Post-earthquake assessment and documentation of timber roofs

Stepinac, Mislav; Andic, David; Pojatina, Juraj

Source / Izvornik: **World Conference on Timber Engineering (WCTE 2023), 2023, 4029 - 4034**

Conference paper / Rad u zborniku

Publication status / Verzija rada: **Published version / Objavljena verzija rada (izdavačev PDF)**

https://doi.org/10.52202/069179

World Conference on
Timber Engineering
Oslo 2023

POST-EARTHQUAKE ASSESSMENT AND DOCUMENTATION OF TIMBER ROOFS

Mislav Stepinac[1], **David Anđić**[2], **Juraj Pojatina**[3]

ABSTRACT: In 2020 Croatia was struck by two strong earthquakes. Croatian building stock is in big part made of masonry with timber floor and roof structures. Given that masonry structures are highly vulnerable to seismic actions, damage occurred to more than 70.000 buildings. Due to widespread damage, there is a great need for a detailed and more comprehensive post-earthquake damage assessment. This paper briefly presents the post-earthquake damage assessment in the historic parts of Zagreb and the surrounding area after the recent earthquakes in 2020. Special focus is set on traditional timber roofs – traditional roof systems in Croatia, damages to the load-bearing elements due to earthquake excitations, maintenance issues, wrong renovation of the attics, etc. Also, the role of UAVs, photogrammetry and laser scanners in the assessment and preservation of heritage buildings is shown.

KEYWORDS: Earthquake, Timber Roofs, Assessment, Laser Scanning, UAV

1 INTRODUCTION

The European building stock consists of a large number of masonry buildings with roofs and floors made of wood. This type of structures often gives ancient European cities a recognizable identity, but are vulnerable to seismic excitation. Therefore, knowledge of their current condition and possible structural upgrading is beneficial. In this context, the continuous assessment and monitoring of the seismic safety and vulnerability of buildings must be carried out at the highest level and according to the most modern principles [1–3].

In 2020, Croatia was hit by two strong earthquakes. After the earthquake in Zagreb in March 2020 (M_L =5.5), which damaged about 25,000 buildings, Croatia was again hit by a destructive earthquake of magnitude 6.2 in December 2020. Sisak-Moslavina County suffered the most severe consequences; many historical and cultural buildings were severely damaged. According to the Croatian Center for Earthquake Engineering (HCPI - in Croatian), more than 57,000 buildings were damaged [4,5]. World Bank estimates the total financial damage from the Zagreb earthquake as EUR 11.3 billion [6] and EUR 5.1–5.5 billion for the Petrinja earthquake [7].

Cities in continental Croatia were built on the legacy and principles of construction in Austro-Hungary at the beginning of the 20th century. Most of the historic city centres were built before the enactment of modern earthquake standards, and the buildings were not designed to be earthquake resistant. After the 1963 Skopje earthquake, the standards were developed and building styles changed, and different materials were used for the construction of new structures. Before the introduction of the earthquake standards, the most common building material used was a combination of masonry and wood. The walls were made of masonry and the mezzanines and roofs were made of wood. A large number of such buildings were not adequately maintained, resulting in significant damage to these facilities. Since the mezzanine structures are mostly made of wood, the structures lack the box effect - they are too weak to withstand horizontal actions [8–12]. While masonry buildings have been severely damaged, recent earthquakes have shown that no wood buildings were extensively damaged by the earthquake. However, parts of the structural systems were damaged, especially the timber roofs of typical masonry buildings.

This paper presents the typology of timber roofs in Croatia and the damage caused by the recent earthquakes. The presented results of the damages and the identification of typical damages after an earthquake should be useful for policy makers and for the future implementation of development strategies in the renovation of cities. Since the roof systems in Zagreb and other historic urban areas are similar, shown figures and photos can be of use in assessment of other damaged roof systems.

2 TYPICAL TIMBER ROOF SYSTEMS IN CONTINENTAL CROATIA

In this paper, the focus is placed on the distinct parts of Zagreb, where older buildings predominate, most of which are built with traditional timber roof systems. The roof structure is usually a king or queen post truss, but there are also many combined forms of timber roof structures. The basic types of traditional timber roof systems in Zagreb are shown in Figure 1. The purlins are almost always supported by brick or parapet walls. Spatial roof stabilization (bracing) is usually not executed. A

[1] Mislav Stepinac, Faculty of Civil Engineering, University of Zagreb, mislav.stepinac@grad.unizg.hr
[2] David Anđić, Studio Arhing ltd., david@studio-arhing.com
[3] Juraj Pojatina, Studio Arhing ltd., juraj@studio-arhing.com

https://doi.org/10.52202/069179-0523

small number of buildings have a concrete slab under the roof systems due to renovation works [13].

