POLLACK PERIODICA
An International Journal for Engineering and Information Sciences
DOI: 10.1556/606.2016.11.3.3
Vol. 11, No. 3, pp. 15–26 (2016)
www.akademiai.com

NEW VULNERABILITIES OF HISTORIC URBAN CENTERS AND ARCHAEOLOGICAL SITES: EXTREME LOADS

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Received 10 December 2015; accepted 20 July 2016

Abstract: Extreme actions represent a high risk for buildings belonging to historic urban areas and archaeological sites. Because of the conformation of the buildings, the low quality of used materials and the current state of conservation, these buildings tend to be very vulnerable to horizontal forces generated during earthquakes and terrorist attacks.

This article analyses the mechanisms caused by extreme actions that are capable to generate a considerable degree of damage or even collapse of international cultural heritage buildings from historic urban centers and sites.

Keywords: Cultural heritage, Earthquake, Terrorist attack, Extreme loads, Vulnerability of historic sites

1. Introduction

The main characteristic of historic buildings, either located in urban centers or archaeological sites, is the typology of the structural system, which in most cases is unconfined masonry. The main feature is that it influences their vulnerability to horizontal and vertical forces that occur when subjected to extreme loads that seldom have been taken into account in the process of design.

Both stonework and brickwork masonry share similar patterns of failure due to: the orientation of the joints regarding the loading stress direction, dimension, anisotropy, joint width, arrangement, mechanical properties and the quality of workmanship. As a result, failure can affect joints, units or both joints and units [1, pp. 122].

In most cases, the structure's response to forces caused by extreme actions is the collapse of macro elements like walls, floors or framing systems, or even the collapse of the entire building due to the progressive failure of the aforementioned elements.

The need of preventing irreparable consequences of possible extreme loads caused by earthquakes and terrorist attacks is a major topic yet to be studied and understood worldwide, in order to safeguard not only the built heritage, but also human lives. At the same time, historic urban centers need to be strengthened and revitalized in order to avoid abandon.

Therefore, a team of researchers made of architects, engineers and archaeologists have started to study these threats within the Faculty of Architecture and Urban Planning from Timişoara, in order to comprehend how horizontal and vertical forces caused by extreme actions can damage historic buildings and archaeological sites.

2. Seismic vulnerability of historic urban centers

2.1. General overview

Recent earthquakes have caused both material and human loses because of the collapse of historic buildings due to seismic vertical forces. For example, the earthquake from 2009 in L'Aquila, with a magnitude of 6.3, has caused the death of 305 people, more than 1500 were injured, and financial damage estimated at over 10 billion euros [2], [3]. Some ground motions were characterized by vertical Peak Ground Acceleration (PGA) values as high as horizontal PGA exceeding the prescriptions of Eurocode Type 1 spectra.

Vertical forces have a huge impact on masonry structures, especially the ones having large openings, like: vaults, cupolas and arches, because these features are being subjected to tensile stress instead of compression, resulting in the detachment of its masonry components. Post-earthquake on-site surveys show that in this case, their effect is devastating and may cause not only the collapse of an entire masonry structure, but also the irreparable damage to the whole urban tissue characteristic to historic urban centers [4], [5].

In order to understand the behavior of masonry buildings subjected to earthquake forces, a step-by-step analysis should be conducted closely related to the particularities of the seismic regions where they are located. Starting with a basic investigation of the building's identity and its material characteristics, and passing on to the structural modelling, the aim of the final step is to determinate the seismic vulnerability and the failure analysis of the structure [1, pp. 125-131].

Usually, failure occurs by in-plane and out-of-plane mechanisms, so when assessing the vulnerability of masonry buildings, it is recommended that interaction between the in-plane shear and out-of-plane bending capacities of brick walls should be taken into account, because the interaction may become very strong when loads are near the wall's ultimate capacity in any of the loading directions [6].

At the same time, for most historic masonry buildings with flexible diaphragms, the stiffness of the horizontal diaphragms and the corner connections between walls can determine the activation of out-of-plane instead of in-plane collapse mechanisms [7].

2.2. Means of evaluating the seismic vulnerability

Given the large number of historic buildings and sites that are exposed to seismic activity all over the world, the foundation of a fast methodology of vulnerability assessment for isolated buildings has been laid through the studies of Benedetti and Petrini in 1984.

The seismic evaluation procedure proposed by Benedetti and Petrini is substantially based on assigning one out of four classes of vulnerability (A, B, C, D) to parameters defining geometrical and mechanical characteristics of the buildings. Based on its class, each parameter is assigned a score *p*, and a weight *w*, used to quantify the parameter's influence in the overall vulnerability of the structure [8].

