Influence of mechanical properties of materials on the stability and safety of masonry sacral towers structures

A. Čaušević, N. Kuljuh & N. Rustempašić
Faculty of Architecture, Sarajevo, Bosnia and Herzegovina

Abstract

High vertical form in architecture demonstrates a tendency towards something higher or divine, something beyond the ordinary life, more than something earthly, as if it is leading us, or helping us to hear voices and sound, or perhaps to see more clearly. High vertical form in architecture is not exclusively associated with religion. It is by all means a power, and demonstration of power. In the case of construction intervention of such objects, two problems immediately emerge: the first concerns the usual and expected approach, in the most number of cases, to keep the role and geometry of constructive, now damaged elements. This situation can be additionally complicated by request, or better to say a need, which is very often present, to strengthen those elements with respect to its original state. Other, perhaps even bigger problems, concerns the possibility of embedding. In this article ten minarets and church towers are presented, carefully chosen as representatives from threatened cultural heritage towers. The computer program SAP 2000 was used to analyze the towers with shell elements. Analysis has been conducted with altered mechanical properties of the materials towers are built from as follows: modulus of elasticity, Poison's coefficient and specific weight of the material for the cases of better material characteristics and bad characteristics of the material in relation to the actual situation.
Keywords: masonry, mechanical properties of materials, tower, minaret, stability.

WIT Transactions on The Built Environment, Vol 118, © 2011 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/STR110351

1 Introduction

High vertical form in architecture demonstrates a tendency towards something higher or divine, something beyond the ordinary life, more than something earthly, as if it is leading us, or helping us to hear voices and sound (bell, Ezan – call to Prayer and Ṣalāt), or just to see more clearly, such as a watch tower. High vertical form in architecture is not exclusively associated with religion. It is by all means a power, and demonstration of power.

Architectural verticals are not only association of religion. They are also power and demonstration of power. High vertical form through the time became a crucial element in the repertoire of forms that serves as landmarks for orientation and identification and marking of space and aura in the centre of urban areas. Beside that it is also used as element in design to balance and anchor dome shapes.

Tower is a term that is closest in defining an architectural vertical and materialization of the same. A. J. Butler and H. Thiersch see origins of towers in models of ancient lighthouses (primarily, Faros and Alexandria).

Of sacral objects, a continuity of architectural science review is presented – architecture of religious objects and architectural towers with them.

2 Characteristic materials – mechanical characteristics, characteristic toughness and other characteristics

Characteristics of construction and geometrical characteristics of construction slenderness of towers or minarets, depends on many factors including knowledge about constructions and implementation of that knowledge during the construction, experience of architect or designer, seismicity of the region, and availability of materials for construction in that area. Depending on type of material used and dimension of the cross section, towers can have significant weight and significant inertial forces occur during the oscillation of soil. Materials can be globally classified into two characteristic groups, these are different significantly: brittle materials and plastic – toughened materials (precise – elastoplastic).

Here, it is necessary to remind on some basic specifications of masonry materials and their mechanical characteristics:

- Mechanical behaviour is not homogeneous;
- Masonry material cannot be considered as isotropic material;
- Resistance to bending can be considered approximate to zero especially in the case of long-term loads;
- Behaviour under the influence of shear forces often represents certain level of ductility;
- In many cases, presence of cracks can be considered especially if we talk about actual rigidity of elements;
- Mechanical behaviour is not linear and often it is not elastic.

2.1 Types and characteristics of materials that are used for load-bearing elements of masonry construction

When we talk about masonry constructions we cannot avoid question about material characteristics that are used for load-bearing elements in the process of building a wall.

Relations of material strength that are used in masonry constructions are very uneven.

For example: relation of strength on pressure of stone (200.0 KN/m2), brick (20.0 KN/m2) and clay strength (0.1 KN/m2) is 200:20:0.1.

Deformability of material is dependent on module of elasticity (E) and it can have an influence on necessary dimensions of construction sections and the way of construction (entering initial deformations of opposite direction and similar) but generally it does not have an influence on the shape of systemic lines of construction.

