The Impact of Timber Roof Framework Over Historical Masonry Structures

Eugen Onescu 1, Iasmina Onescu 2, Marius Mosoarca 2
1 Polytechnic University of Timisoara, Romania
2 Centre for Research and Sustainable Development, Polytechnic University of Timisoara, Romania
iasmina.apostol@upt.ro

Abstract. Romania is a European country, crossed by Carpathian Mountains and Danube River, with two important seismic zones. First and most dangerous one is Vrancea zone, near the capital of the country, Bucharest. The second most important seismic area is Banat, characterized by shallow earthquakes and a peak ground acceleration of 0.2. The most important city located in the second seismic zone is Timisoara, a city known in the past as Castrum Regium Themes which dates from 1212. Timisoara has been influenced by many cultures, such as Ottoman, Hungarian and Austrian, influence that can be seen also through the architecture of the city, especially in the historical zones, characterized by 1-4 storey masonry buildings with very complex and elegant timber roof framework. The dominant architectural styles are Secession and Art Nouveau. During the life period of the historical buildings, there were registered few seismic events, but the actual state of the buildings is a good one, with small problems caused by lack of proper maintenance or time-passing over construction materials. The global good behaviour of the buildings from the historical areas of Timisoara, despite the small seismic site-source distance and epicentral depth, remained a subject of interest for years. This article studies if and how the existence of such a complex timber roof framework influence the seismic behaviour of the masonry structure and entire building. The study was made based on non-linear analysis obtained with Tremuri software, determining the seismic vulnerability of the case study buildings with and without considering the timber roof. In the context of Timisoara European Capital of Culture 2021, the assessment of the seismic vulnerability of the most important buildings of the city is highly relevant. In the same time, considering the actual trend of replacing the historical timber roof framework with more modern structures, there is mandatory to understand how this specific timber structure contributes to the structural integrity of the historical masonry buildings.

1. Introduction
Heritage represents the base of authenticity and cohesion between new and old, understand through its tangible and intangible parts. One of the most important tangible heritage parts is represented by the architectural heritage, a great value of historical communities that offer the specific ‘sense of place’ to each region.

Architecture represents one elements that we experience day by day as users or inhabitants, influencing directly or indirectly our lives. Preserving the architectural heritage represents an interest point of discussion since decades, coming with several issues such as specific construction typologies, particular materials mechanical proprieties, economical or juridical aspects and other.
2. Seismicity and history of Timisoara city, Romania

Romania is a country with almost 20 million citizens, located in the eastern part of Europe, surrounding by the Black Sea, Danube River and Carpathian Mountains. This interesting relief was developed above the Moldavian Platform, Scynthian Platform, Moesian one and Pannonian Depression [1], [2].

The seismicity of the country is divided in two major parts. The area with the most important seismicity is Vrancea area, characterized by strong earthquakes with big focal depths. The second most important seismic area is represented by Banat region, located in the western part of the Romania, characterized by shallow earthquakes of crustal types. Usually, in Banat seismic area, the focal depths are small, between 5 and 50 km, with a small number of pre-shocks but an important amount of after-shocks, with magnitudes between 0.5 and 5.8 Mw. The distribution of the most important registered earthquakes from Banat seismic region is illustrated in Figure 1a [3].

![Figure 1. Distribution of the main seismic faults (a) and main registered seismic events in Banat region (b).](image)

The most important city in Banat seismic area is Timisoara, with an area a bit over 150 km² and over 300,000 inhabitants. The first official writing about this settlement dates from more than 730 years ago as a Dacian village that was later developed into an important military center, becoming a fortified town under Ottoman administration. During the Habsburgic administration, the city grew up culturally and architecturally, forming a very strong city center protected by massive masonry walls built in Vauban bastion style and several nearby residential areas [4]. At first, the residential areas outside the defensive walls were built with a safety ‘non buildable’ area, but after the massive walls were demolished, the areas merged with the city center, forming a homogenous historical large area. In the city, there are two active seismic faults, as shown in Figure 1b that could cause a seismic event with small epicentral distance from the historical areas of the city [5].

