Moderate seismic activity and architectural heritage: methodological aspects and application in Wallonia

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Abstract

During numerous centuries, the heart of the historical cities of North Western Europe was enriched by an invaluable architectural heritage contributing to their specific character. So, most of our cities that originated from the Middle Age are distinguishable by a colourful and sinuous layout of streets bordered by historical houses and enlarging often the perspective in the direction of a belfry or an emblematic building. Since a few decades, we are aware of the value of this patrimony, as well as for the « irreplaceable cultural, social and economic values represented by historic monuments, groups of old buildings and interesting sites in both town and country » [1].

In Wallonia, the seismic history provides us with evidence that our building patrimony suffered from disorders of seismic origin. It is advisable to estimate this risk facing varied specific notions before identifying, with a methodology devoted to emblematic buildings, the seismic origin of some damages of our patrimony, and to propose remediation.

Seismic activity - site effects

The regions of northwestern Europe from the Rhine valley to the southern North Sea are characterized by a weak seismic activity compared to the most active regions of the world. Nevertheless, nearly each year, some earthquakes are felt by the population and, regularly, they cause damages to buildings that are sometimes significant (fig. 1.)

Figure 1 – Consequences of the Liège earthquake on November 8, 1983 (M = 4.7)

The most seismic active region of the northwest of Europe is the bordering region between Belgium, the Netherlands and Germany. The strongest known seismic event occurred on 18 September 1692, producing significant destructions, including most of the patrimonial building, in the northern part of the Belgian Ardenne. The earthquake caused widespread damage from Kent in England to the Rhineland in Germany and to Champagne in France [2] [3].
Historical sources provide also information on other earthquakes that caused important damages to houses but that also affected the patrimony. The most significant are the earthquakes on May 21, 1382 (M ~ 6) in the southern North Sea, on April 6, 1580 (M ~ 6) in the Strait of Dover, on September 18, 1692 (M ~ 6 ¼) in the north of the Belgian Ardenne, on February 16, 1756 (M ~ 5 ¾) in the region of Düren-Aachen (in Germany) and on February 23, 1828 (M ~ 5) in the Hesbaye region. For this last seismic event, a great number of sources mentioned damages, particularly to churches.

Local topographic and geologic conditions can modify the amplitude, the duration and the frequency content of the ground motions generated by earthquakes. This phenomenon, called site effect, can increase significantly the earthquake consequences and can be at the origin of large loses and damages. Thus, in the same city, site effects can induce important variations of the earthquake intensity in different districts (Fig. 2.). An example is the city of Mons, located in a sedimentary basin, which has been strongly affected during the 1692 earthquake, already at great distance of the epicenter.

By combining knowledges in seismology and geology, a precise cartography of the seismic hazard can be established at the scale of a city or of one of its suburbs. The hazard represents the probability of occurrence of an earthquake ground motion parameter that can be related to damages (intensity, peak ground acceleration, response spectra…) for a given return period. The local hazard should take into account potential site effects [4]

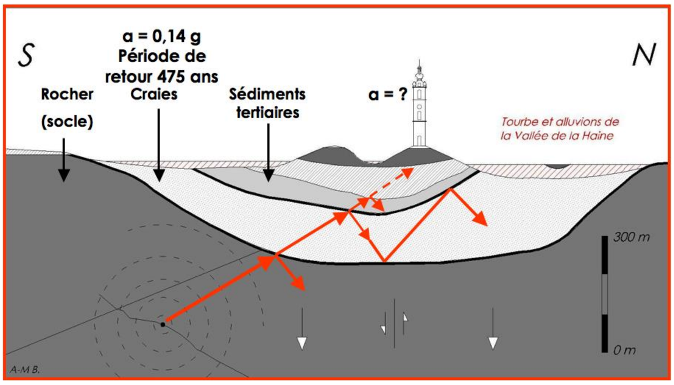

Figure 2 – Site effects [5]

Exposure and vulnerability

This hazard acts on the human and material exposures. Each exposure is characterized by its vulnerability and by its value, material or immaterial. Taking into account this last characteristic in the risk definition is a first step towards the patrimony preservation, because patrimonial buildings possess an historical, anthropological,… values and are a strong exposure with an undabatable and unestimable richness.

The seismic vulnerability of a building represents its sensitivity to earthquake ground motions. It is particularly depending on the building materials and on their working up, but also on the building geometry, particularly its dimensions, its high, its planar shape or its architectural characteristics. This fragility is expressed by a vulnerability index taking all those factors into account. Therefore, by adequate constructive precautions, it is possible to conceive less vulnerable buildings [4].

