Seismic Performance and Recommendation of Structural Intervention on Masonry Heritage Clock Towers: Representative Examples in Bosnia and Herzegovina

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Abstract. The paper deals with selected examples of clock towers in Bosnia and Herzegovina, representing high masonry heritage buildings made of stone, and explains the approach used in their preservation and restoration. The aim of this paper is to present a specific method of conservation used on stone structures. Three clock towers from Bosnia and Herzegovina were selected as representative examples: Sarajevo Clock Tower from the 16th century is an example of well-preserved building; The Clock Tower in Gradačac, the youngest building of this type in Bosnia and Herzegovina, is in poor structural conditions and in danger of collapsing; The Clock Tower in Banja Luka, the first clock tower in Bosnia and Herzegovina, was demolished in 1993 but the reconstruction project is planned for the current year. This paper addresses the structural properties of masonry clock tower from the Ottoman period, with special attention to preservation, analysis and strengthening. These tasks are still a challenge for masonry practitioners even if significant advances in research have been made in the last decades. The dynamic behavior of the historical buildings is usually analyzed to design repair intervention solutions and retrofitting. The structural behavior is analyzed using FEM modeling to examine how far the structural defects endanger the stability of the tower. The soil properties problem under the tower has been considered. Simplified yet effective procedures have been used as well. Results of the analysis have confirmed insufficient performance of the structure under horizontal action and the need for improvement.

1. Introduction

One of the most important parameters of the space within Ottoman urbanization is a vertical marker. It is clear that these are the minarets, church towers, and of course the clock towers.

It should be noted that the tower clocks were not a vertical marker of any urban or rural space. They were meant to be improvements in a spatial sense, and were built in specific environments with all the other contents of the waqf already implemented, which was supposed to be used for performance of all religious and secular activities.

What we consider to be indicative is the fact that this type of a building was most often planned and constructed along religious buildings to indicate the exact time for prayer. We anticipate that this is a historical period in which the eastern and western civilization was largely recognized. That is the time in which religion and ethnicity, imported from the east and the west, had a similar and close approach to religious learning, so the clocks are on the clock towers as vertical markers along the mosque minarets but also on the towers of churches or cathedrals.
When we are talking about the need for vertical markers in space, analyzing the urban aspect of a matrix, we can state that a vertical marker is the most accentuated point in space that is the most visible point which helps in spatial orientation at a given locality. Regardless of whether a space is urban or rural, we do not perceive markers a priori as a vertical highlight, but as a spatial highlight. This fact helps us to understand the theory of space, referring to urban landscape, but even rural and natural landscapes, each with a specifically defined urban matrix. What we observe in the structure of the Ottoman urban matrix clearly outlines the need for separate parts of urban values. Thus, housing is separated from the shops and, depending on the geomorphologic characteristics of the terrain, the housing segments are gravitating from all directions towards the commercial part. The specificity of Bosnia and Herzegovina is the number of religions and their constant representation in the functions of the city, so that the "main" religious building of Islam is accompanied with a tower, located in the central part of the urban area of a settlement. In the historic ambience, the markers had their symbolic value within the general image of the city, which has been retained for centuries. The markers were sometimes linked to individual quarters, for example, the marker of a minaret within a street, but clock towers contained a specific message and were unique.

It seems that once all the spaces that were treated as "towns" had clock towers, but in principle, due to a very sensitive construction, these buildings were not completely preserved. Their structure of a high-masonry building, which only occasionally had a top floor made of lighter material, which reminds us of the housing fortifications that we call the towers, led to a frequent collapse of all or part of these buildings. Depending on the historical time of their construction, during almost five hundred years of domination of the Ottoman empire in this area, these high buildings had different techniques of construction, but in most cases retained stone as building material, recognizing that only in this case the historical material would surpass the waqf founder forever, and provide long life to the building itself [1].

2. The causes of the destruction - structural aspects

The causes of the destruction of the architectural heritage are diverse and range from natural effects, and human activity (either destructive or inadequate in the form of design errors, building errors) to factors contributing to the deterioration of materials from which heritage buildings were built.