The major part of the historical areas and city center of the city are considered as protected historical areas, with a lot of historical monument buildings. This historical areas are Cetate district (the city center), Iosefin district in the western part and Fabric district in the eastern part. Considering the fact that Timisoara was selected as European Capital of Culture 2021 based on a strategy that will connect the visitors with the local community through different events organized in public spaces and historical buildings and courtyards, there was proposed a cultural promenade that is expected to be very visited. This proposed promenade starts from Iosefin district, gets through Cetate and finishes in Fabric district, as illustrated in Figure 2 [5].
Figure 2. The proposed cultural promenade for Timisoara European Capital of Culture 2021

3. Case study building

3.1. Location and history
The selected historical masonry building is located in Iosefin district at the intersection of main boulevards 16th December 1989 and King Carol the 1st, as shown in Figure 3a. The building was made between years 1886 and 1888 with a café shop at the ground floor and working spaces for the economy fund of Timisoara’s municipality, as an imposing eclectic building (Figure 3b) that was named Elite’s Palace [4]. The building presents basement, ground floor and two levels above the ground floor, representing one of the tallest buildings of Iosefin district.

Figure 3. Elite’s Palace Iosefin: a) location; b) historic picture

3.2. Complete survey and on site investigation
From structural point of view, the buildings was made in brick masonry with lime, having massive masonry walls (90 cm at the basement, 80 cm at the ground floor and 70 cm at the other floors) on the streets direction and another structural massive wall parallel with the façade wall on each direction. The transversal walls are usually nonstructural, helping only at the definition of the interior spaces and at the global rigidity of the building. The transversal walls are not connected with the façade walls, increasing the risk of activating the out-of-plane failure mechanism. Above the basement, there are masonry vaults with a thickness of 15 cm, while in rest there are wooden floors. A complete survey was made in order to be able to identify the structural and nostructural elements, showing the fact that the main front of the building has a length of more than 38 meters, while the left front has a length of a bit over 36 meters and the right front a bit over 37 meters, as illustrated in Figure 4. Between the three wings of the building, there was formed an interior courtyard, which represent a characteristic of the building typology in Timisoara city, Romania, as it can be seen in the air view illustrated in Figure 5.

Regarding the facades and decoration elements, the first register of the building (the ground floor) is highlighted by a bosses-like elements that give a rhythm to the façade and brings it at human scale. The
other floors present this kind of intervention only on the corner of the building, marking the change of direction of the façade, as shown in Figure 6. The highest level is the ground floor, with a height of almost 5 meters, while the total height of the building is a bit over 14 meters at the beginning of the roof. The roof is made from wooden frameworks, with a height of almost 5 meters and an opening of a bit over 14 meters. The level of decay is a medium one, mostly due to lack of proper maintenance and exposure of materials to climate factors.

Figure 4. Basement plan for Elite’s Palace, Iosefin district, Timisoara

Figure 5. Aerial view of Elite’s Palace and its interior courtyard

Figure 6. Main façade of Elite’s Palace in Iosefin district, Timisoara city and decay map
4. Nonlinear analysis
The bearing capacity and the seismic behavior of the building was determined using nonlinear analysis made with Tremuri software [6], [7] for two different scenarios: without considering the contribution of the heavy roof and with the contribution of the wooden frameworks considered, based on the complete survey and on site investigation that was carried out in the first step of the study. In order to be able to perform the pushover analysis, there was to need to have a series of input data, such as type of structure, distribution and dimension of structural elements, type of floor and mechanical characteristics of materials. The specific seismic spectrum that was used for the study is characteristic for Banat seismic region and is illustrated in Figure 7 [8]. The mechanical properties of the masonry (Table 1) were determined based on a series of experimental tests carried out on material extracted from Elite’s Palace [9], [10] and also on material extracted from different buildings from Timisoara with similar characteristics and from the same period of time [11], [12], [13].