Considering the fact that historic urban tissues are made of aggregates of buildings, the methodology is subjected to a continuous development process in order to be able to estimate the vulnerability of aggregates that show a specific response to seismic activity, compared to isolated ones which depend on the way they interact with adjacent structures.

In order to properly evaluate the I_v index in case of aggregate buildings, the methodology is supplemented by adding other five parameters, regarding differences or similarities between them, like: the proximity to solid walls, position in the aggregate, thickness of slabs, structural system, opening percentage among adjacent facades [9, pp. 116−138], meaning that when subjected to seismic actions, a building situated in an aggregate of buildings has a better response than an independent one.

2.3. Seismic activity in Timișoara

The city of Timișoara is located in the northern part of the Banat Seismic Region from Romania characterized by its tendency to group epicenters in well-defined areas, related to a complex system of crustal faults reactivated in a tectonic trans-tensional regime, confirmed by major seismic events with a magnitude Mw>5.0. The earthquakes produced so far are normal, crustal type ones, with outbreak depths between 5 and 30 km, caused by the sliding of three types of faults: NE-SW oriented faults, E-W oriented faults, NNW-SSE to N-S oriented faults [10]. The Banat Region is one of the main seismic areas of Romania and also one of the highest seismic regions of the Pannonian Basin, [11], [12].

Due to the recent rehabilitation proposals for the urban space of the historic Cetate District described in *Fig. 1*, more attention has been drawn over the importance of heritage buildings, which have been often neglected and left under a continuous process of adjustment according to the changing needs of their owners and tenants. Having an urban tissue that consists mainly in clustered historic buildings dating back to the Habsburg Era, and two currently opened archaeological sites in Liberty's Square and Saint George's Square dating back to the Ottoman Era, Cetate District recalls its importance within the social and cultural life of the city as a whole.

Taking into account that more than 85% of the buildings have a structural system made of masonry walls and wooden framing, the fragility curves of local mechanism analysis show that they are prone to a moderate to significant probability of damage referring to the simple overturning mechanism of macro elements in correspondence to a peak ground acceleration of $a_{max} = 0.2$g prescribed for the city of Timișoara. In most cases, the level of damage for simple overturning mechanisms is estimated between 40% and 70%, and the level of damage for vertical bending mechanisms is estimated between 10% and 50%, [13], [14].

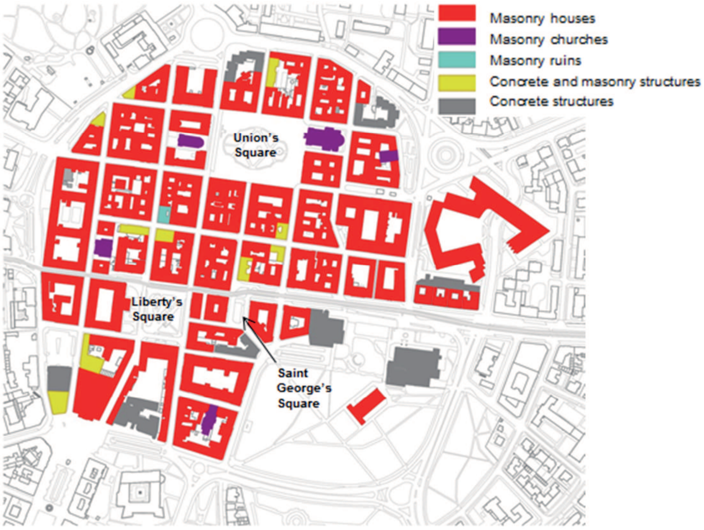

Fig. 1. Cetate historic district of Timișoara

2.4. Case study: Saint George's Square, Timișoara

In order to estimate a vulnerability index of historic buildings, the methodology of vulnerability assessment has been applied on three clustered buildings situated on the northern side of Saint George's Square (see *Fig. 2*) erected in the XVIIIth century around the Grand Mosque, later transformed into a Jesuit Church in 1718, and demolished in 1913, [15].

