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Conservation-Oriented Structural Analysis of the Spire of Barcelona Cathedral

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Abstract: The spire of Barcelona cathedral suffered from severe problems due to the corrosion of the steel ties used in reinforcing its stone masonry beams. Wide visible cracks were noticed in the stone beams and large parts were detached. Therefore, the full spire was dismantled and reconstructed using titanium ties to eliminate the corrosion problem. A finite element model of the spire was created and analyzed using DIANA software to support this decision. This analysis helped in understanding the role and strength contributions of these ties in resisting the applied loads on the spire, specifically, the lateral loads of earthquakes and wind. A nonlinear static (pushover) analysis was carried out to assess the spire capacity under the lateral loads. A number of constitutive models for modeling the masonry behavior were tried. Also, a number of seismic actions patterns were considered. As a main conclusion of this study, the ties were highly needed to carry the tensile stresses caused by earthquakes and wind loads. Therefore, in the reconstruction of the spire, such ties must be kept in the masonry beams.

Keywords: Conservation, Structural Analysis, Spire, Corrosion, Ties, Pushover, Wind, Earthquake

1. Introduction

Structural analysis plays an important role in conservation of historical structures. In the assessment phase, it helps in understanding the structural behavior under different loads. As well, it is an efficient tool for identifying the weakness places where intervention is possibly needed. In designing the intervention, a numerical model may work is a virtual laboratory in which different intervention proposals could be simulated to reveal its efficiency. There are many successful cases in the literature in which structural analysis have been used as an efficient tool for restoration of historical structures [1-8].

This paper deals with the structural analysis of the spire of Barcelona cathedral (Fig. 1) as a useful tool for its conservation. The builders of the spire reinforced all of its stone masonry beams with steel ties. Due to the coastal weather of Barcelona city which is full of rains and also because of sea spray and pollution products these ties were corroded and the spire faced severe problems. Wide visible cracks were noticed in the stone beams and large parts were detached. This situation led to carry out a complete project for the restoration of the spire. In this project, the entire spire was dismantled and reconstructed and the steel ties were replaced by titanium ones to eliminate the corrosion problem.

To understand the role and strength contributions of the steel ties, a finite element (FE) model of the spire was created and analyzed using DIANA software [10]. Specific concern was given to the analysis of the spire under lateral loads because it reaches a height of 90 m over the ground level which makes it vulnerable when subjected to such type of loads. The earthquake and wind loads were estimated using the Eurocodes [11, 12].

A FE nonlinear static (pushover) analysis was performed using the estimated lateral loads. To reveal the dependency of the results on the used constitutive models, a number of constitutive models for modeling the stone masonry were tried. As well, a number of load patterns were tried to study the dependency of the results on the used load pattern.

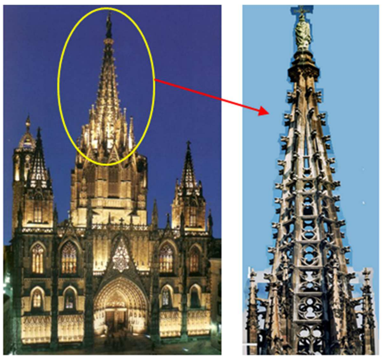


Figure 1. *Main façade of Barcelona cathedral (left) [9] and the spire of the cathedral (right).*

2. Barcelona Cathedral

The construction of the cathedral (Fig. 2) started in 1298 and continued for more than a century. The apse and the entire nave were finished in 1327 and 1417, respectively. The span of central nave is 12.80 m and the maximum high is 25.6 m. The span of the side aisles is equal to one half the span of the nave. The total length of the cathedral is 93 m. The plan of the temple is not conventional because the cimborio was not constructed over the crossing but over the first bay of the nave close to the façade. A similar distribution can be observed in very few cases, such as the German cathedrals of Ulm and Friburg [14].