A strong earthquake is often preceded by a series of many weaker earthquakes, resulting in accumulation of permanent deformations in structures, which increase its stiffness and sometimes lead to minor damage in the form of smaller cracks. The strongest earthquakes, foreseen for some area, and particularly devastating earthquakes, occur very rarely and the time intervals between these most powerful earthquakes can be greater than the normal exploitation life of the towers of religious buildings. In order to design and build with cost effectiveness in earthquake prone areas, these reasons should be taken into account, especially when it comes to towers of shorter duration.

Obviously, historical buildings cannot meet the current constructive criteria of the existing laws and recommendations. These buildings were not built according to these criteria. Evaluation of the safety of the construction of old masonry towers is one of the central issues of preservation of national and global architectural monuments. In order to understand the significance of this field of research, it is enough to remind ourselves of the interest caused by the works on the Leaning tower of Pisa, or to look at the sudden demolition of the bell tower of the Saint Mark in Venice (1902), the City Tower of Pavia (1989), the bell tower of St. Magdalen church in Goch (Germany) (1992), or the bell tower of the town hall in Folignou in the earthquake of 1996. Vertical construction is a significant risk to towers, not only because of the high stress that impact their foundations but also because of their high sensitivity to the effects of thermal variations and especially the dynamic activities. Vertical loads can, in particular, cause the appearance of crumbling of stone, as in the case of the Cathedral Bell Tower in Monza, or the failure of the foundation soil and hence the additional activity generated by the resulting inclination, for example in the case of Garisenda Tower in Bologna. The wide cracks detected in many structures testify to decay associated with thermal variations [2].
Masonry Structures such as minarets, towers, lighthouses and bell towers are in many cases exposed to a strong impact of soil subsidence. Even the slightest initial geometrical imprecision and vertical deviation can cause the tilting of such structures, thus changing the pressure on the foundations, which is accompanied by the occurrence of horizontal tensile stresses or vertical micro-cracks. Depending on the type of material used and their cross-section dimension, towers can be of considerable weight, and significant inertia forces occur when the ground oscillates. In the case of an eccentric position of the mass, the building can rotate due to the horizontal load [3].

3. General design features – Cantilever construction
3.1. Aseismic designing
Aseismic design implies/ensures: protection of human life, limitation of damage and the usability of buildings that are important for the protection of people.

The criteria for asymmetric design are: Determination of seismic risk levels, selection of alternative design techniques, monitoring of generally accepted principles as well as decision-making regarding the expected activities in zones for which there are no officially verified seismic parameters.

The guiding principles in a project, considering seismic hazard are: Simplicity of constructive system, symmetrical and concise basis, uniformity and symmetry, with no sudden changes in mass, static indeterminacy, two-axial (uniform) resistance and stiffness, torsion strength and stiffness, adequate foundation and respect for tradition and function.

Factors affecting such thin structures and reducing their load bearing capacity are as follows: uniformity of the thickness of the walls, load eccentricity, presence of the niches, and greater strength of the corners, previous changes and incomplete reconstruction, interaction of towers and soils that often in this type of construction leads to the tilt, since the lack of uniformity of soil leads to initial eccentricities which cause an extra momentum, which all together leads to gradual enlargement of this phenomenon and dynamic action [4].

3.1.1. Specificities of design of seismically resistant towers
Evaluation of the structural safety of historical masonry towers in accordance with principles of heritage preservation is one of the central issues in the maintenance of the national and worldwide architectural heritage. The investigation of existing towers addressed: geometry, building techniques and structural performance. With respect to geometry a literature research had been performed in order to get typical configurations and element sizes, in different regions. From these data charts relating height to thickness, side to thickness, and gable height to tower height have been evaluated.