Characteristics of materials are always observed as the sum of simultaneous effects of parameters such as composition of material, manufacturing technology and the structure that has been achieved in production. For engineers it was always challenging to analyze and design these kinds of objects because of very complex characteristics of materials that were used in its construction. Although masonry constructions are used widely and they have very simple structural schemes, they often, because of the non homogeneity of masonry material, require very complicated methods of analysis so it could be correctly calculated and designed.

3 Limitations of shifts

Parameters according to which side rigidity is calculated is an index of shift. It is defined as a ratio of maximum embedment at the peak of the building and total height. There is no state regulation for index of shift, but h/400 is a limitation that is traditionally accepted. In different countries, values in the range of 1/1000 to the even lower 1/200 are used. Lower values are used for hotels and objects in condominiums. In the case of conventional constructions, the desirable range is from 1/700 to 1/350.

Limitation of floor shifts is calculated according to the form:

$$f_{\max} = \frac{H}{600} \tag{1}$$

where:
H - Height of the object, not taking into account influence of soil.
Limitations of maximum relatively shifts are:
- Maximum relatively shift for linear behaviour of construction cannot be greater than

$$\frac{H}{350}$$

www.witpress.com, ISSN 1743-3509 (on-line)

- Maximum relatively shift of floors for projected level of earthquake, or for moderate amount of nonlinear deformations in the construction cannot be greater than

$$\frac{H}{150}$$

Despite the large level of approximate values that are being imposed into it, the equivalent static method is a method that is mostly used and it can give reliable information about behaviour of masonry constructions influenced by seismicity activities, as from a global point of view, as for analysis of individual elements of construction.

From the previous considerations it is obvious that for calculation of equivalent static force it is necessary to know the base period or frequencies. Base period of oscillation can be calculated with relatively precious numerical procedures of construction dynamic, but it can be also estimated based on empiric formulas. For first orientation rough estimates are needed, and in further development of project more precise methods can be applied.

In professional literature large number of empirical terms can be found for the calculation of basic dynamical characteristics of buildings [B1, C10, H1, P3, P4, P6]. Between themselves they are similar, and here are some terms [M6].

$$T_1 = \frac{H}{13C_S\sqrt{l}}\,[s],\ T_1 = \frac{13C_S\sqrt{l}}{H}\,[Hz] \qquad (2)$$

where:

H – Height above foundation construction
T_1 – base period of oscillation
C_s – coefficient of soil,
For rigid soil C_s = 0.9 ÷1.1,
For medium rigid soil C_s = 0.7 ÷ 0.9.

Similar empirical formulas also can be found in various engineering handbooks, and in some technical standards and its following literature. Shifts are also the best indicator of the actual state and very important for flexible constructions.

The problem of seismicity is primarily a problem of shifts and deformations of objects during an earthquake. Beside the formal proof of the main stress in tension and similar, more important is the concept of construction, quality of building and details of building.

In the analysis of constructions, influenced by earthquake, variable inertia forces and elastic-plastic work through time are occurring.

For calculation of equivalent static force it is necessary to know the base period or frequencies. Base period of oscillation can be calculated with relatively precious numerical procedures of construction dynamic, but it can be also estimated based on empiric formulas. For first orientation rough estimates are needed, and in further development of project more precise methods can be applied.

4 Basic setting of calculation

- Regional seismicity characteristics
- Historical and significant seismicity
- Probabilistic (or deterministic) estimate of seismicity hazard
- Numerical modelling and estimate of masonry towers

Masonry towers are characterized with two prominent (conspicuous) characteristics. From one side, its height and plastic have for corollary lack of adequate reception of stress distribution (tension), lack of energy of dissipation along the structure with concentration of stress in basis and brittle behaviour due to the dynamical behaviour of masonry towers and brittle value of damaged wall. From the other side, concerning dynamical behaviour of masonry towers, a positive characteristic is their longer basic period of vibration. Because of these reasons dynamical behaviour is limited with a decreasing branch of spectrum response. This conveniently depends after all on seismicity hazard of the area that is the research subject, as to the actual state of structure and materials of which the same is built.

A combination of these two contrasting characteristics, generate appropriate mandatory seismic estimation of a masonry tower.