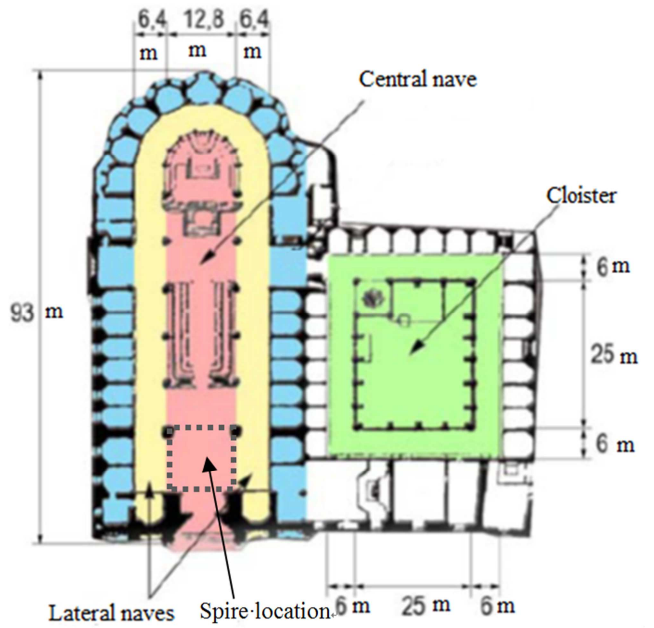


Figure 2. *Plan of Barcelona cathedral showing spire location (adopted from [13]).*

3. Spire of Barcelona Cathedral

3.1. Description

The spire of Barcelona cathedral is a symmetrical stone masonry structure built at the beginning of the 20th century. It has an octagonal shape in plan, Fig. 3. It consists of 8 columns connected together by 8 beams. The columns have irregular shapes with an average cross sectional area of about 0.3 m^2. The beam section can be approximated as a rectangle of 25 cm × 60 cm reinforced at the center with a steel tie of 1 cm × 4 cm. The shortest beam span is about 1 m (at the last level of the spire) and the longest one is about 2.5 m (at the first level of the spire). The eight columns rise up to the top of the spire until they are attached together forming a base for a stone statue (Fig. 1) which has a height of 5 meters and a weight of 6.25 t.

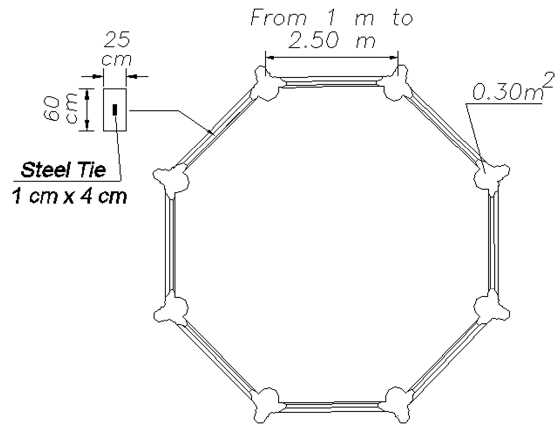


Figure 1. *Typical plan and cross sections of the spire.*

Figure 2. *Corroded steel ties extracted from the spire.*

Figure 3. *Wide cracks due to corrosion products.*

Figure 4. *Corrosion products resulted in stone fall down.*

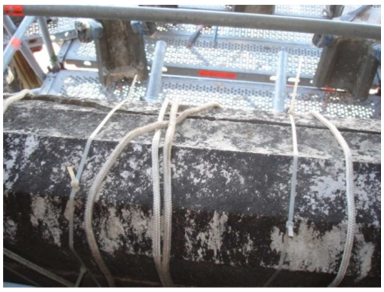


Figure 5. *Detached parts kept temporary in position by ropes.*

3.2. Damage

The steel ties used in reinforcing the spire beams suffered from severe corrosion due to the rainy weather of Barcelona city, Fig. 4. Due to corrosion products the steel ties increased in volume (the volumetric increase may reach ten times the original volume) which caused pressure on the surrounding stone masonry and led it to crack (Fig. 5) or furthermore to fall down (Fig. 6). Big parts of some of the stone masonry beams were about to fail due to corrosion products and were temporary kept in position by some ropes (Fig. 7).

3.3. Restoration Project

The spire was completely dismantled and reconstructed. Before doing so, the spire and the supporting cimborio were documented using 3D laser scanning (Fig. 8).

In order to execute the restoration works, complete scaffolding started from the roof level and extended to the last top part of the spire was employed (Fig. 9). Another steel structure was constructed inside the spire (Figs. 10-11). This steel structure was used to support the spire during the dismantling and as well as scaffolding for the reconstruction process.