Figure 1: *Typical timber roof structures in Zagreb*

3 DAMAGES TO TIMBER STRUCTURES

The damage methodology for the roof elements and structure was divided into five damage levels: no damage, very minor damage, moderate damage, significant damage, severe damage. Figure 2 shows the extent of damage to roofing and wooden roof structures in the historic districts of Zagreb. In Donji Grad (Lower Town), the buildings are larger in plan than in Gornji Grad (Upper Town); therefore, the structural systems are also different. In the Upper Town, single-family houses and villas predominate, while in the Lower Town, multi-family houses with mostly 7 to 9 housing units are the most common buildings. According to the engineers' decision, the total number of severely damaged roofs was 274 in the Lower Town and 189 in the Upper Town. Damage to roofing was found on 598 buildings in the Lower Town and 516 buildings in the Upper Town [4,13].

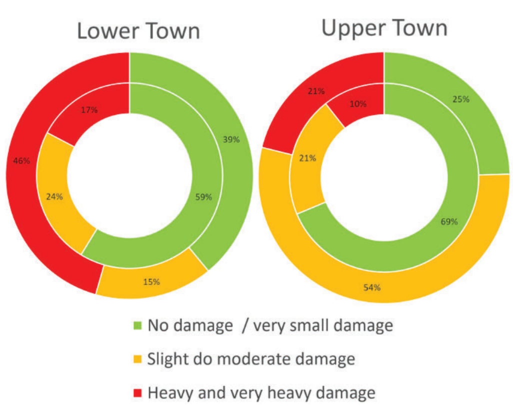

Figure 2: *Statistical data about damage to roofs (inner circle: damaged roof systems, outer circle: damaged roof coverings)*

In summary, the load-bearing parts of the roof structures remained mostly undamaged. The main damage observed at the roof level is damage to the roof coverings, i.e. tiles, decorative elements and non-structural elements.

The failure of non-structural elements such as chimneys and decorative elements on facades was observed on almost all buildings in the city center. Failure of gable walls, masonry columns, wall sections between or under windows, vaults, ceilings, staircases, etc. was common. Since the two materials (timber and masonry) have very different properties and masses, the post-earthquake damage was also very different. The two most typical masonry damages, due to the "pushing" of timber elements and the poor connection with masonry walls, are shown in Figures 3 & 4.

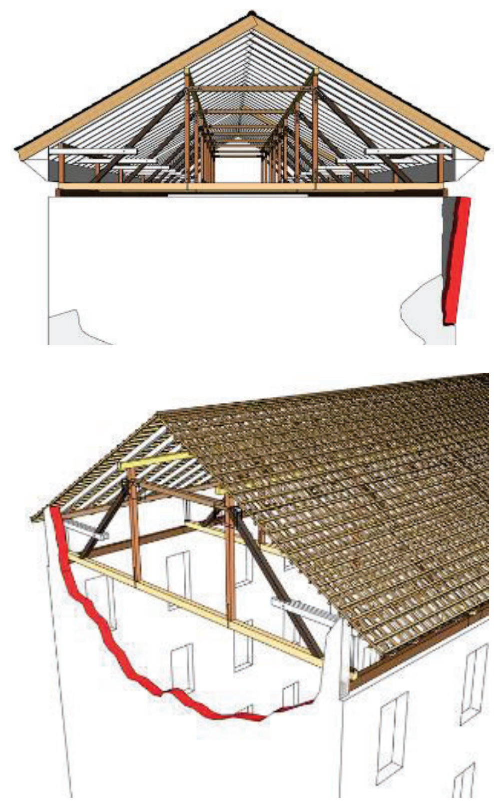

Figure 3: *Typical damages to masonry walls*

Figure 4: *Failure of gable walls (photo credit: M. Stepinac)*

Roof systems often become unstable due to the collapse of individual load-bearing walls beneath them or severe chimney failures (Figure 5 & 6). Post-earthquake inspections showed that many of the chimney failures resulted in direct damage to the roofs. In some locations, the chimneys damaged the supporting roof structure, but in most cases only the rafters broke and the integrity of the roof was maintained (Figures 7 and 8).