For structural analysis of the minarets and towers design spectra according to Eurocode 8 were used as well. The behavior factor of $q=1.5$ was estimated and it represents rather conservative value. For the corresponding seismic zone appropriate values of PGA were used, as follows: Zone VII – PGA 0.10g; Zone VIII – PGA 0.20g; Zone IX – PGA 0,30-0.40g. The analysis was performed using program SAP 2000, the towers were modeled with shell and brick elements.

In the case of particularly tall masonry structure, wind action must also be considered. For this purpose, it is essential to collect meteorological data on wind speed and direction and theoretical profiles of wind speed for certain types of site (changes in wind speed by altitude), and to use these data to compute the distribution of wind pressure for the corresponding contours of the building. (Čaušević, 2009; Čaušević, Kuljuh, & Rustempašić, 2011; Čaušević & Kudumović, 2011)

Analysis of tower/minaret models with modified mechanical characteristics of materials of which they are constructed, are carried out and those are: module of elasticity, Poisson’s coefficient and volume weight of materials for the case of better material characteristics, or for the case of worse material characteristics comparing to the actual state.
Many empirical formulas for the calculation of the basic dynamical properties of buildings [B1, C10, H1, P3, P4, P6] can be found in the literature. They are similar to each other, and here are just a few formulas [M6].

\[
T_1 = \frac{H}{13C_s\sqrt{l}} \quad \text{[s]} \\
T_1 = \frac{13C_s\sqrt{l}}{H} \quad \text{[Hz]}
\]

The following appear in the formulas:
- \(H\) - height above the foundation structure
- \(T_1\) - base oscillation period
- \(C_s\) - soil coefficient,
  - for stiff soil \(C_s = 0.9 \div 1.1\),
  - for medium stiff soil \(C_s = 0.7 \div 0.9\).

Similar empirical formulas can also be found in various engineering manuals and in some technical standards and their accompanying literature [4].

3.2. Basic calculation settings

- Regional seismic characteristics
- Historical and significant seismicity (data on earthquakes in a given area through history) - it is difficult to find "earthquake catalogue for a specific area".
- Probabilistic (or perhaps deterministic) estimate of seismic hazard. Seismological zoning - balanced combination of geological and seismological information
- Numerical modelling and estimation of masonry towers

3.3. Displacements

(1) Movements occurring due to seismic activity of the structure are calculated based on elastic deformations of the construction system using the following simplified formula:

\[
d_s = q_d d_r
\]

\(d_s\) shift of the point of the construction system caused by seismic activity;
\(q_d\) characteristic factor of the movement, which is taken to be equal to \(q\);
\(d_r\) movement of the same point of the construction system, determined by linear analysis based on the design response spectrum

The seismic upgrading is not compulsory. What is required is a comparison between the current safety level and the safety level after the intervention, adopting an aseismic protection level (\(gI\) factor) that varies according to the relevance (limited, average, high) and the use (irregular or not used, frequent, daily) of the building, and that is used to reduce or increase the reference seismic action.

| Table 1. Relevance category |
|-----------------------------|
| Relevance category         |
| Use category               |
| Limited                    |
| Average                    |
| High                       |
| Irregular or not used      |
| 0.50                       |
| 0.65                       |
| 0.80                       |
| Frequent                   |
| 0.65                       |
| 0.80                       |
| 1.00                       |
| Daily                      |
| 0.80                       |
| 1.00                       |
| 1.20                       |

Safety assessment: structures designed and based on earlier codes, or designed and constructed in accordance with good construction practice when no codes applies, may be considered safe to resist actions others than accidental actions (including earthquake) provided that:
Careful inspection does not reveal any evidence of significant damage, distress or deterioration. The structural system is reviewed, including investigation of critical details and checking them for stress transfer. The structure has demonstrated satisfactory performance for a sufficiently long period of time for extreme actions due to use and environmental effects to have occurred. Predicted deterioration taking into account the present condition and planned maintenance ensures sufficient durability. There have been no changes for a sufficiently long period of time that could significantly increase the actions on the structure or affect its durability, and no such changes are anticipated. Interventions on preserved buildings should be designed to "improve" and not to “retrofit” their structural performance [4].