Figure 8. *3D laser scanning for the documentation of the spire (by TT12 Gabinet de Topografia i Construcció).*

Figure 9. *Complete scaffolding for restoration works.*

Figure 10. *The columns of the steel structure and its connections with the spire.*

Figure 11. *Inside the steel scaffolding (looking up).*

Figure 12. *Cutting at the mortar Joint using electrical saw.*

Figure 6. *Storing the dismantled parts on the cathedral roof.*

The different parts of the spire were numbered and then were cut at the locations of the mortar joints using electrical saw, Fig. 12. The spire pieces were stored on the roof of the cathedral, Fig. 13. The stone was cleaned and then the spire was reconstructed again.

4. Numerical Model

The spire was modeled using the DIANA FE code [10]. The model (Fig. 14) consisted of 4011 nodes and 5055 elements. The maximum element size was 0.1 m. Both of the columns and the beams were modeled using frame elements, in specific, the element type L13BE was used. The arches supporting the spire and the base of the statue were modeled using shell elements. The statue was not modeled; instead, it was taken as a concentrated load at the top of the spire. The steel ties were modeled as reinforcement for the beams from B1 to B9.

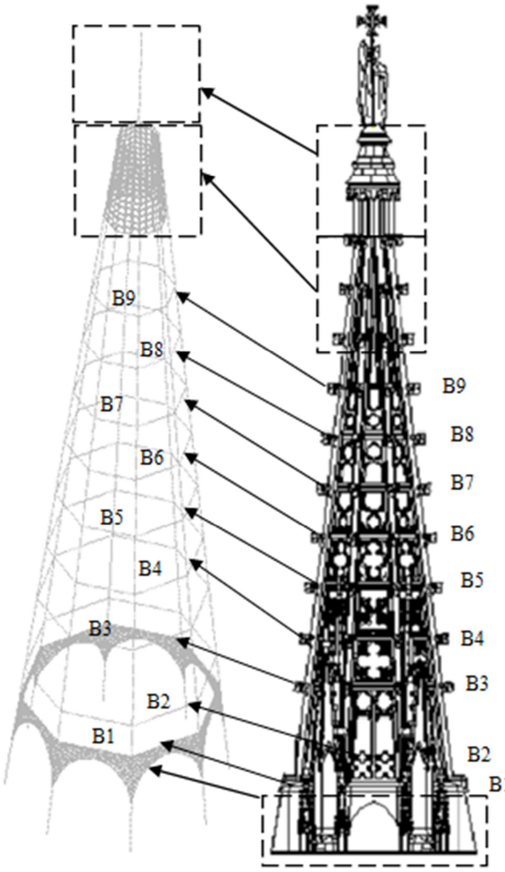


Figure 7. *3D FE model of the spire (left) and corresponding parts in the spire (right).*

To simulate the nonlinear behavior of the masonry, both cracking (tensile regime) and crashing (compressive regime) were considered. The two regimes were modeled using smeared cracking, in specific; the Total Strain Fixed Crack Model was used. This model proved its efficiency in many previous studies, see for instance [5] and [6]. Two softening models were tried. The first was the ideal softening in both tension and compression (Fig. 15). This model in tension does not represent the masonry nonlinear behavior, but it is an approximation to obtain an idea about the model nonlinear behavior with less computational troubles.

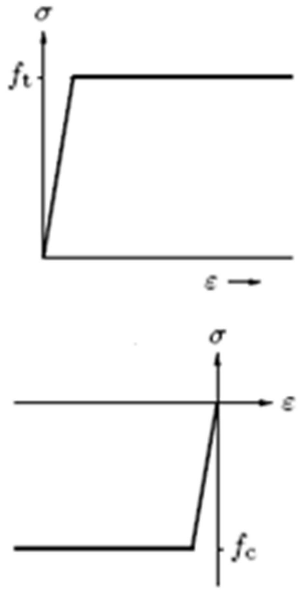


Figure 15. *Ideal softening model in tension (left) and in compression (right) [10], see Table 1 for symbols definitions.*

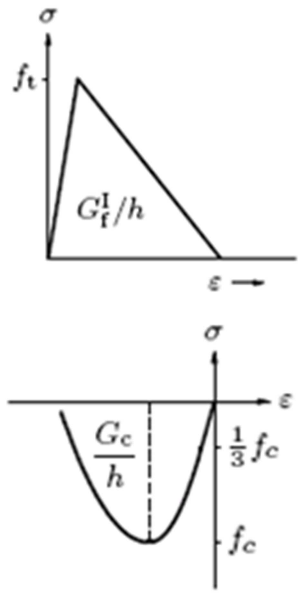


Figure 16. *Linear softening model in tension (left) and parabolic softening in compression (right) [10], see Table 1 for symbols definitions.*

The second model was linear softening in tension and parabolic softening in compression (Fig. 16). The steel nonlinear behavior was modeled using Von Misses model.