![Figure 7. Banat seismic region spectrum](image)

**Table 1.** The mechanical properties considered for the masonry in the pushover analysis

| Mechanical properties                      | fk [N/mm$^2$] | fvk0 [N/mm$^2$] | E [N/mm$^2$] | G [N/mm$^2$] | Density [kg/m$^3$] |
|-------------------------------------------|--------------|----------------|-------------|-------------|-------------------|
| Masonry without reinforcement             | 2.35         | 0.06           | 2350        | 940         | 1800              |

The analysis was made considering the in-plane failure mechanism and following three major states: first crack, maximum shear force and horizontal displacement in limit state starting from the bilinear force-displacement curve determined with Tremuri software.

4.1 Nonlinear analysis without considering the roof
The first scenario was made on the masonry historical building, without considering the possible contribution of the roof structure at the seismic behavior of the building. The most probable in-plane failure mechanism is shown in Figure 8 for the longitudinal x direction and in Figure 9 for the transversal y direction. The specific SDOF bilinear force-displacement curves were defined based on the results obtained with the nonlinear analysis, both for x direction (main façade longitudinal direction) and y direction (transversal direction), as illustrated in Figure 10.

![Figure 8. In-plane failure mechanism on longitudinal x direction: a) first crack; b) maximum shear force; c) horizontal displacement in limit state;](image)
Figure 9. In-plane failure mechanism on transversal y direction: a) first crack; b) maximum shear force; c) horizontal displacement in limit state;

Figure 10. Specific bilinear force-displacement curve for Elite’s Palace: a) on longitudinal x direction; b) on transversal y direction;

Starting from the results of the force-displacement specific curve, there were determined the building displacement in ultimate limit state (Du) and the yielding displacement (Dy), the results being visible in Table 2.

Table 2. Yielding and ultimate displacement and shear forces for Elite’s Palace on both directions

|                | X direction |     | Y direction |     | X direction |     | Y direction |     | Fmax [KN] |
|----------------|-------------|-----|-------------|-----|-------------|-----|-------------|-----|-----------|
| Elite’s Palace | 0.51        |     | 0.53        |     | 2.21        |     | 2.44        |     | 18094     | 13366    |

In order to be able to evaluate the possible damages to Elite’s Palace in case of an earthquake, there were considered five major damage states from D1 to D5, as illustrated in Table 3 [14].

Table 3. Damage states correlation to damage level

| Damage state [Di] | Damage level [DL]                |
|-------------------|----------------------------------|
| D1                | slight                           |
| D2                | moderate                         |
| D3                | Substantial to heavy             |
| D4                | Very heavy                       |
| D5                | Near collapse/collapse           |

The fragility curves express the possibility that a specific damage state and damage level is reached at a specific spectral displacement. The fragility curves represent a function of yielding displacement and ultimate displacement of the previously determined bilinear systems, following Eq. (1-4) [15].

\[
S_{D1} = 0.7 \times D_y \\
S_{D2} = 1.5 \times D_y \\
S_{D3} = 0.5 \times (D_y + D_u) \\
S_{D4} = D_u
\]
where and Dy represents the maximum horizontal displacement and Du represents the building displacement in ultimate limit state.

Mathematically, the fragility functions are defined with Eq. (5), representing the expected performance level for the structural system, according to a deterministic approach [9].

\[
P[D_k \mid S_d] = \Phi(\frac{1}{\beta} \cdot \ln(\frac{S_d}{S_d, Ds}))
\]  

(5)

where \(\Phi\) represents the cumulative distribution function \(S_d, Ds\) function previously determined with Eqs (1-4). The dispersion \(\beta\) represents the standard deviation of the lognormal distribution, depending on different contribution of uncertainties in the seismic demand and determined with Eq. (6) [9].

\[
\beta = 0.45 \cdot \ln(\mu)
\]  

(6)

where the ductility of the structure \(\mu\) represents the ratio between the ultimate displacement in limit state \(Du\) and yielding displacement \(Dy\) [9]. Based on this consideration, the fragility curves for Elite’s Palace, both for longitudinal x direction and transversal y direction are presented in Figure 11.