4.1 Shifts

Shifts that occur because of seismicity activity of construction are calculated based on elasticity deformation of construction system using the following simplified term:

$$d_s = q_d \cdot d_e \cdot \gamma_i \tag{3}$$

where:

d_s – Shift of point of construction system caused by seismicity activity;
q_d – factor of shift characteristics, that is taken to be equal q;
d_e – shift of the same point of construction system, defined with linear analysis based on spectrum of structure reaction.

In the project, presented are results for a total of ten minarets and church towers, historical and cultural heritage, that through entire history were endangered from structural aspects or experienced collapse and five with circular cross section and five with polygonal cross section.

Forming and improvement of the presented models were followed and other kinds of analysis and calculations. By that, it primarily refers to the results of "traditional" calculation, ordinary in engineering practice, as a control calculation of the structural static system, appreciate familiar characteristics of

www.witpress.com, ISSN 1743-3509 (on-line)

Table 1: Used design spectrum.

EC 8 – VII level of seismicity	coefficients
Category of soil B	S=1; β_0=2,5; K_1=1; K_2=2; T_B=0,15; T_c=0,6; T_d=3
q –Factor of behaviour	
System of reversed pendulum	2
Low ductility	1,5
Proper structure	K_r=1
Dominating mode of aberration	K_w=1
Factor of behaviour	q=1,50
Category and factors of importance	γ=1,20 (cultural institutions)

embedded materials and familiar dimensions of elements, with the aim of defining stability and safety of structure.

Towers are modelled with shell elements that are three dimensional with all six degrees of freedom and on both ends with connected nodes. Shell element includes biaxial bending, torsion, axial deformation and biaxial shear strain. The tower is modelled on an appropriate number of levels (depending on height of tower and change of cross section) with defined change of cross section and height.

Also, linearly elasticity behaviour of materials is predicted, and a decrease of rigidity is neglected. In analysis geometrical effects of second stage are neglected due to the limitations of computer programs and relatively smaller weight of plastic minaret structures. Viscous damping with coefficient of damping of 5 percent is used in every dynamical analysis.

The work represents results for a total of ten minarets and church towers, of historical and cultural heritage, that throughout its history have been imperilled from the constructive aspect or have experienced collapse, namely five with circular cross-section and five with polygonal cross-section.

Forming and development of represented models were observed also by other types of analysis and calculations, primarily concerning on results of "traditional" calculations, common in engineering practice, as control calculation of static structure system, respecting known characteristics of built-in materials and known dimensions of elements, with the aim of defining stability and safety of the structure.

Towers were modelled with the shell elements, which are three-dimensional with all six degrees of freedom at both ends with bounded nodes. Shell element includes biaxial bending, torsion, axial deformation and biaxial shear deformation. The tower is modelled by the appropriate number of levels with a defined change of cross section and the height. Also, it is assumed linear elastic behaviour of material, and decrease of stiffness (rigidity) is omitted. In the analysis, geometric effects have been omitted because of limitation of computer programs and relatively smaller weight of plastic structures of minarets. Viscous damping with damping coefficient of 5% is used in all dynamical analysis.

The following towers/minarets are analyzed:

1. Tower of St. Maria del Carmine Church, Naples, Italy

Complex of Church St. Maria del Carmine is placed on the outer periphery of the ancient city Naples in Italy. Bell-tower has height 68 m (with additional cross of 4.5 m) and it consists of 6 floors and a basement. This bell-tower was first mentioned in the chronicles "Chronistoria del Real Convento del Carmine Maggiore" (Moscarella et al. 1589-1825.), in which it says that during the time of earthquake in 1456, upper part of the monument crumbled, that resulted with the damage of other parts. Construction works of a new bell-tower were initiated in 1458, but till 1615 further significant works on building had not been started. According to the drawings of architect Giovano Giacoma di Conforta, above old base three more floors were built (Filangieri, 1885.). Works have been stopped and it was continued, after two years, by Dominican priest and architect Giuseppe Donzelli (also known as Fr'Nuvolo), who has finished the bell-tower with octagonal part and pyramidal peak, closing peak with characteristic "peak-shaped" form covered with poly-chromatic glass tiles. This period of construction was completed till 1631.