Figure 5: *Failure of timber elements due to chimney failure (photo credit: R. Gulić)*

Figure 6: *Timber roof collapse – Sisak cathedral (photo credit: Studio Arhing d.o.o.)*

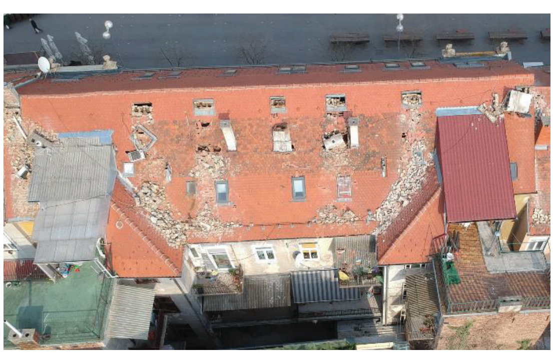

Figure 7: *Failure of chimneys (from outside) (photo credit: M. Stepinac)*

Figure 8: *Failure of chimneys (from inside) (photo credit: M. Stepinac)*

Maintenance was identified as one of the most important aspects that contributed to the condition of buildings after the earthquake. Since a large number of buildings were poorly maintained or not maintained at all, the properties of the masonry deteriorated over the years, and the seismic performance of such buildings was worse [5]. In many cases, water penetration degraded the properties of both masonry and wood elements (Figure 9).

Figure 9: *Failure of timber elements due to water leakage and seismic excitations (photo credit: Studio Arhing d.o.o.)*

Timber beams on wall parapets along with attic ceiling wooden beams were severely deteriorated due to aforementioned lack of maintenance and due to original defects at the time of construction. The inadequate connections and bad detailing is common and one example is shown in Figure 10. As carpentry joint were used for connections, often, “secondary constructive” screws were missing. Although carpentry joints are considered good in terms of characteristic load combinations, when it comes to dynamic loading with cyclic nature, like earthquake, poor behavior was observed in several cases.

https://doi.org/10.52202/069179-0523

Figure 10: Bad detailing (photo credit: Studio Arhing d.o.o.)

Typical conversions of building spaces convert non-living spaces into living spaces (e.g., basements, attics, or utility rooms). This room conversion often involved demolition of partition walls, and undesirable intervention in the load-bearing walls is also common. The conversion of the attic for living purposes resulted in numerous changes to the roof structure. Often timber tie elements were cut to insert the door (Figure 11), which significantly changed the basic static system of the roof structure itself. Also, traditional timber structural systems were replaced by masonry or concrete elements as shown in Figure 12.

Figure 11: Improper attic modifications (photo credit: HCPI [4])

Figure 12: Improper attic modifications (photo credit: HCPI [4])

4 USING OF MODERN TECHNOLOGIES IN POST-EARTHQUAKE ASSESSMENTS

Regular post-earthquake assessments should be facilitated and improved by state-of-the-art technologies for preservation and digitization of cultural heritage buildings. The construction sector is the slowest to adopt new technologies and this should be changed [14,15]. This motivates the search for a technological solution for the safety assessment of existing structures and the digitization of cultural heritage buildings. The advantages and disadvantages of the new technologies, which are intended to complement the traditional methods, are discussed by [16–18].

Unmanned aerial vehicles (UAV) have proven very useful during the rapid assessment of roofs, as well as detecting defects/damage in hard- to-reach places. Figure 13 shows a post-earthquake assessment scenario using a UAV. An engineer cannot see what has happened on the higher floors or on the roof of a building during an on-site assessment from the street. With a UAV device the above information can be easily assessed.

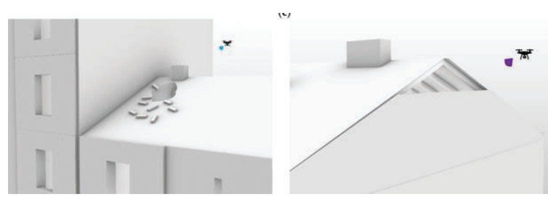

Figure 13: Possible damage on the roof level of a building after an earthquake [16]

While drones are very useful in rapid inspections of unreachable spots of buildings, detailed inspections, especially of heritage buildings, should be conducted in a more comprehensive manner. Since the entire city center of Zagreb is under heritage protection, special care was taken to document the building condition in terms of architectural style, details and design, but also in terms of structural impact and peculiarities.