Generally, old buildings are relatively vulnerable, either by their initial conception, or by their decay and because they have been already previously shaked. Hazardous modifications can also awakened the structures: supression of parts of the frame, large opening in the walls or the ceilings,…

In the framework of a recent master thesis, we evaluated the vulnerability for the different houses of a block in the historical center of Mons [5]. This evaluation has been done in different phases, based on the basic and urbanistic typologies and on the typology of the face, and in function of aggravating factors. It considers 11 parameters fundamental for the building resistance to earthquakes, as the ceiling rigidity or the state of the construction. These parameters come from the Italian experience [6] and are based on the inventory of damages observed during past earthquakes. They have been adapted to the characteristics of the Belgian framing. In a first step, a basic vulnerability index (Vi) is determined based on the typologies of a building. In a second step, particular characteristics not always observable from outside of the buildings have been investigated. The sum of the basic index and the penalties based on those particular characteristics is then calculated to estimate the vulnerability index. The analysis in a district of the historical centre of Mons is shown in Figure 3.

Figure 3 – Determination of the vulnerability index Vi in a part of the historical centre of Mons [5]

Seismic risk and damages

Hence, seismic risk for a building is depending on the local hazard and the exposure that it represents. In the case of architectural heritage, a good management of seismic risk consists mainly in reducing the buildings vulnerability as we have no influence on their importance and on the hazard.

As a consequence, seismic risk assessment on the architectural heritage implies the evaluation of an expectable damage level on buildings. The level of damages indicates here the ratio between repair costs and reconstruction costs. To reach this evaluation, vulnerability curves have to be defined and used. They express the relationship relating vulnerability indexes with parameters of the earthquake ground motions and the expectable damage levels. The most frequent kinds of damage are the collapse of chimneys, bringing also damages on roofings, diagonal cracks, cracks in angles indicating the breaking away of walls, … .

The presumed vulnerability (Vi) of the buildings of the studied block in Mons is high. It indicates that more than half of the buildings could suffer important damages for the value of the peak ground acceleration to take into account in the Eurocode 8 building code. Buildings at the corners of the street and very irregular or willowy constructions are the most vulnerable.

This high vulnerability leads to a high seismic risk, even for a moderate seismic hazard. Thus, we can compare the damages observed in Belgium to those in more seismic prone areas steeped in an earthquake-resistant culture.

Mitigation

At each epoch, after destructive earthquakes, builders have always tried to carry out suitable constructive actions in order to reduce the vulnerability of their buildings [7]. However, the long duration of the return period between two very destructive earthquakes in our regions has often minimised the introduction of such mitigation actions.

In Belgium, earthquake-resistant design is then often ambiguous. The architectural techniques that our forebears left us have been developed during centuries, sometimes in agreement with actions that reduce earthquake destructions. We notably find the principle of stone chaining clearly marked in brick masonries as real skeleton. This can define a specific style, like the mosan style. Obviously, the basis of this principle is the concern of reinforcing the resistance of constructions, notably against horizontal loads and sollicitation, corresponding to those of an earthquake.

Other less obvious principles have sometimes been observed by some privileged people on buildings that experienced important seismic events, as in Soiron, for the 1692 earthquake, where we can find retrofitting solutions integrated to the masonry. The retrofittings means used in our regions are mainly the chaining by metalic ‘hooping’ and anchorage or link in angles.

Thus, some arrangements that we can observe today and that have been introduced trough time contribute to a resistance towards the lateral forces imposed by earthquakes. Therefore, we can improve the seismic behaviour of existing buildings. We have to overcome conceptual shortcomings and backdraws introduced by modifications of the original structure.

To define an earthquake-resistant repair, we have to distinguish mitigation strategies from techniques [8]. A strategy indicates the global approach while techniques are the practical means that helps us to reach it.

At our level, two families of strategies exist: those that consist in decreasing seismic loads acting on the building (reduction of masses, prevention of the knocking of different parts of the buildings, limitation of the global torsion, …)

and those aiming to increase the performances of the construction (retrofitting for the increase of its resistance, improvement of its dissipation capacity, removing or redistribution of weak zones, …)

Among the various techniques at our disposal (execution of efficient anchorages, addition of new construction elements …), several ones can give an answer to more than one strategy. A set of studied solutions should be collected in a catalogue for common buildings.

Nevertheless, a specific reflexion has to be led for listed buildings. A course of actions notably inspired by the Venice Charter [9] impose among others a principle of reversibility. The reasoning should be enriched by the Belgian and foreign scientific experience as well as by the building professional experience, from the architects to the workmen.

Identification of seismic traces on the cultural heritage

Based on these notions in earthquake science, it is now important to consider the effects that earthquakes can leave on our architectural heritage. We have first to analyse the pathologies of our heritage buildings to identify those that are due or potentially due to an earthquake.

In the framework of another master science thesis [10], we developed a trans-disciplinary methodology helping to detect traces of seismic damages of legacy buildings. This was then applied to a case study, the Saint-Lambert church of Petit-Hallet (figure 4).

Figure 4 – Saint-Lambert church in Petit-Hallet [10]

To get onto this question, we have notably investigated the consequences of the February 23, 1828 earthquake. In spite of its moderate magnitude (5.0), historical sources relating damages to housing and religious buildings are numerous, mainly in Hesbaye.