2. Campanile St. Mark, Venice, Italy

All visitors to Venice, no matter where are they coming from, come on the St. Mark's Square, a unique architectural defined area. Campanile St. Mark (*Campanile di San Marco*) bell-tower of St. Mark's Basilica was formed in 16th century by Jakop Sansovin. It is positioned on the corner of the St. Mark square, near the entrance to the Basilica. The exact time on the tower show moon phases and movement of the sun through the zodiac. Campanile St. Mark represents one of the most recognizable symbols of the city. The tower has height of 98.6 meters. It has unique appearance and mostly it consists of a simple, square opening made of brick, whose sides are 12 metres, and height 50 metres. Above there is vaulted bell tower in which there are five bells. Today's tower is the result of reconstruction that was completed in 1912, after the collapse that happened in 1902.

3. Tower Torre del Mangia, Siena, Italy

Tower Torre Del Mangia is situated on Piazza del Campo in Siena, Toscana region, Italy. Over the building, the high tower dominates, Torre Del Mangia, with the height of 102 metres. It was built in the period 1325-1348, and in that period it was one of the highest towers in medieval Italy. Its name comes from the nickname of first carillonneur (bell ringer), who's name was Giovanni di Duccio, and he was known as *il Mangiaguadagni*, or "the one who eats profit." A large copper bell placed on the highest opening of the tower was cast in 1666. It was known as "campanone," large bell, or Sunto, because it was dedicated to the Assumption of the Virgin Mary.

4. Tower St. Luka, Jajce, Bosnia and Herzegovina

In the old, historical part of Jajce there is St. Luka's basilica which is, because of its cultural-historical value, under the state protection. On the corner of the basilica, the tower was built that was structurally connected with the wall of the basilica, forming a unique unit. Above the walls of the basilica, the tower continues as an independent stone structure. From the former basilica till today, only voluminous walls were preserved, that during the existence of this building were upgraded, due to the extension and certain modifications that were made and lately removed. Today on the tower only horizontal iron braces are visible, placed from the outside of the tower at a certain height, which were embedded during the time of Austria-Hungarian occupation and with the aim of construction strengthening.

5. Qusun minaret, Cairo, Egypt

City Cairo, through history, was named as the city of a thousand minarets. It possesses a huge number of old Islamic minarets originating from the time of the early Islamic period (641g.n.e.). After the earthquake in Dahshur in 1992 it was registered that a large number of these minarets suffered various kinds of damage. The most seriously damaged minarets were built in the period of Mamluk. Minaret Qusun is situated in the cemetery Al-Suyut on the south side of the city. It has an impressive rectangular stone body which carries an octagonal second floor, on whose top is a stone Mabkharah. At first sight it seems that the minaret is a detached construction. However, with careful viewing it is observed that the prince Seif Eldin Qusun Al-Saki constructed is as part of the object (Khanqa) where the rules of Islam were studied. This can be concluded according to the clearly visible parts of alcove that creates the frame of the wall tops on the rectangular part. Total height of minaret is 40.28 meters.

6. Minaret of Mosque Dolmabahçe, Istanbul, Turkey

Mosque Dolmabahçe is part of the site Complex of Dolmabahçe palace, also known as Dolmabahçe Camii, Bezmi Alem Valide Sultan, located in the District Besiktas, Istambul, Turkey. Architect Garabet Balyan designed it for Sultan Bezmialem Valide, Abdülmecid I in the 19^{th} century, from 1853 till 1855.

7. Minaret of Ferhadpaša Mosque, Banjaluka, Bosnia and Herzegovina

Ferhad-paša Mosque was built on the area between the creek Crkvine (Crkvene) and river Vrbas, in the former Donji Šeher. The way in which it was built indicates on Sinan's student who wanted to examine new structural solutions and to make a prototype for construction of endowment (foundation) of Sultan Murat III in Manisa – mosque Muradija. The Ferhadija Mosque is the work of a highly-qualified mimar (constructioner) and muhendis (engineer), a product of Sinan's school. The Mosque had been raized on the spot, undermined till the foundation on 7th May 1993 at 03.05 o'clock, and material was carried away on the city depot in Ramići.