In the following figures, an example of laser scanning is shown, which helped to better understand the structural system. Laser scanning was used to create a 3D point cloud of the interior and exterior of the building. The laser scanner used in the following case study is a Leica BLK360, a compact imaging laser scanner that uses a 360° laser distance meter and high-resolution panoramic images. The collected data is then processed using the Cyclone Register 360 software package. Using three spherical HDR panoramic cameras and a thermal imaging camera, 3D point clouds are delivered with millimetres accuracy. The point cloud can be further used to create an accurate 3D model, to create a precise 2D floor plan, or to convert it into a mesh for visualization. Since, in this particular buildings, it was not easy to see the force path, the point cloud of the laser scanner was very useful (Figures 14-16). Laser scanning has also proven to be a very useful tool for very complex geometries, both for heritage documentation and for easier navigation during post-processing to create 2D and 3D drawings. An added value is also a 360° image for a specific location in the building. Figures 17 to 19 show the case study of the Zagreb Cathedral.

Figure 14: *Point cloud of a case study building*

Figure 15: *Point cloud of a case study building: cross section with "filming positions" (red dots)*

Figure 16: *Typical cross-section of the case study building*

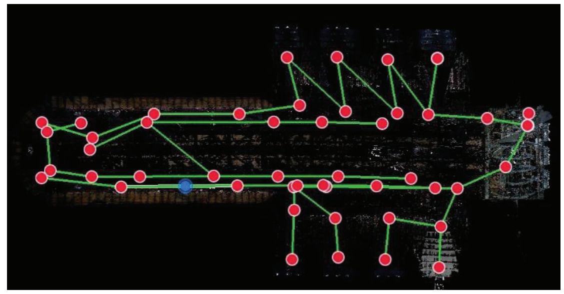

Figure 17: *Zagreb Cathedral with laser scanning "filming positions" (red dots)*

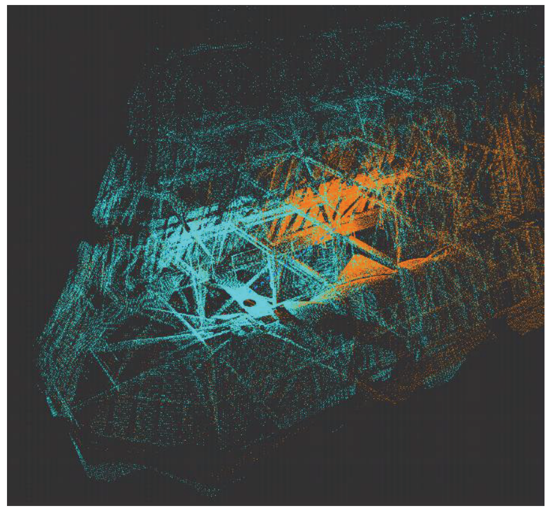

Figure 18: *Zagreb Cathedral – alignment of two scanning positions*

Figure 19: *Zagreb Cathedral – 360° image*

5 CONCLUSIONS

In this paper, a brief overview of damage to timber structural members after a moderate earthquake is presented. Basic statistical data on damage to roof structures after the Zagreb earthquake show the good behavior of timber roofs and give us an idea of why some of the roof structures collapsed.

When repairing roof structures, in most cases worn elements are replaced, elements with insufficient load-bearing capacity are strengthened and cracked elements are filled. During retrofitting, the influence of spatial stability of the roof structure is often forgotten, especially when spatial changes are made. The structural system

https://doi.org/10.52202/069179-0523

recognition and proper evaluation of former is also often miscarried. Unusual hybrid roof structures also add to the complexity of properly analysing and choosing the correct repair strategy. The influence of secondary elements such as chimneys and gables is also forgotten when the roof plays a stabilizing role in earthquake actions. In addition, the issue of details is questionable. The condition of the carpentry details is usually taken as given without considering the possibility that the distribution of forces in the system may change during lateral actions. In order to ensure the correct type of repair, it is important to have appropriate and high quality data on the condition of the structure and to use it for more detailed analysis so use of modern technologies is welcome. In this paper several benefits of laser scanners and UAVs is very briefly presented on two case studies.

ACKNOWLEDGEMENT

This research was partially funded by the Croatian Science Foundation, grant number UIP-2019-04-3749 (ARES project—assessment and rehabilitation of existing structures—development of contemporary methods for masonry and timber structures), project leader: Mislav Stepinac.