4. Clock Tower in Sarajevo
The Clock Tower in Sarajevo, with a total height of 30 m, with a base dimension of 3.32 x 3.20 m, together with the minaret of the Bey’s mosque, represents the main vertical highlight of Baščaršija. Unlike other buildings of this type, the Clock Tower in Sarajevo expands towards the top, and this difference is 10cm in some spots. The entrance to the Clock Tower is located on the south facade and the four-floor wooden staircase leads to the top and the clock mechanism. The entry of natural light into the staircase is enabled by narrow openings on the walls of the tower. The walls are between 79 and 85 cm thick, and made of lime stone (smaller part) and cut tuff (mostly). The height of the stone blocks is 25 cm. There is a horizontal line of white limestone at every 2.50 meters. At the top of the clock tower, above a simple, profiled tuff crown which is 24 cm thick, there are two window openings oriented towards each side of the world. The width of the windows is 65 cm and their height are about 1.73 meters. The window top is made as a semi-circular arc. There are seats for the clocks above these windows, in the geometric center of the tower. Above is another 20 cm high crown, above which there are three rows of openings, with the finish in the form of split arches. The width of the window openings, on average, ranges from 47 to 50 cm, and their height at the center of the opening is 89 cm [5].

The masonry of the Clock Tower is completed by a profiled roof crown. At the top of the tower is a four-sided pyramid roof structure, covered with copper sheet, with a roof spear with four balls. The Clock Tower in Sarajevo was declared to be a national monument of BiH in 2006 by the Commission for the Conservation of National Monuments.¹ The decision was made on the basis of a series of criteria that dealt with the temporal determination and the historical value of the building, the artistic and aesthetic value that is manifested in proportion and composition, and the origin of the building, which includes the form and design, purpose and use, and location and position in space. The symbolic and ambient value of the Clock Tower is of utmost importance because it reflects the traditional value, importance in the structure and image of the city, and harmonious relation with other parts.

4.1. Proposed intervention
Unlike other buildings of the same type, the Clock Tower in Sarajevo is, conditionally speaking, in a structurally good condition. Specific risks to this building, as stated in the Decision on proclaiming

¹ (Decision on proclaiming buildings as national monuments: Historical monument – Clock-Tower in Sarajevo, 2006.)
buildings as national monuments (2006), are aerial pollution and penetration of rainwater. There are also some minor physical damages caused by warfare 1992-1995.

The first step in the prevention of adverse consequences is deterioration analysis. In order to propose adequate protection methods, and in order to overcome and prevent deterioration, the causes of the deterioration process of the building must be determined.

"Since no protection measures were taken, minor damage to the building occurred, which was mainly related to the leaking of the existing roof cover and the high degree of aerial pollution that caused the façade to be dirtied. The mortar dropped out of the joints in some places on the walls. One part of the crown (total length 1.50 meters) was damaged during the war. There was also peeling off oil paint from the metal parts of the windows and the doors." (Decision on proclaiming buildings as national monuments – Clock Tower in Sarajevo, 2006) It is important to emphasize that there is no detected structural damage, i.e. danger to the static stability of the building has not been detected for the time being.

Causes of surface damage to the building, i.e. stone, are: soluble salts (when moisture containing soluble salts is vaporized white spots on the surface of the stone or salt crystals remain in stone pores, salt crystals are accumulated in the pores until the stresses become too large and cause crushing of the stone); atmospheric pollution (sulfur dioxide reacts with oxide and water and produces sulfuric acid that destroys the surface of the stone and creates the so called black bark); freezing and defrosting (damage occurs on parts of the structure that are often damp and frozen such as roof crowns etc.); corrosion of metal parts (corrosion of copper couplings causes stains of green color while corrosion of iron joints causes rust stains that are difficult to remove from the stone), etc.

