were applied.

First of all, the presence of seismic protection provisions and devices was checked for each church. From this first analysis, the absence of tie rods in the majority of the churches with vaults or arches was pointed out. Only in one case, the tie rods were found. This is the case of a church in the historical centre of Montreal, classified as 'A' according to the regional scale of value of protection and conservation elaborated by the Council of the Religious building stock of Québec (Conseil du patrimoine religieux du Québec). This aspect motivates to say that there is a low awareness of seismic vulnerability for these historical buildings.

As a second step, the interpretation of the church structure was performed by identifying the principal macro-elements and the associated kinematic chain mechanisms, referring to the listed 28 ones. Immediately, this action pointed out the difficulty to apply directly the procedure. Indeed, some of the specific characteristics of the different typologies identified and the construction practice of this geographical area make it difficult to interpret directly the structural behaviour in case of an earthquake. Some of the considerations that have emerged, distinguished by typologies, are the following:

- Baillargé typology.

In this case, the façade is not directly connected with the longitudinal walls of the nave, but it is attached to the two bell towers. Moreover, the façade and the bell towers, for their configurations, constitute a diaphragm, structurally located before the beginning of the colonnade of the nave and the rest of the church structure. A global numerical model could facilitate the comprehension of the influence of such a massive structure directly connected with the nave. The position of the gable, incorporated between the two bell towers, as the rest of the façade, is also interesting to be studied, recurring to local numerical modelling to provide an interpretation of the mechanism on the overturning of the gable. Another characterising aspect for these types of churches is the mixed use of masonry and timber for the structure of the bell tower: the first is used up to a level above the façade, while the second is employed in the higher portion. The transversal response of the nave as well as the longitudinal one of the colonnades require a deeper study. Indeed, the mixed use of timber and masonry makes the structural interpretations difficult for these aspects. The in-plane mechanisms from the listed 28 ones, which describe possible shear cracks in the walls, are valid here, due to the similarities with the Italian churches for the masonry box structure.

- Conefroy typology.

The particularity of this typology is the position of the bell tower and the way it is built in relation with the rest of the church structure. The columns of the bell towers do not interact with the façade structure, just at the roof level, the beams enter the façade wall. The kinematic chain mechanisms, associated to the façade and the bell tower, have to be reconsidered in the light of these specific characteristics. The rest of the structure can be easily read recurring to the rest of the listed mechanisms. The interlocking between the walls that constitute the masonry box of this type of church is generally well-defined with square stone blocks. Some identified cracks that, in case of earthquakes, can facilitate the activation of some mechanisms, were observed. In particular, they were found in correspondence of the central rose window and symmetrically in the façade plane in proximity of the openings. To interpret the implication of the bell tower in such a position, a deeper study on Conefroy churches is in progress.

- Néo-Roman typology.

In this case, the position of the bell tower, that interrupts the façade plan, and the mixed use of timber and masonry do not make it possible to interpret directly the structural behaviour according to the identified mechanisms usually associated to the macro-elements “façade” and “bell tower”. This church typology is under investigation: some numerical models are being developed to understand the implications of such a mixed structure and to set up criteria for the seismic vulnerability assessment (Sferrazza Papa et al. 2019). Also in this case, some cracks were identified. In particular, some symmetrical cracks were observed in the longitudinal walls of the nave in proximity of the façade and in the façade plane in correspondence of the large windows at the second order.

- Italian baroque typology.

This was the typology most similar to the Italian cases. The lofty façade without any seismic devices presents a high vulnerability. At the same time, for the examined case the interior changes, from a vault and arch system to a flat slab, have modified the structural response of the church structure to lateral forces. Although the churches corresponding to this typology are only a few left, it is a clear example of how modifications not related to structural needs can alter the structural conception of a historical building.

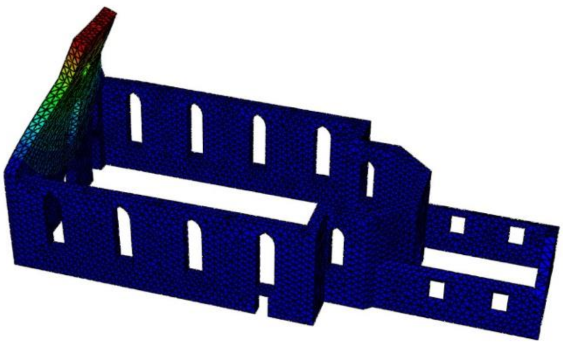
4.3 First numerical results

Among the identified church typologies, a first deeper study is in progress on the néo-roman typology. Saint Joseph, one of the visited churches (Figure 2), was chosen as a case study. A detailed geometrical survey was performed onsite, and a 3-D model of the entire church was elaborated to understand the relation between the different structural elements, due to the structural complexity. This stage was fundamental for the next stage, the elaboration of the global numerical model. To understand the implication of such a mixed structure, timber and masonry, and the global structural behaviour, a first model with just the masonry part was done. As first stage, the contribution of the timber roof and the bell tower was considered as applied masses. **Errore. L'origine riferimento non è stata trovata.** summarizes the first results of the modal analysis of the entire church. They will be compared with those from the modal analysis that is going to be performed including the timber structure of the roof and the bell tower.