The methodology consists in two steps. The first step allows inferring with a certain degree of certainty if an earthquake has affected the building. It includes the search and the analysis of historical sources, the study of typologies of heritage buildings, the study in situ of visible pathologies that could have a seismic origin and a complementary seismological study.

The historical analysis consist in the study of past earthquakes (date, epicentre, magnitude) as well as in the picking and the analysis of historical sources (texts, iconography) attesting damages to buildings. For the church of Petit-Hallet, close to the epicentre of the 1828 earthquake, three historical sources have been found, of which:

"23th of February 1828 … the church has not been exempt from this event, the vault is collapsed, in many places, several candlestick that were on the altar were spilled (sic) on the floor" [Lettre du Bourgmestre au gouverneur de province, 1828, ROB database]

The typological study allow us to list the characteristics of vulnerability to earthquakes as the thickness of walls, the asymmetry in plane and elevation, the simplicity of form of the building, the recess or projection of parts of buildings … In the case of the church of Petit-Hallet, we conducted a specific analysis to identify the major part of these characteristics of vulnerability (figure 5).

Figure 5 – Typological study [10]

The pathological analysis includes all the pathologies and repairs that are visible on the building. It should be concerned to disorders that are recognized as being of seismic origin:

- the presence of vertical cracks being widened in the direction of the top, in the angle between the face and the partition walls;

- the presence of 45° cracks in cross or in diagonal from the angles of the openings;
- the presence of horizontal cracks in the masonry joints;
- the relative movement of walls;
- the unsealing, the rocking or the descent of keystones;
- the downfall or the cracking of structural vaults;
- the partial destruction or the collapse of the building;
- …

Numerous cracks on or down to the openings and at the vault level, the fall or the rocking of keystones and the presence of numerous anchors on the tower face are some of the pathologies observed on the church of Petit-Hallet.

Finaly, the analysis can be completed by a seismological study to verify if site effects could be related to the building natural frequency and at the origin of an amplification of the seismic action on the building.

If in conclusion to the first step of the analysis, it can be concluded, with a certain degree of certainty, that an earthquake affected the building, the second step is undertaken. The purpose of this part of the analysis is to consider other causes than the seismic one to explain the building pathologies. This detailed analysis concerns more specifically:

- the soil nature and structure (based on geological and geotechnical maps, borehole data, geophysical investigations,…);
- the adequacy of the foundation (undermining, levelling and measurements with a theodolite,…) (figure 6.)
- the presence of horizontal loads at the wall heads (vaults, framing, chaining,…);
- the existence of humidity problems;
- the incidence of possible slope movements.

The building cracking state is often revealing of most of those causes. It is suitable to appreciate their present evolution by installing gauges. Indeed, earthquakes created instantaneously cracks, but can also trigger crack evolution by a conjunction of different reasons.

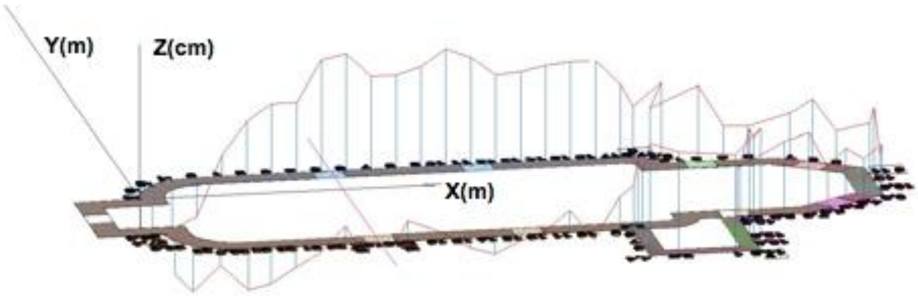

Figure 6 – Levelling [10]

In most of the cases, it will be always possible to eliminate the causes other than the seismic ones. Complementary studies, as numerical modelling, are then necessary to better constrain the problems. In the case of Petit-Hallet church, a number of problems have to be considered like a subsidence or a bad soil quality.

Conclusions

Our bearing is a first step in the field of seismic risk and building patrimony in our regions. It is the result of an evolutive reflexion, initiated by the study of the seismic activity and of the historical sources on past earthquakes. It has been developed in the framework of a nearly 10 years successful cooperation between the Polytechnic Faculty of Mons and the Royal Observatory of Belgium. Nevertheless, the developed methodology will have to be validated with different emblematic buildings.

Our works show without any ambiguity that it is fundamental to simulate the consideration of seismic risk during initial studies and the repairing works, especially by the identification and the understanding of the traces imprinted by past earthquakes on our emblematic buildings.

In this way, the proposed approach intends to elaborate tools investigating the patrimony with respect to seismic risks and the paraseismic reinforcing actions specific to the patrimony. In this perspective, it is proposed to establish a repertory of the patrimony affected by past earthquakes, as well as to realize cards analyzing patrimony buildings and their sanitary state.

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