REFERENCES

[1] Dimovska S, Saloustros S, Pelà L, Roca P. Seismic Vulnerability Assessment of Representative Building Typologies from Barcelona‘s Eixample District 2021. doi:10.23967/sahc.2021.239.

[2] Funari MF, Silva LC, Mousavian E, Lourenço PB. Real-time Structural Stability of Domes through Limit Analysis: Application to St. Peter’s Dome. Int J Archit Herit 2021:1–23. doi:10.1080/15583058.2021.1992539.

[3] Stepinac M, Kisicek T, Renić T, Hafner I, Bedon C. Methods for the Assessment of Critical Properties in Existing Masonry Structures under Seismic Loads—The ARES Project. Appl Sci 2020, Vol 10, Page 1576 2020;10:1576. doi:10.3390/APP10051576.

[4] The Database of Usability Classification, Croatian Centre of Earthquake Engineering (HCPI - Hrvatski centar za potresno inženjerstvo), Faculty of Civil Engineering, University of Zagreb and The City of Zagreb, June 2020. n.d.

[5] Stepinac M, Lourenço PB, Atalić J, Kišiček T, Uroš M, Baniček M, et al. Damage classification of residential buildings in historical downtown after the ML5.5 earthquake in Zagreb, Croatia in 2020. Int J Disaster Risk Reduct 2021;56:102140. doi:https://doi.org/10.1016/j.ijdrr.2021.102140.

[6] Government of the Republic of Croatia and the World Bank. The Croatia Earthquake - Rapid Damage and Need Assessment 2020. 2020.

[7] World Bank Report: Croatia December 2020 Earthquake – Rapid Damage And Needs Assessment, 2020, March 2021, Government of Croatia. n.d.

[8] Ortega J, Vasconcelos G, Rodrigues H, Correia M. Assessment of the influence of horizontal diaphragms on the seismic performance of vernacular buildings. Bull Earthq Eng 2018. doi:10.1007/s10518-018-0318-8.

[9] Mirra M, Ravenshorst G, de Vries P, van de Kuilen JW. An analytical model describing the in-plane behaviour of timber diaphragms strengthened with plywood panels. Eng Struct 2021;235:112128. doi:10.1016/J.ENGSTRUCT.2021.112128.

[10] Stepinac M, Rajčić V, Barbalić J. Influence of long term load on timber-concrete composite systems. Gradjevinar 2015;67. doi:10.14256/JCE.1170.2014.

[11] Mirra M, Ravenshorst G, van de Kuilen J-W. Comparing In-Plane Equivalent Shear Stiffness of Timber Diaphragms Retrofitted with Light and Reversible Wood-Based Techniques. Pract Period Struct Des Constr 2021. doi:10.1061/(asce)sc.1943-5576.0000602.

[12] Moretić A, Stepinac M, Lourenço PB. Seismic upgrading of cultural heritage – A case study using an educational building in Croatia from the historicism style. Case Stud Constr Mater 2022;17. doi:10.1016/j.cscm.2022.e01183.

[13] Perković N, Stepinac M, Rajčić V, Barbalić J. Assessment of timber roof structures before and after earthquakes. Buildings 2021;11. doi:10.3390/buildings11110528.

[14] Bughin J, Manyika J, Woetzel J, Mattern FM, Chui S, Lund A, et al. A Future That Works: Automation, Employment, and Productivity. McKinsey Glob Inst 2017.

[15] McKinsey Global Institute. Global Media Report 2014. Glob Ind Overv 2014.

[16] Stepinac M, Gašparović M. A Review of Emerging Technologies for an Assessment of Safety and Seismic Vulnerability and Damage Detection of Existing Masonry Structures. Appl Sci 2020, Vol 10, Page 5060 2020;10:5060. doi:10.3390/APP10155060.

[17] Grazzini A, Chiabrando F, Foti S, Sammartano G, Spanò A. A Multidisciplinary Study on the Seismic Vulnerability of St. Agostino Church in Amatrice following the 2016 Seismic Sequence. Https://DoiOrg/101080/1558305820191575929 2019;14:885–902. doi:10.1080/15583058.2019.1575929.

[18] Baiocchi V, Dominici D, Mormile M. Uav Application in Post – Seismic Environment. Int Arch Photogramm Remote Sens Spat Inf Sci 2013;XL-1/W2:21–5. doi:10.5194/isprsarchives-xl-1-w2-21-2013.