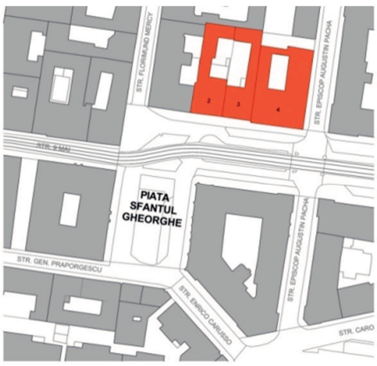

Fig. 2. Modern state of Saint George's Square

Highlighted in *Fig. 3*, each building has two storeys above the ground level, an irregular shape in plan and each one is covered by wooden framing systems. The slabs over the ground level are made of masonry and are usually vaulted, but the ones over the first and second storeys are made of wooden beams with poorly connected to the masonry walls.

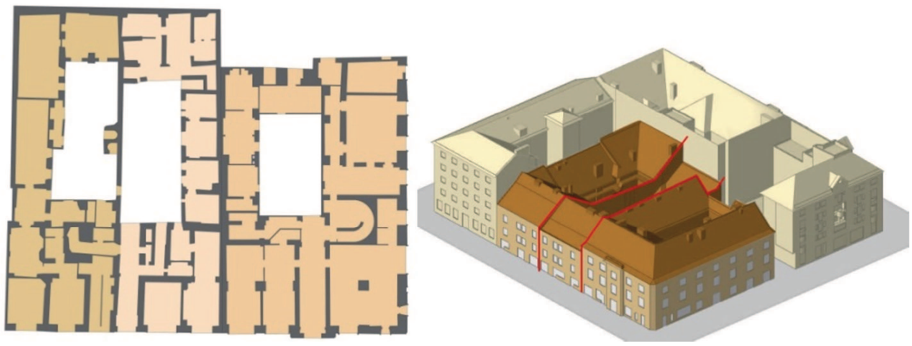

Fig. 3. Current ground floor and axonometric view of the selected buildings

Given the fact that the vulnerability index can be used to quantify and therefore compare the state of vulnerability between aggregate buildings, a direct correlation to the level of damage depending on the earthquake's intensity has been made.

Based on the vulnerability index calculated, the level of vulnerability in correspondence to the European Macro Seismic (EMS98) scale can be obtained using formula (1), where μ_D is the mean damage grade; S is the macro-seismic level ranging from 1 to 12 on the Mercalli scale; and V_I is the vulnerability index correlated to the I_V value according to formula (2). As a result, the buildings can be classified according to the following EMS98 scale [9, pp. 131–135], [16] (see *Table I*).

$$\mu_D = 2.5 \cdot \left[1 + \tanh\left(\frac{S + 6.25 \cdot V_I - 13.1}{2.3} \right) \right], \tag{1}$$

$$V_I = \frac{113.66 + I_V}{619.59}\,. \tag{2}$$

Table I

EMS 98 scale according the degree of damage

1. Low	$0 < \mu_D \leq 1$
2. Moderate	$1 < \mu_D \leq 2$
3. Strong	$2 < \mu_D \leq 3$
4. Very strong	$3 < \mu_D \leq 4$
5. Collapse	$4 < \mu_D \leq 5$

For the case study of Saint George's Square, the three buildings may suffer a low degree of damage during an earthquake of intensity VI, VII or VIII on MSK scale, and moderate damage during an earthquake of intensity IX on MSK scale [17].

3. Anti-seismic urbanism of historic building centers

Usually, 'Earthquake Urbanism' is associated with the analysis of risks and vulnerabilities in the built environment on an urban texture scale and with seismic mitigation measures. In the context of extreme loads, references to a series of aspects less visible and less tangible will be made. Therefore, Earthquake Urbanism will be understood in a different way, and not just as a gathering of over ground risks but as a complex system of ground factors that involve both natural hazards (stratification of soil between surface and epicenter) as well as man-made hazards (built environment densification that alters ground motion in case of earthquake).

Earthquake Urbanism is dealing with urban efficiency in case of earthquake, having as a first priority the directive to protect people and second to protect the built heritage [18].

If in the past, the field dealing with seismic design was limited to earthquake engineering, nowadays the area of anti-seismic design and planning implies a trans-disciplinary approach with earthquake engineering, architects, urban planners, geologists, etc., acting as equal partners. Nevertheless, there still is not a clearly defined framework of cooperation between them in order to mitigate the effects of earthquakes in the design phase. They are still working separately because each side is fulfilling her own tasks being 'hidebound' trough ultra-specialization, to note the separation of preoccupations and diminishing the bridge linking them [19].

New issues that can complete an anti-seismic morphology scenario may come precisely from these holistic approaches, multi, inter and trans-disciplinary, of the specialists involved in the design process. Anti-seismic morphology too often refers and research visible aspects above ground and too little analyze under the ground factors that can drastically alter the behavior of buildings in urban areas.