8. Minaret of Mosque Handanija, Prusac, Bosnia and Herzegovina

Mosque Handanija was built in 1617. The Mosque was named by its founder, Handan-aga, a wealthy Ottoman officer. Today, the tombstone can still be seen beyond the wall of “mihrab.” The monument takes center place in the village, not far from the medieval fortress on the adjacent hill. The Mosque has a square layout with dimensions 16.30 m x 12.70 m, with a minaret partly built in the south-east wall. The whole monument is built from four kinds of limestone, and all are whitewashed and plastered. This is the only mosque in Prusac with a stone minaret. Mosque Handanije, because of several direct hits with grenades in 1993, suffered serious damages of walls, roof and minaret.

9. Karađozbeg Mosque, Mostar, Bosnia and Herzegovina

Mostar, in the street of Brothers Fejić, was built in 1557-1558; according to the drawings of famous Ottoman architect Sinan. The supervisor and the major donor of the works was Mostar macena Mehmed beg Karađoz, brother of legendary Ottoman vizier Rustem-paša Opuković. Karađozbeg mosque and minaret had suffered huge and serious damage during 1992-1995, but during the reconstruction of Old Bridge and the old core of Mostar city 2002-2004, it was restored. According to some data the builder of Karađoz-beg mosque was Kodža Mimar Sinan. Karađoz-beg mosque is a semi dome mosque with the porch under small domes, the exterior porch with an elegant minaret. The minaret was built beside the right wall, and its height till "alem" is 34.50 m.

10. Minaret of Mosque Valide Sultan, Istanbul, Turkey

Mosque Valide Sultan is part of the site Vakif Gureba Bezmi Alem, also known as Valide Sultan Camii, located in Köyü/Mahallesi, Istambul, Turkey. Architect Sevilay Tuncer Uludağ (Rest. Mimar) designed it for Sultan Bezmialem Valide, Abdülmecid I in the 19^{th} century, year 1827.

5 Results of tower/minaret analysis

Table 2: List of Towers/Minarets.

	Name of Tower / Minaret	Total height (m)	*Cross - section	Seis. lvl.
1	Tower – St. M. del Carmine Church	70.36 (51.36)	P	VIII
2	Tower – St. Mark Campanile	96.61	P	VIII
3	Tower – Torre Del Mangia Church	90.86 (70.01)	P	VIII
4	Tower – St. Luka Basilica	26.38	P	VIII
5	Minaret – Qusun	40.28 (33.28)	P	VII
6	Minaret – Dolmabahce Mosque	40.25	C	IX
7	Minaret – Ferhat Pasa Mosque	41.65 (32.34)	C	IX
8	Minaret – Handanija Mosque	29.70 (22.90)	C	VII
9	Minaret – Karadjozbeg Mosque	35.80 (28.00)	C	VIII
10	Minaret – Mosque Valide Sultan	28.62	C	IX

*Represents: C – circular and P – polygonal cross-section of tower/minaret.

6 Conclusion

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, Poison's coefficient and volume weight of materials for the case of

Table 3: Results of analysis.

*	Volume weight *(kN/m³)*	Puason coef.	Module of elasticity *(MN/m²)*	Periods of oscillation *first mode*	Shifts *(cm)*	Extreme stress *(kN/m²)*	
						min	*max*
1	22	0,27	1050	1.029301	20.43	-119	720
	16	0,22	350	1.287239	28.32	-159	762
	19	0,25	850	1.1128	23.01	911	
2	22	0,22	8000	1.071185	29.98	-1296	4427
	16	0,20	3500	1.378993	23.98	-894	2863
	19	0,26	5500	1.150457	26.35	-1093	3427
3	20	0,25	5500	1.97001	16.94	-1034	4550
	24	0,26	6500	1.97001	32.49	-2391	5433
	18	0,23	3500	1.891907	30.28	-2542	4177
4	20	0,23	5000	1.171452	9.31	-63	511
	24	0,25	6500	1.122299	10.18	-180	580
	18	0,20	3500	1.322523	12.66	-175	432
5	21	0,20	3630	0.600746	13.31	-2347	4496
	23	0,28	4500	0.50023	2.96	-844	2037
	18	0,20	2800	0.653074	9.66	-747	1641
6	23	0,24	7200	1.178683	31.89	-1050	3451
	25	0,28	9000	1.098735	28.83	-1413	4135
	20	0,21	5000	1.319263	37.07	-943	3041
7	20	0,22	5000	1.000268	16.2	-2138	3157
	23	0,26	7500	0.86328	11.41	-1942	3411
	18	0,20	3500	1.117531	21.34	-2463	3064
8	20	0,23	6000	0.590844	3.92	-467	985
	24	0,27	8000	0.546313	3.47	-1081	1852
	18	0,20	3500	0.715801	5.36	-854	1498
9	25	0,25	7000	0.649242	24.74	-2086	3272
	22	0,22	9000	0.572608	13.9	-931	2538
	18	0,20	3500	0.779255	22.4	-1425	2012
10	23	0,22	6000	1.029543	23.8	-2010	2134
	26	0,25	8500	0.908206	20.1	-1100	1765
	18	0,20	3500	1.178303	28.9	-1395	1534