The used properties of the stone masonry and steel are summarized in Tab. 1. The values were taken as recommended by some previous studies carried out using the same stone masonry [16].

Table 1. *Properties of stone masonry and steel.*

Density (kg/m^3)	**Modulus of Elasticity (E) (GPa)**	**Poisson's ratio**	**Compressive Strength (f_c) (MPa)**
2200	12	0.30	8
Tensile Strength (f_t) (MPa)	**Fracture Energy in Tension (G_f^I) (N. mm/mm^2)**	**Fracture Energy in Compression (G_c) (N. mm/mm^2)**	**Steel Yield Strength (F_y) (MPa)**
0.60	0.1	17.8	280

5. Earthquake Analysis

A pushover analysis was performed to assess the behavior of the spire under seismic actions. Two seismic actions were tried. The first was forces at the nodes of each level of the spire, and the second was prescribed displacements at the same nodes.

The tried combinations of the aforementioned constitutive models and the seismic actions are summarized in Tab. 2. For the ideal softening model, two seismic actions were tried: (1) forces proportional to the mass of each level of the spire, (2) displacements proportional to the 1st mode which had the highest mass participation (49%). For the second softening model, two seismic actions were tried: (1) displacements proportional to the 1st mode and (2) displacements proportional to the Square Root of Sum of Squares (SRSS) of the modes number 1, 3, 10 and 13. These modes had mass participation ratios of 49%, 11%, 10% and 13%, respectively which were the highest of all the modes.

For the estimation of the applied forces on the spire, the lateral force method of analysis described in Eurocode 8 [12] was employed. The base shear was estimated as 30 tons which represented about 11.5% of the spire weight. More details can be consulted at [15].

For the all examined cases, a phased analysis was followed. In the first phase, the self-weight of the spire was applied in two load increments, each of 50% of the spire weight. In the second phase, the seismic action was applied incrementally at a chosen control points at each level. These points were the corners of the octagonal section of the spire.

The obtained capacity curves for the four cases are shown in Fig. 17. The displacement is for the top point of the spire. For the effect of the used constitutive model, it was found that the ideal softening model gave higher capacities than the

Table 2. *Tried combinations of constitutive models and seismic actions for earthquake analysis.*

Case no.	**Softening model**	**Seismic action pattern**
1	Ideal (tension and	Forces proportional to mass
2	compression)	Displacements proportional to 1st mode
3	Linear (tension) and	Displacements proportional to 1st mode
4	Parabolic (compression)	Displacements proportional to SRSS of 1st, 3rd, 10th & 13th modes

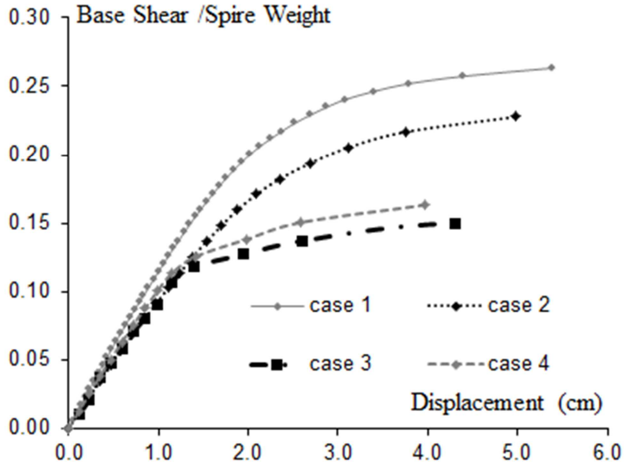
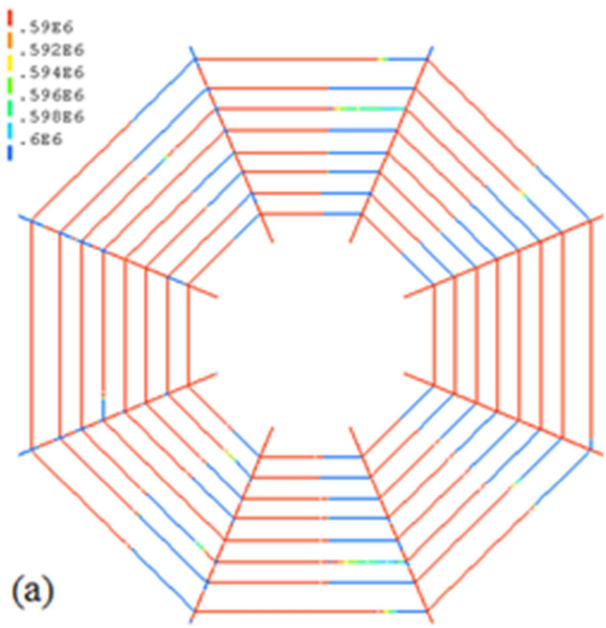