Visual inspection shows that there is no permanent maintenance, monitoring and control of the condition of the building performed by professional persons and competent institutions. In order to prevent further deterioration of the building, it is necessary to act on the outer sheath of the building, i.e. façade, roof structure and wooden structure inside the building. The façade should be cleaned of aerial pollution and a protective layer should be applied (impregnation) role of which is to protect natural stone. The decision on the cleaning method and types of impregnation agents should be made by an expert person. Damaged parts of the arch should be inspected, stabilized and protected from further decay, and missing segments replaced in accordance with conservative action. Renovations on the roof structure are necessary to prevent the penetration of water into the building.

All openings on the clock tower also need to be repaired and special interventions made to prevent the entry of birds and other animals.

The wooden parts inside the building are in a bad condition and it is necessary to examine them and determine the durability of the material from which the elements were built and their aspect of durability, and to propose repair (cleaning and impregnating the wood, replacing elements with a large percentage of damage, etc.)

5. Clock Tower in Gradačac
The Clock-Tower in Gradačac has an approximate square footprint of 5.23 x 5.11 m long, making it the widest clock tower in BiH. Its total height is 22.0 m. The wall is made of beautifully cut stone, with thickness of 0.75 m, which has larger dimensions at the base. The upper part of this building is made of bricks. The lifted entrance is accessed by ladder and it is located on the northwest side. Above the entrance door there is an inscription that attests to the time of construction of the building. The stone part of the building has three openings and there are six on the part made of bricks. Throughout the entire height of the building there are spaced openings that extend to the interior, and their purpose is to provide light inside of the Clock/Tower, i.e. wooden staircase leading to the top. According to the experts in the field and the analysis of the building, it was assumed that the Clock/ Tower in Gradačac began to tilt after the construction itself, and that today's inclination is $\alpha = 50$. This knowledge implies
an alarming condition and requires urgent interventions for the purpose of protection measures. Cracks have emerged in the field as a result of the tilting of the tower, and they are most noticeable on the north-eastern façade, which is the weakest point because the stone is under heavy load [6].

5.1. Proposed intervention

We believe that due to the lack of geotechnical data available on the soil of the Clock Tower, three hypotheses are needed to explain the possible reasons for the tilting of the tower. The first assumption is that the foundations of the tower are on soft ground, and that stiff rotation of the foundations could lead to the tilting of the tower whose inclination now is 5.1°, implying further that the tilt should be progressive. Another assumption is that tilting can be attributed to the heterogeneity of the stiffness of the soil along the same horizontal level. This can lead to differential movement, which is probably the reason for tilting of the structure. The first two theories are based on the premise that foundation structures do not reach the rocky part of the ground. The third hypothesis is based on the assumption that the tower is on the accumulation of stone blocks of various sizes that can be found in its environment. Perhaps erosion through time caused significant movement and transfer of some of these stone blocks, thus affecting the verticality of the tower.

The intervention recommendation is to reduce the tilt of the tower (using a hydraulic system) combined with the horizontal and vertical tensioning of the building. It is necessary to insert the tension on both sides of the walls in the already prepared channels. Tensioning should be performed from the bottom to the top of the outside and the inside if possible. The tension rings must form an enclosed ring around the building. It is desirable to carry out further research in order to preserve the Clock Tower. Detailed studies on geotechnical and structural aspects are required.
6. Clock Tower in Banja Luka (1985)

The Banja Luka clock tower was one of the major buildings of its period, and a specific public facility that was indispensable to the architectural and urban development of the town. It still remains a crucial element in the identification of the "Banja Luka čaršija", of which it is an integral part, always forming one of the key features of all views of the area. (Commission to Preserve National Monuments [CPNM], 2001; Husedžinović, 1989) [7].