*Represents: Tower/Minaret by numbers from Table 2

better material characteristics, or for the case of worse material characteristics comparing to the actual state.

Models of towers (minarets) with better mechanical material characteristics decreased were also critical shifts of tower peak (minaret) comparing to the shifts given at the actual tower (minaret) in relation to 12-28 %, and extreme stress of tension for 10-30%.

At the tower (minaret) models with worse mechanical characteristics of materials increases were also critical shifts of tower peak (minaret) comparing to the shifts given at the actual tower (minaret) in relation to 20-40%, and extreme stress of tension for 20-44%.

These results clearly show that for example with procedures of injection into the joints of masonry structural elements that can have an influence on the module of wall elasticity and on that way it can realize better mechanical characteristics of masonry construction materials, and by that significantly decrease shifts of tower (minaret) peaks and extreme stress of tension.

It is clear that from the executed calculations during the design and construction of the analyzed towers and minarets of historical and cultural heritage, it did not take into account about loads caused by seismicity effects, and regularly in analysis of towers (minarets) significant stresses in tension are occurring that should in a regular way be taken with the aim of providing an appropriate level of security.

Comparing results given with the executed researching and presented results of earlier executed calculations and researching in situ, it is clear that the tower models used in this research give sufficient precise results.

Sizes of extreme stresses depend beside of the material type, geometry of tower, seismicity also:

- Module of material elasticity
- Supporting of tower
- Poisson coefficient of material

Most church towers and minarets would, according to executed research and analysis of calculations, have to be increased for eventually seismicity effects. A special problem is the convergence of necessary structural measures with demands for protection of cultural heritage. Basic concepts in protection of cultural heritage structures are: protection of monuments, restoration, reconstruction of building, reparation, reinforcement of structure, seismicity structural repair could be reduced, as for structural aspects, in a generalized term – intervention on structure. It is necessary to emphasize that intervention on a structure can be not only for the purpose for recovery of actual damage but for prevention of possible damage. Intervention on a structure can be done with improvement of the structure, or reinforcement of the same or reduction of seismicity effects i.e. energy dissipation. Every intervention has for a consequence some changes, those further cause a loss of part of the object authenticity, so decisions about preventive interventions should be done carefully.

It is necessary to take into account the risk of possible occurrence of impacts (mostly seismicity forces) on the observed object, and after that to bring decision for intervention or not.

References

[1] A. Čaušević, M. Hadžirović: "Protection of and interventions on the towers of religious buildings", Second International Conference on Heritage and History of Engineering, Las Palmas of Gran Canaria, Spain , June 2007

[2] Amir Čaušević, “Architectural - structural conceptions of sacral object’s towers – behavior on the atypical excitation”, doctoral dissertation, Faculty of architecture, Sarajevo, 2009
[3] A. Čaušević, N. Rustempašić: “Ferhad-Pasha’s Mosque - Rehabilitation of historic masonry buildings in seismic areas“, 2nd H & mH International Conference on “Vulnerability of 20th Century Cultural Heritage to Hazards and Prevention Measures” Kos, Greece, 3-5. October 2005, organized by CICOP, Italy
[4] A. Čaušević, L. Kudumović: “Evaluation of stability of sacral and historical towers depending on seismic zone”, SEWC -Structural Engineering World Conference ,Como, Italy 2011 April 4- 6, 2011.