Structural Analysis of Gradačac Clock Tower Aiming Towards Intervention in Preserving Authenticity

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Abstract. Old masonry towers, in all their variety – be it a bell tower, a city tower, clock tower, inhabited residential towers, and/or guard/watchtowers – can be found all around the world representing typical urban centre feature, and in some cases – they are the countryside panorama landmark. Statics analysis and calculation are the first steps towards engineering interventions on cultural and historical heritage buildings. In the structural analysis of clock towers, the typical critical points and places where crucial damages that could lead to the collapse, are expected are in the top sections of the building - where the oscillation amplitude reaches its maximal value. Effect on building structure is observed concerning the oscillation frequency and building's own frequency and energy, which can explain why minaret towers and high slim towers, in some cases, can better withstand earthquakes than extremely rigid buildings; given that the resonance, low-quality materials and other factors can lead to the vulnerability of a building structure. This type of building is designed on a simple, regular shape ground plan, or, in other words, the towers have a symmetrical ground plan and uniformly distributed mass and height. The second statement provides that, depending on building materials used and the cross-section dimensions, towers can be very heavy, which can cause the appearance of significant inertia forces during earthquake oscillations. If there's mass eccentricity, the horizontal loads could tip the building over. Gradačac clock tower's load-bearing structural walls are built with masonry stone blocks. The vertical loads are, via slabs and wooden beams, conducted to the walls and down to the foundations. Foundation structure consists of a slab, 80cm thick, positioned at -8.25m which sits on a well-compacted layer of soil. Wooden staircases are used for vertical transportation between storeys. Structural analysis calculation is based on a 3D model of a building and is performed by using the finite elements method (FEM) in Tower calculation software. The requirements for the authenticity in preservation actions imply that the interpretation and the presentation must correlate with basic authenticity principles, in compliance to Nara document (ICOMOS, 1994), protecting cultural values, from both – the hazardous influences of intrusive infrastructure and load of visitors, and incorrect and inappropriate interpretations.

1. Introduction

Before analysing the clock tower in Gradačac Old Town, we will, in general terms, discuss the clock tower phenomenon in Bosnia and Herzegovina, given it is characteristic for the Ottoman period settlements.

1.1. Clock towers - in general

Vertical landmark is one of the most important and prominent spatial parameters of urbanization by the Ottomans. It is obvious that, when speaking of the verticalization, we refer to minarets, church
towers, and finally - clock towers. It should be underlined that clock towers are not mandatory vertical landmarks in every rural and/or urban space. They are rather spatial developmental upgrade elements built in specific ambiances where a waqf¹ content, required for exercising all the common, daily, both secular and religious, activities, has already been realised.

The indicative feature of this landmark is the fact that most often this type of facility has been planned and erected nearby the sacral buildings to show the exact time of prayer. We shall assume that this reflects historical period earmarked with already a great deal of recognition between the Eastern and Western civilizations; times when religion and ethnicity, imported both from the east and the west, have a similar and close approach to religious teachings, thus clocks are placed in clock towers as the vertical landmarks along minarets of mosques, as well as on towers of churches or cathedrals.

Speaking of the vertical landmark needed in spatial set, analysing the urban aspect of a pattern, we can state that the vertical landmark is most commonly accented spot in the spatial set, the most prominent and visible one, which helps in getting spatial orientation within given location.

Regardless to the nature of the space itself, be it an urban or a rural setting, the landmarks are not perceived as an a-priori vertical feature but are primarily seen as spatial accented ones. This fact aids us in understanding spatial theory that pertains to urban, rural, and even natural landscapes; each of them respectively defined by the specific urban pattern. Features detected in the Ottoman urban pattern/matrix structure clearly outline the need for separate parts of content related values of urbanity scheme. Thus, we have a pattern where the accommodation and living sphere is separated from the trading sphere and, depending on geomorphological characteristics of the area – we have accommodation and living segments that are, from every course, gravitationally bound to the segments of the trade related ones. The numerous religions and their constant representation in the functions of the city is the precise specificity of Bosnia and Herzegovina, so there we have a clock tower set besides the "main" sacral object of the Islamic province, in the central part of the settlement's urban space.

Speaking of the historic ambiance, landmarks have had their symbolic value within the general image of the city, which has been maintained for centuries. The landmarks are sometimes tied to individual quarters, e.g. rapper minarets inside the mahala (a neighbourhood), but when it comes to clock towers, they contain a specific message and are unique.