Figure 17. *Capacity curves of the spire (see Tab. 2 for cases definition).*



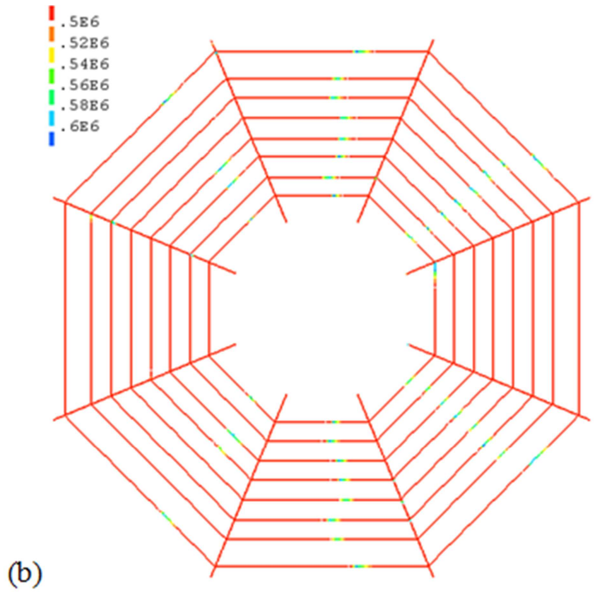


Figure 18. *Spire in plan showing damage (locations in blue with stresses (MPa) higher than masonry tensile strength) at collapse for case 2 (a) and case 3 (b) (see Tab. 2 for cases definition).*

second softening model. Case 2 was around 35% higher than case 3 (0.23 compared to 0.15). For the effect of the used seismic action pattern, it was noticed that representing the seismic action in the form of prescribed displacements resulted in a lower capacity than the case of using forces. Case 2 was about 13% lower than case 1. For the second softening model, changing the pattern of the prescribed displacements didn't result in a significant effect neither in the capacity nor in the maximum displacement. Regarding to the maximum displacement at failure, all the cases gave near values from about 4 cm to about 5.5 cm.

For the failure mechanism, the two cases 1 and 2 showed that the damaged places at collapse were at: (1) the columns of the first level of the spire, (2) almost half the span of almost all the beams at all the levels and (3) at the connections between the columns and the beams, Fig. 18. For the two cases 3 and 4, less damaged locations were noticed, as the middle span of the beams were damaged at collapse, see Fig. 18 for case 3.