The topic analyzed in this paper calls into question issues previous studied by V.Gioncu and F. M. Mazzolani [20], in a larger urban context, in the context of previews previous studies in structural robustness [21] and in the light of the built environment evolution.

3.1. City-site interaction

City-site interactions refer to the influence exerted on the ground by the built environment and to the modification of ground motion as a result of building densification. Actual building weight and the urban density can cause stiffness in the soil that determines a change in acceleration and frequencies of the ground motion [20].

The ever growing fingerprint of the urban habitat can become an extreme load due to severe interactions between the vertical load on the soil and the density caused by diminishing of distances between buildings. The built environment evolved from simple settlements where the church was the highest building to a complex mechanism where new functional buildings overcome in height the old ones. Gradually, as the evolution of the cities by growing in density and height in urban centers and by absorbing satellite communities, the city-site interactions become more complex.

From a taxonomical perspective of the built environment, where the complexity of the building is classified in three classes: mineral, vegetal and animal [22], the cityscape shape can be synthesized into a curve similar with the Gauss bell. The outskirts are residential (basic complexity), the middle zone represents the second wave in urban development (industrial facilities), and the center, which is the highest point, represents modern state of the art office building.

In present days, the profile of the modern city represents a mix of different scale buildings, closely spaced, and derived from the uncontrolled growth based on economical premises. The impact on the soil varies as the height, weight and the built configuration complexity increases, determining a complex system of underground loads. Bigger economy means bigger footprint, larger impact on the soil and denser and heavier pressure point buildings. Similar to nature laws, an increase in density (seen as a relation between high-rise and proximity) leads to an increase of stiffness, which related to the complex system of city configuration in turn leads to a complex system of stiffer points and ductile points.

3.2. Near-source factor

Near-source effects brings into discussion a vertical dimension of seismic actions on buildings/cities located above near-fault regions, a component less studied but which although has a short duration is more violent because is governed by a pulse with very high velocity and high frequency. As showed in the research of V. Gioncu and F. M. Mazzolani, [20] the propagation of the seismic wave in the ground and in the building structure is taking place with very high velocity, determining the system to behave as a Newton Cradle. On a larger scale, the building acts like the last ball from the cradle and on a smaller scale, the upper floors act as the last ball. The point where the actions and reactions are equal, as a result of opposing forces, a mechanical deformation can occur that can lead to brittle fractures in the structure. The consequences of near-source effect in conjunction with city-site interactions on the ground and on the building are chaotic and require further studies.

3.3. Para-seismic forces

A consequence of Newton's Cradle behavior of the analyzed scenarios, after the retransmission of the vibrations into the system that produces echoes of the initial momentum, determining the building to act as a secondary seismic source, due to the fact that this secondary source is built by man, there can be can further referred to this aspect as a man-made hazard - para-seismic activity. Para-seismic forces are earth vibration caused by people [23]. Although the para-seismic excitation, vibration, tremors are linked with other causes than those derived from earthquake, it could be taken into consideration that it could be framed and defined the secondary seismic source as a para-seismic force. As shown before, cities are complex systems of interactions between different kinds of destinations, high-rise and densities.

A good example of this kind of mixture is represented by the following real case, where a religious building stands near a modern tall office building in a neighborhood of XXth century block of flats. All three types of constructions have different building configuration and complexity based on different understanding of the structural necessities, different weight on the soil and different inertia in case of seismic forces. The office building being the heaviest point object will have tremendous effect on surrounding buildings by developing a bigger para-seismic force on the soil, affecting all the building in the vicinity. The para-seismic force is developed as a vertical compound as well as a horizontal one, according to seismic wave type (*Fig. 4*). Due to the stiffness of the soil caused by the weight of the buildings, the effect of seismic forces of the earthquake and the para-seismic forces of the office building onto the church, it can only be predicted that this will have a devastating effect. Further research and analysis is required.

Fig. 4. Influence of tall buildings in the proximity of historic ones, photo of a real situation, photo credit Bogdan Stamatin/Mediafax Photo

In search of means of mitigation of seismic and para-seismic risks, the best place to look for is nature. It provides the best forms and structure configuration to answer to the dynamic forces of natural hazards. In this case the tree provides a good example of a complex system of

- rigidity - the stem is composed of concentric layers of different rigidity and densities, ranging from elastic to plastic properties, previous studies in dual-steel structures shows structural efficiency [24];
- dissipation - the tree crown offers a system of inertia and dissipation of efforts through the branches, like a form of passive seismic control through dynamic oscillators;
- flexibility - the root is anchored in the ground through a complex system of rhizomes or tap roots.