It appears that at one point in time, every space treated as kasaba (a borough) had a clock tower, but as a rule due to their rather delicate construction, these facilities failed to be preserved completely. Their high masonry structure, which only sometimes has a ĉatma/çatma² on the top, and resembles the fortified residential facilities called towers, has led to frequent, either total or partial, collapse of these facilities. Depending on the historical timestamp of its origins, throughout the nearly five hundred years of the Ottoman Empire domination in this region, masonry techniques for these tall buildings may have varied, but in most cases they remained built in stone, recognising that only in such a case

1 Waqf, also known as hubous, an innaliable charitable endowment. In the tradition of the Islamic civilization circle, it is common for individuals with large capital to build a system of different facilities that can be divided into two groups: the first group are non-profit buildings (mosques, madrasahs, maktabi, clock towers ...) and the second group are profitable facilities (shops , khans, hamams ..) whose profits are used to maintain the non-profitable facilities

2 Čatma/ from Turkish catma/ is by the rule, the top floor of a high facility with walls made of light materials(wood, brick and/or porous stone) statically downsize the burden on the lower parts of the facility. At the same time, ĉatma/çatma is also a watch post that gives a good view of the surrounding area, given we speak of a fortified facility.
the historic material used is the sufficient one to outlive the *waqif*³ and provide for a long life expectancy of the facility itself.

Surely, the period given has been the one of numerous wars and armed conflicts, thus the mere destruction, which in this region is considered as a part of the heritage, has significantly threatened the existence of the clock towers, but also many years of them being in use, and also affected by the negligence, have led to the poor condition of these facilities nowadays, and the kind of degradation in times.

1.2. Clock towers in Bosnia and Herzegovina
In Bosnia and Herzegovina, the emergence of clock towers begins in the Ottoman period and they are a characteristic feature in other European parts of the Ottoman Empire too. The tower with a clock embedded in it serves residents to tell time, which is required to timely perform five daily prayers. They also represent an accented and significant spatial landmark, prominent elements in the vistas of space, always located at the kernel of the urban centre, next to the mosque, and as an integral part of a larger urban complex.

Throughout period from 1463 to 1878, there were 21 clock towers built in our region. All of them have been erected in coherence with the traditional building style with local materials used – stone predominantly, with exception of Vratnik clock tower in Sarajevo, which had been built in timber, and has been demolished due to its instability and posing the risk of collapsing. Although clock towers are built in line with the same principles, they can be differentiated in respect to their dimensions (the template/pattern and the height), their location, and the time of construction. These tall and slender facilities rest on a square base that ranges from 3.07m to 5.5m. The height of clock towers in Bosnia and Herzegovina is recorded to be in range from 10m (Gornji Vakuf clock tower) up to 28m (a clock tower in Sarajevo). The thickness of the masonry structure, with corners made of fine ashlar and the other parts of coarser cut stone, varies from 0.65 to 1m. The openings in upper section of the tower, where the clock is positioned vary in shape: be it circular, rectangular, with or without arches. There is a cornice between the aforementioned openings and the tented roof structure.

2. Gradačac Old Town Clock Tower
Gradačac Clock Tower has an approximately square base of 5.23 x 5.11m, which makes it the widest clock tower in the BiH. The total height of the construction is 22.0 m. It is built of nicely 0.75 m thick carved stone pieces, which at the bottom of the tower are of larger dimensions. The upper section of the facility, total of 2.15m high, is brick-built and is covered by a pyramidal roof with shingle cover that is now in a state of decay. The raised entrance measuring 0.77 x 1.83 m, accessed by a ladder, is positioned on the northwest side. Above the front door there is a caption that testifies on the time of the facility construction. On the stone section of the building there are three openings, while six more are embedded in the design of its brick-built section. Throughout the vertical of the facility, there are openings that widens inwards and are intended to provide light to the inside of the clock tower, i.e. to a wooden 0.75 m wide staircase with 90 steps leading to the top. The building has a ground floor and five storeys [1].