The results have shown the fact that, due to the symmetry that Elite’s Palace presents, the results are similar on both direction and therefore the fragility curves doesn’t present substantial differences in terms of expected damage. The probability of damage is a bit lower on transversal y direction. There can be noticed the fact that, for the ultimate displacements identified on both direction for the case study building, the probability of reaching damage state D4-D5 is around 50%, meaning significantly chances of having serious damages to structural elements and reaching a damage level near collapse.

4.2 Nonlinear analysis considering also the influence of the roof

The building dating from XXth Century in Timisoara present two different types of roof structure that is representative to that time. Supplementary, there was identified also a standardized roof structure present in the new plazas of the early XXth Century, due to the monumental roof shapes that define the specific silhouette of the historical plazas [16]. Similar details of roof structure are presented in Figure 12 [17].
The results of the nonlinear analysis made with Tremuri software [6] are presented in Figure 13 for the longitudinal x direction and in Figure 14 for the transversal y direction, showing the fact that the existence of the roof structure determine moderate but considerably changes in the way of the appearance of cracks and failures in the elements of the masonry.

The specific SDOF bilinear force-displacement curves were defined based on the results obtained with the nonlinear analysis, both for x direction (main façade longitudinal direction) and y direction (transversal direction), as illustrated in Figure 15.

Following the nonlinear analysis, there were determined the yielding and limit state displacement and the maximum shear forces for x and y direction, as presented in Table 3.

Table 4. Yielding and ultimate displacement and shear forces for Elite’s Palace on both directions, with roof considered

|                  | D_y [cm] | D_u [cm] | F_max [KN] |
|------------------|----------|----------|------------|
| Elite’s Palace Iosefin | X dir | Y dir | X dir | Y dir | X dir | Y dir |
|                   | 0.75   | 0.65     | 2.41 | 2.59     | 19694 | 17395 |

Following Eqs. (1-6) there were determined the fragility curves for Elite’s Palace with roof considered, both for longitudinal x direction and transversal y direction, which are presented in Figure 16, showing the fact that the contribution of the roof structure determine a decrease of almost 5% of the probability of reaching damage level D4-D5, so the chances of having serious damages to structural elements and reaching a damage level near collapse are about 45% when the roof structure is considered.
4.3 Comparison of results
The results have shown a good improvement of the bearing capacity due to the presence of the heavy wooden roof structure leading to increased maximum shear forces and horizontal displacements in limit state, but is also changing the failure mechanisms of the facades, as presented in Figure 17. Also, the probability of having serious damages to the structural elements presented a decrease of 5% when the roof was considered. Also, a comparison between the failure in-plane mechanism without and with roof for the entire 3D model is presented in Figure 18.

5. Conclusions
Heritage masonry buildings represent complex structures, with specific failure mechanism, that need to be studied and analysed globally as a sum of elements. The wooden framework that is representative for heritage buildings present not only an aesthetic and formal role, but also a structural one, compressing the masonry massive walls and giving stability to the entire building.

This paper presents a comparison for one of the most representative historical buildings of Timisoara city with and without the roof structure considered in order to be able to analyze the impact of the wooden framework for the seismic behaviour of the entire building. The results have shown the fact that the presence of the roof structure increases the bearing capacity of the historical building, reducing the probability of having serious structural damages and even collapse risk with a bit over 5%. In the same
time, the presence of the wooden roof structure changes also the stiffness of the historical Elite’s Palace building, showing a different type of failure for the three exposed facades.

This study aims to provide a better understanding of the complex assessment of historical masonry structures generically, representing one small part of a larger multidisciplinary study for the seismic assessment of historical urban areas, but for more accurate results there should be performed technical reports and more detailed numerical analyses.

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