A quick analogy with the tree can be made in order to extract design principles for seismic mitigation so that future investigations are worthwhile.

4. Extreme loads on masonry building due to asymmetric threats

The first symptom of an asymmetric threat is unpredictability. It cannot be anticipated, and it usually is imminent. The study of asymmetric attacks has shown that they are successful in more than 90% of the cases [25], and they cause significant human and material losses. A fair amount of research and studies were performed to analyze the extreme loads on masonry walls. S. Ahmada et al. in Experimental study of masonry wall exposed to blast loading [26] exposed a brick masonry wall, at scaled distances to different blast loads. There were performed six testes with varying amount of explosives at various distances and compared the results with simulations and other researches.

A conclusion was formulated, that the time lag is not only related to the scaled distance but also to the velocity of the wave propagation and that for a deeper understanding a the masonry wall response to blast loads extensive experimental work must be undertaken. The Federal Emergency Management Agency (FEMA) [27] advises that the main step in predicting blast effects on a building is to predict blast loads on the structure. If a detonation is exterior to a building, the pulse of blast pressure is the one that causes most damage to the building. The pulse varies based on stand-off distance, angle of incidence, and reflected pressure over the exterior of the building. The prediction of the blast load should be performed at multiple locations.

FEMA provides guidelines for architects and engineers to help design safer and more blast resisting buildings but it is clear that heritage urban areas are not excluded from the long list of possible targets and for this reason it is imperative that a comprehensive study and research must be performed to evaluate the impact of blasts on masonry structures.

5. The vulnerability of archaeological sites

As any other structures, existing buildings located in historic sites are vulnerable to various forces and actions that take place after the process of excavation, both in open fields and urban centers.

During the archaeological and seismological research conducted in Armenia by the French National Centre for Scientific Research, between 2004 and 2013, studies have shown that the effects of extreme loads caused by earthquakes have been disastrous for stonework and adobe masonry. According to the study, the adobe blocks were broken by effect of shocks resulting from a nearly vertical acceleration from the ground upward, rather than a static gravity charge in other directions [28].

Nowadays, archaeological sites are reopened and highlighted in order to revitalize certain urban or rural areas. Uncovering without means of protecting them afterwards, may result in exposing the archaeological sites to severe degradation factors in comparison to their covered state and to extreme loads that have not been taken into account.

A case study where research has been conducted in this field is the archaeological site found in Liberty's Square from Timișoara. The 'Oriental' town was forgotten and remained unstudied until the above mentioned works when preventive archeological excavations uncovered small earth and timber dwellings and massive public edifices like the Grand Mosque and the Grand Baths. The baths uncovered in Timisoara's Liberty Square are very imposing and constitute one of the largest baths from this region, along with the edifice of the Grand Mosque in nearby Saint George Square, marking the center of the Ottoman city [29].

Given the thin layer of sand that according to the preservation project shall be placed over the site, it is probable that the heritage site will be damaged and the objective of preservation cannot be achieved. As a consequence, the chosen pavement will assure a direct transmission of forces from above onto the old structures.

Before the excavation and the beginning of the reconstruction of the square, the Turkish baths were placed under a layer of soil and grass untouched by traffic and people. If the new site would have been treated the same way as it was, the solution of covering the Turkish baths would have been a better one. At this stage the site will be subjected to new loads that will deteriorate the structure from bellow.

6. Conclusions

There is an urgent need of developing specific regulations that address potential threats caused by extreme actions on historic masonry buildings and archaeological sites that are endangered, in order to protect both buildings and people. In order to do so, the methodology of evaluating the vulnerability index of historic buildings and archaeological sites should be supplemented taking into account the effect of both horizontal and vertical forces.

The aim of the vulnerability assessment is to initiate a process of revitalization of historic centers that have been neglected, mishandled or abandoned due to their lack of structural stability. Interventions on a large scale require a complex and hierarchical system of intervention starting with buildings with a high-vulnerability index, in order to prevent further degradation.

At the same time, in order to quantify each building's vulnerability index, cultural and artistic values should also be taken into account, because these characteristics define the cultural identity and importance of the built heritage. Architectural features like embellishments, stained glass, mosaics, sculptural elements, balustrades and carvings are identified with specific historical periods and events, and should be defined through similar parameters as the ones previously described in the case of a structural analysis.

Acknowledgements

The Authors would like to thank the Doctoral School of 'Politehnica' University of Timişoara for its financial support in participating at the congress and the publication of this article.

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