According to the evaluation, done by experts at the site, and the estimate and the analysis of the facility performed, it has been assumed that Gradačac Clock Tower began to slant as early as the 1970s, and that the gradient nowadays, relative to the vertical, is approximately α = 5°. This finding implies an alarming situation, and demands for urgent interventions and the protection measures to be undertaken. Due to the aforementioned incline, the tower is now exposed to an external torque that borders its bearing capacity limit. Furthermore, during the site visit, as a result of the tower slanting,

³ *Waqif* - A *waqif* is a person who establishes a system of profitable and / or unprofitable objects and that level of endowment is regulated by a document called *vakifm*. *Vakif* je osoba koja uspostavlja sistem profitabilnih i/ili neprofitabilnih objekata koji taj nivo zadužbine reguliše dokumentom koji se naziva *vakufnama*.
there have been cracks observed, with the largest of them recorded to be at the north-east facade, which are the weakest points because the stone is under the highest load. Due to this, there are visible cracks, and parts in the masonry load-bearing structure are thrashed out. Given these information, the conclusion drawn is that there is a great danger of the tower collapsing under its own weight and/or under the strong effects of horizontal forces—the winds above all.

Figure 1. The Clock Tower in Gradačac Old Town.

2.1. The structural analyses of a clock tower
Towers of sacral buildings are frequently the key landmarks of an urban complex and, with tendency to dominate over other constructions and structures, they create recognisable city image. Many cities are famous for their church towers, minarets, and/or clock towers. Structural performance of these facilities significantly differs from auxiliary buildings. In general, a tower could be described as tall and slender construction. Use of traditional building materials, method of masonry works applied, and rather slender and efficient design system, makes the towers rather interesting and, at the same time, challenging for planners and architects.

2.2. Description of the site [1]
The site where the facility is located is a flat one. Gradačac Clock Tower location is defined by following environmental parameters:

- Wind Zone, rating I with \( v_{b0} = 18 \, m/s \)
- Snow Load Zone III, with \( s_k = 2.0 \, kN/m^2 \)
- Seizmic Zone: The value of the reference maximum acceleration of type A soil for a recurrence interval of 475 years: \( a_{gR}/g = 0.17 \)

The static calculation was done on a three-dimensional construction model by the finite element method, using the Tower programme.
Masonry towers are characteristic for their two prominent (striking) features. On the one hand, their height and slenderness inevitably results in lack of adequate reception of stress distribution (the strain), a lack of energy dissipation throughout the length of the structure, with the stress being concentrated at the base, the brittleness moment feature due to the horizontal effects, and the brittleness of the damaged masonry structure. On the other hand, with regard to the masonry towers dynamic performance, their long basic vibration period is a positive feature. For this reason, dynamic performance is limited by the descending branch of the response spectrum. Whether this is going to be favourable depends primarily on the seismic hazard of the area studied, as well as the actual condition of the structure and the building materials used. The combination of these two contrasting features generates an appropriate (correct) mandatory seismic masonry tower estimate [2].

The static calculation on cultural heritage facilities is the first step of making engineering intervention on such buildings. The static model of such a construction is a console, fixed in its lowest fixing point, bearing vertical central load of its own weight and the horizontal stress (continuously/permanently) throughout the height of the building (commonly the winds and earthquakes).

Wind load calculation parameters:
- Basic velocity of wind for location of Gradačac $v_b = 18$ m/s
- Site category II EN1991-1-4 § 4.3.2
- The Orography Factor: $c_0(z) = 1.0$ EN1991-1-4 § 4.3.3
- The Turbulence Factor: $k_I = 1.0$ EN1991-1-4 § 4.4
- The Construction Factor $C_fC_d = 1.0$, of a framework building with bearing walls height under 100m and lesser then quadriple lenght, windwise EN1991-1-4 § 6.2
- $\rho$ air density = 1,25 kg/m³ EN1991-1-4 §4.5

Height $z = 19.8$ m; $v_{b,0} = 18.0$ m/s

Basic velocity of wind

$$v_b = c_{dir} \cdot c_{season} \cdot 19 \text{ m/s} = 1.0 \cdot 1.0 \cdot 19 = 18.0 \text{ m/s}$$ EN1991-1-4 §4.2
Basic wind load
\[ q_b = 0.5 \cdot \rho \cdot v_b^2 = \frac{1}{2} \times 1.25 \times 18^2 = 202.5 \ \text{N/m}^2 \]  

Load due to wind speed at impact
\[ q_p(z) = [1 + 7 \cdot l_v(z)] \cdot \frac{1}{2} \cdot \rho \cdot v_b^2(z) \]  

Average velocity of wind at height point \( z \)
\[ v_m(z) = c_r(z) \cdot c_0(z) \cdot v_b \]  

Coefficient of Surface Roughness
\[ c_r(z) = k_r \cdot \ln\left( \frac{z}{z_0} \right) \]

for \( z_{\min} < z < z_{\max} \)