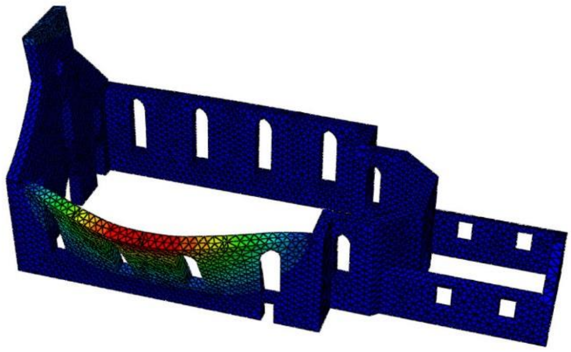
Table 2. Principal modes, periods, and participating masses of Saint Joseph church.

Modes	Period	%Participation mass ratio (Long. direction)	% participating mass ratio (Transv. direction)
1	0.7	0.000	10.400
2	0.3	8.300	0.029
3	0.3	10.800	0.022
4	0.2	0.000	6.240
8	0.2	23.200	0.000
9	0.1	4.270	0.227
10	0.1	2.030	0.428
11	0.1	2.970	0.007
18	0.1	0.014	28.100
19	0.1	0.014	0.172
23	0.1	1.700	0.146
24	0.1	3.570	0.240

The first modal shapes are shown in Figure 8, interesting the façade and the lateral walls of the nave and showing the highest periods for the structure. In particular, for the first mode the value of 0.7 s is justified observing Figure 8a. The behaviour of the structure is symmetrical for consecutive modes, this aspect was observed in Mode 2 - Mode 3 and Mode 23 - Mode 24, involving the lateral walls of the nave, Mode 18 - Mode 19, interesting the lateral walls of the sacristy. These results are interesting to be compared with those from the modal analysis on the model including the roof and the bell tower. Such a comparison aims at understanding how the modes and the relative values of period are influenced by the combination of the two material structures, the masonry and the timber parts.



(a)



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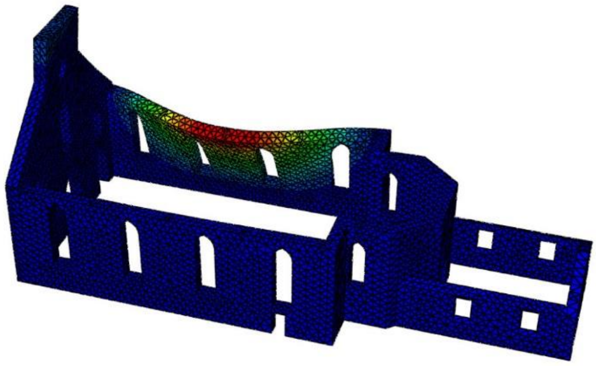

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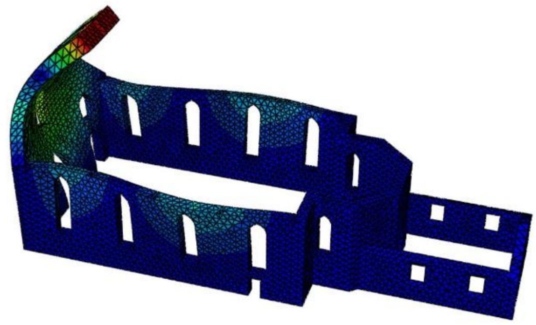

(d)

Figure 8The first three modal shapes: a. Mode 1, b. Mode 2, c. Mode 3, d- Mode 4.

5 CONCLUSIONS

Masonry churches belong to a building category for which the seismic vulnerability has been thoroughly investigated. Results, as well as the procedures developed for vulnerability assessment are based on Italian damage data and are particularly suitable for the most frequent Italian typologies.

The documentation of church damage, occurred in the province of Québec, and the seismic risk of the city of Montreal have motivated the study presented here, and still in progress, aimed at defining an approach suitable for assessing the vulnerability of historic churches in such territory. Attention to specific architectural aspects has allowed to select out of an inventory of 108 cases some churches to be surveyed and investigated with particular depth. A first seismic vulnerability interpretation was performed with reference to the main characteristics of each church typology. The recommendations contained in the Italian Guidelines have been applied to these church cases pointing out the necessity to adapt the methodology to a different geographical context with its own construction tradition. The mixed use of masonry and timber, as construction materials for Québec churches, has shown the necessity to recur to global or local numerical models to interpret the structural behaviour. Indeed, the two materials have a such strictly interrelation that cannot be independently investigated. The study is still at the beginning: two of the identified typologies, the Conefroy and the Néo-Roman, are currently investigated through specific 3D numerical models with the aim to identify possible mechanisms that could help to predict the structural behaviour in case of an earthquake. In this work, the first results of the modal analyses have been discussed.

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