The clock tower was closely linked in composition and concept with the Ferhad-Paša mosque and other buildings in the old Banja Luka čaršija. The clock tower had a single interior space with an almost square ground plan measuring 3.20 x 3.30 meters. Its walls were unusually massive. (CPNM, 2001; Bejtić 1953) It took the shape of a tower gradually narrowing towards a point some 14.40 meters high, from which point the vertical section newly built after the 1969 earthquake, began. The clock tower had a total height of 18.89 meters and was topped by a pyramidal roof (Figure 10). The clock tower was built of rough-cut limestone blocks in quicklime. The quality and type of stone varied but was mainly cut tufa on the exterior walls and "lauš" (a marly limestone of poor quality from the Banja Luka area) on the interior, so constructed that the blocks on the interior interlocked with those of the exterior walls. The new, upper sections of the building were made of Jajce tufa in cement mortar. The foundations of the building were of larger, regular limestone blocks, also bonded with quicklime. The building stood on a 4-meter-high embankment which meant that as such it stood on a wooden grid foundation of sound oak beams. The entire stone structure of the building was dappled here and there with ashlar stone spolia, pieces of terracotta pipe, and the remains of "tubla" bricks, which was particularly noticeable around the walled-up openings of the former clock. During the war in Bosnia and Herzegovina (1992-1995) The clock tower had been razed on the spot. During the earthquake in Banja Luka in 1969, the upper part of the tower was seriously damaged and reconstructed and even upgraded to the height of 18.9 m above ground level. During the next strong earthquake in Banja Luka in 1981, the Clock Tower was seriously damaged and structural intervention for its stability was necessary. Prof. Tahirović and Prof. Folić was invited to design reconstruction works for structural stability of the tower. They thoroughly analyzed the structure, condition and damages of the Tower. The special attention was paid to the action’s analysis, self-weight of the structure, wind load and seismic load. Their structural analysis confirmed the assumption that the seismic actions have dominant effect on the stability of the tower and horizontal displacements. Based on the analysis of the vertical and horizontal tensile forces caused by seismic forces in the tower structure, their design took into consideration the interpolation of RC ring beams within the stone walls from the interior side at multiple levels of the tower, connected by vertical steel ties. The design also suggested reinforcing the tower substructure with RC walls. Due to the development of cracks in stone walls, it was also necessary to apply injectable emulsion to connect stone blocks in the walls [8] [9].
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Figure 4. the Clock Tower in Banja Luka displacement caused by wind and seismic loads

Figure 5. Structural rehabilitation-drawings for the Clock Tower in Banja Luka

7. Conclusions

Masonry towers have two prominent characteristics. On one side, their height and slenderness have, because of lack of proper stress distribution (strain), lack of energy dissipation along the structure with a concentration of stresses in the base and fragile behavior due to the dominant vertical effects and the fragility of the damaged walls. On the other hand, in terms of dynamic behavior of masonry towers, the positive characteristic is their long basic vibration period. For this reason, their dynamic behavior is limited by the decreasing range of response spectrum. Whether this will be favorable depends primarily on the seismic hazard of the area under investigation, as well as the actual state of the construction and the material from which it was built. The combination of these two contrasting characteristics generates the appropriate (exact) required seismic evaluation of the masonry tower.

It is necessary to express a positive opinion on the relationship between the achieved seismic safety, through a intervention consistent with the needs of conservation, and the reference protection level, which is desirable with reference to the seismic hazard and the conditions of use; this assessment will be expressed in global terms, not only on the basis of a numerical comparison between collapse acceleration and expected acceleration at the site, but also considering other aspects that were qualitatively evaluated and cannot be explicitly considered in the calculation.

A “to do list” in case of strengthening intervention is not viable, since specific and effective intervention in one case can be ineffective or, even worst, detrimental to the seismic capacity of the structure in other cases.

In order to respect the existing features of the considered constructions special care has to be paid in order to limit in any case as much as possible variations not only of its external appearance, but also of its mechanical behavior.

Attention has to be focused on limiting interventions to a strict minimum, avoiding unnecessary strengthening, a goal that is clearly in agreement with the principles of sustainable development.
The actual contribution of any traditional/innovative material and techniques, and of their possible combinations, can be adequately and scientifically exploited in order to ensure durability, compatibility and possibly removability of repair/strengthening interventions.

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