Terrain kind/category III
\[ \rightarrow z_0 = 0.3; \text{ for } z > z_{\min} \]  

\[ k_r = 0.19 \left( \frac{z_0}{z_{0,0}} \right)^{0.07} = 0.19; c_r(z) = 1.13; c_0 = 1.0; v_m(z) = 20.456 \text{ m/s} \]

\[ k_t = 1.0; l_v = \frac{k_t}{\ln\left( \frac{z}{z_0} \right)} = 0.167; q_p(19.8) = [1 + 7 \cdot 0.167] \cdot 0.5 \cdot 1.25 \cdot 20.456^2 = 0.568 \text{kN/m}^2 \]

Wind loads on the building surfaces

Vertical wall

Width \( b = 5.60\text{m} \); Length \( d = 5.55\text{m} \); \( \frac{h}{d} = \frac{19.8}{5.55} = 3.568 \)

\[ \text{Figure 3. Dimensioning the wind load} \]

Coefficient of Pressure Interior
\[ c_{p1} = +0.200 \text{respectively } c_{p1} = -0.3 \]  

Wind load
\[ w_e = q_p \cdot (c_{pe} - c_{p1}) \text{ [kN/m}^2] \]

Course/Direction: X directly to the surface

| Zone | Cpe | Cpi |
|------|-----|-----|
| D    | -0.63 → w= -0.47; Cpi= -0.300 |
| E    | -0.51 → w= -0.186 [4] |
Figure 4. Analysis of Seismic and Wind Load of Gradačac Clock Tower

Figure 5. Design spectrum
Figure 6. Calculation results

The horizontal response spectrum corresponds with the recurrence interval, of let's say 500 years, chosen for the structural estimation of the tower with intention to demonstrate the effect of low (still realistic) level of ground movement for the current state of strain/stress in the tower. Seismic activities that correspond with larger recurrence interval would surely be better for performing the estimate of a valuable historical monument. Never the less, there is no agreement within the scientific community in regards to the recurrence interval which would be the one matching for the construction with the homologous cultural values. This issue if further complicated by the incertitude that affects the results of seismic hazard probability analyses for longer recurrence interval [1].

3. Conservation recommendations

- Temporary and/or interim foundation stabilisation measures
- Permanent foundation stabilisation measures
- Additional works on stabilisation of the foundation

The overall weight is supported by the walls. The walls are built of stone, calx, and mortar. Due to the tower slant, there is uneven distribution of loads to the masonry wall structure. We also want to remind that in 1985 and 1986 there was a line of rehabilitation works performed on the clock tower after detailed analyses and recordings, namely: photogrammetric imaging of the facility, geomechanical testing of the terrain, archaeological probing investigations, architectural imaging of the
facility and ultimately the seismic sensitivity of the facility testing by the method of ambient vibration have been performed. All the aforesaid resulted in the action implemented in those two years to secure the conditions of the construction site. Namely there was tightening of the spots identified as the most critical zones of facility damage, performed by means of utilising and setting up rings made of iron fittings. Furthermore, the foundations were rehabilitated and reinforced by means of injecting and setting reinforced concrete walls on both sides. Drilling on the inside surface of the masonry walls followed by application of reinforced concrete cerclages—stitches at the vertical distances of every 240-300 cm, at the locations of former wooden tie-beams was also done. It was followed by installation of iron rods FI 20 mm in four corners of the facility that were then connected with the horizontal cerclages by utilising anchored brackets L 120x13 mm and welded anchors (I 120). Upon the prestringing-up of the upper zones vertical bars/rods cement emulsion was injected into all of the cracks, and also the entire masonry mass - up to 14.40 m in height. Structural evaluation of the masonry tower construction is a complex task that involves both the aesthetic and the constructive aspect. The financial aspect is not discussed in more detail, but it always plays an important role.

This type of facility construction rests on a simple and correct design of the base, that is, a symmetrical base and a uniform mass-to-height ratio of the building. The latter requirement is based in fact that, depending on building materials utilised and the vertical cross section of the construction, towers can be rather weighty buildings, which, during oscillation of ground results in occurrence of significant inertial force. In the case of the mass eccentricity, the tower (the minaret) may rotate due to the horizontal loads.

These structures belong to the group of slender structures whose vibrations depend primarily on the bending stiffness feature of such a structure. Deformations due to the shear have little effect on the rigidity of tall slender structures, so in practical calculations those can be neglected. Most of the old towers are national and cultural heritage monuments. Thus, during the assessment of these structures one must take into account both - the structural, and the aesthetic requirements. The results of structural analysis show an inadequate seismic resistance or seismic characteristics when exposed to stronger earthquakes [3].

The recommendation for intervention in this example is to reduce the inclination of the tower (by use of a hydraulic system) combined with the weighting of the facility - by use of horizontal and vertical weight-ties. The weight-ties are to be inserted on both sides of the building walls into already prepared channels. Tightening is to be performed from the bottom to the top from the inside and the outside, if possible. Positioned weight-ties are due to form a closed ring around the facility. It is advisable to perform an additional research for the clock tower preservation. Further, more detailed geotechnical and structural studies are required.

The intervention has to be performed adhering precisely to the determined action and procedure schedule, which means following these operational phases:

1. Potential removal of mortar or the surface finish to check the condition of the masonry structure.
2. Deepening and cutting of mortar joints using adequate tools; the recesses/grooves must be at least 10 mm high and 50-70 mm deep so that the reinforcement can be inserted and that the remaining mortar in the walls can take on the active loads.
3. Precise inspection of walls structure: if necessary, some large cavities/cracks should be filled in by injecting process or some bricks could be replaced.
4. Removal of damaged material by air-blasting and/or with water (water-blasting), or by applying special solvents, depending on the existing materials and the ones that shall be used in the intervention. Water can be used in cases where the mortar is selected for repointing, so that excessive absorption of the mortar in the brick can be avoided. The joint flutes should remain dry when using synthetic mortars (resin additives).
5. Mortars are usually made of hydraulic lime when better compatibility (chemical, physical and mechanical) is desired with the existing mortar, and those may contain special additives (e.g. expansive properties to compensate for shrinkage during the hydration phase). Synthetic resins (epoxy, acrylic or polyester) can be used for special cases, for example, when it is required to achieve adequate strength in a short period of time.

6. Installation of reinforcement materials: steel bars or plates (stainless steel, generally) or the FRP lamellae can be used. It is necessary to increase the friction between the reinforcement and the mortar. Moreover, the placement of spacing may be appropriate for separating the reinforcement from the brick surface. It is recommended to use multiple rods of smaller diameter. Due to the small size of the ties/clamps (usually about 10-15 mm), only reduced sizes of reinforcement (diameter 4-6 mm for bars) can be inserted.

7. The second layer of material utilised must be applied over the bars so as to cover them completely.

8. The final layer of mortar/plaster should be applied in the last 15-20 mm. To achieve certain effects, special sands or pigments can be used [2].

4. Conclusions

Authenticity and integrity as the terms would explain the relation between universality and relativity in the concept of truth and value judgments in different cultural frameworks. To be considered appropriate, a contemporary intervention should meet the following criteria: physical protection of a historic building or complex, including conservation and restoration actions, active preservation of a historic building or complex, incorporation into a modern urban matrix, and the permanent use of the facility/complex. When a historic building is significantly damaged, it is more than just properly carved stone blocks that is needed to fully restore its physical appearance; it needs to make connections with its context, past glory and the present meaning in its community.

Structural analysis results reveals inadequate seismic resistance of masonry towers when exposed to effects of stronger earthquakes. The decision on the method of intervention should be carefully taken, and, if possible, respecting the principle of the minimum of intervention. Preserving the aesthetic and cultural value is of the utmost importance. Successful interventions, of any chosen preservation and protection method, first and foremost have to be based in the understanding of the historical context of the facility and its ambiance. Interventions involving reinforcement actions on tall and slender facilities have to be thoroughly analysed, and traditional construction methods and experience of old master builders have to be taken into consideration. The decision on the intervention has to be the result of precise evaluation of the current state of the structure and level of its security. To achieve satisfactory level of security, it is necessary to consider the scope and the type of the intervention planned. Measures that are to be taken for seismic protection and safety (measures like injecting or similar) include enhancing the characteristics of building materials so as to increase its individual elements’ bearing capacity, and/or the foundation stiffness. Intervention on ancient masonry towers should be encompassed by a wider scope rehabilitation actions on historic centres, which brings us to the multidisciplinary aspects. Prevention and rehabilitation can only be successfully performed if the diagnosis on condition of the facility has been thoroughly investigated. In the case of tilted towers, the earthquake load is applied in the direction of the maximum inclination of the tower. The values of the maximum response in terms of its footing sheer, capsize moment, and axial forces for both scenarios should be given in the table. Comparing the obtained tensile stress values with the permissible tensile values for masonry structures often leads to the conclusion that it is impossible to avoid the appearance of relatable horizontal cracks.
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