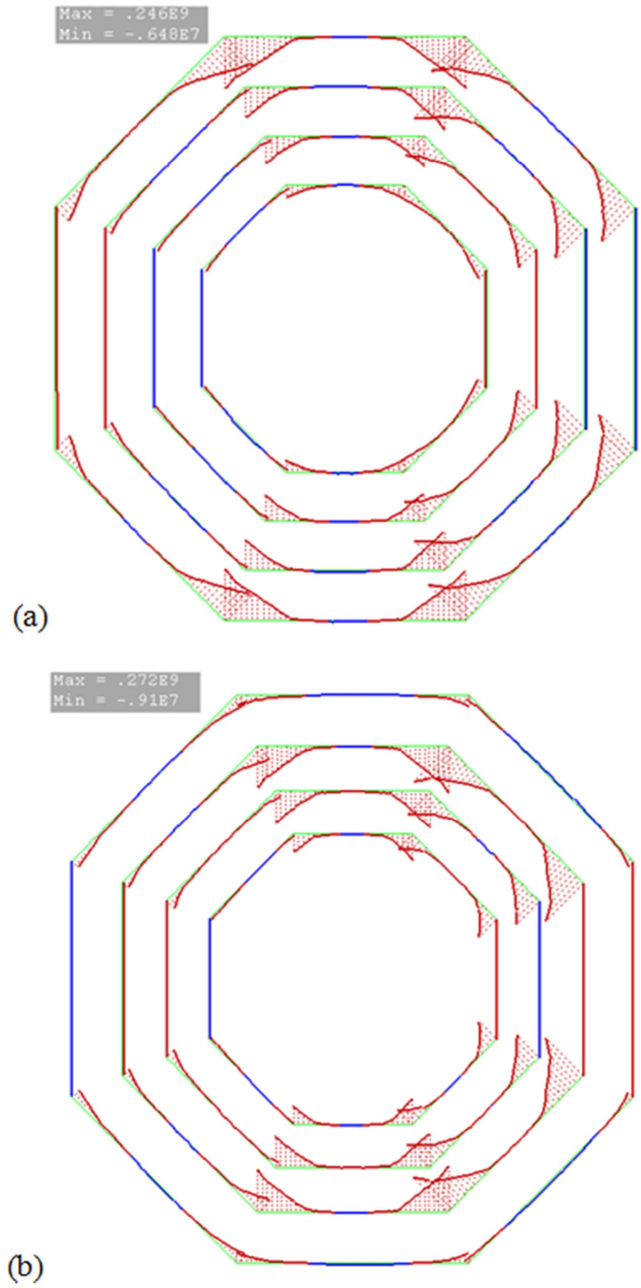


Figure 19. *Axial stresses (MPa) in reinforcement at failure for case 2. Odd beams (B3, B5, B7 and B9) (a) and even beams (B2, B4, B6 and B8) (b).*

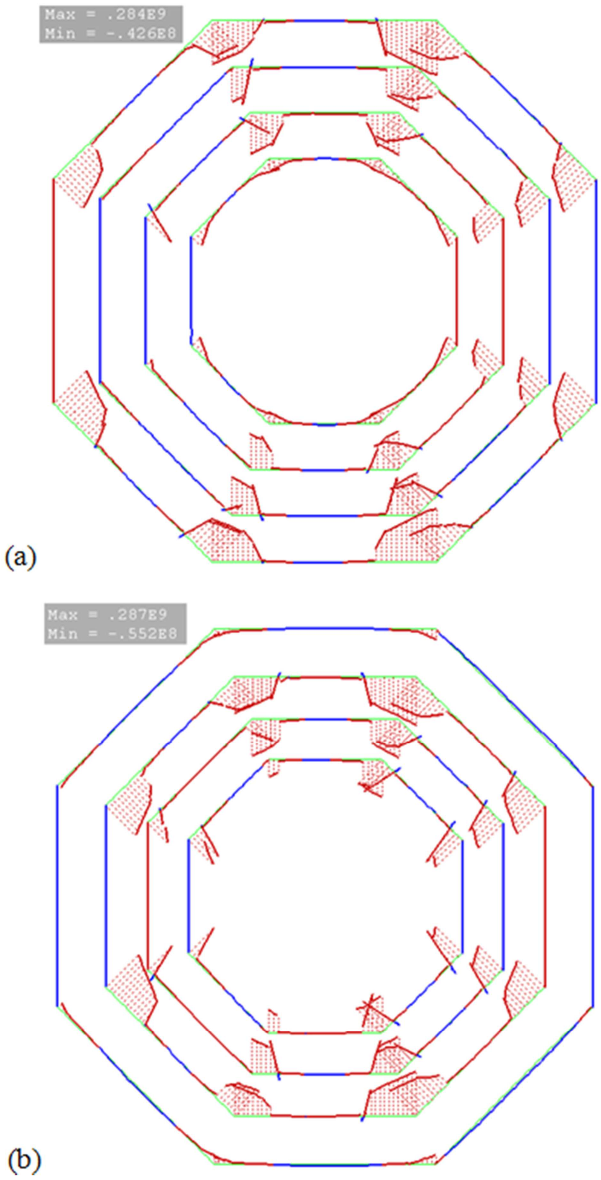


Figure 20. Axial stresses (MPa) in reinforcement at failure for case 3. Odd beams (B3, B5, B7 and B9) (a) and even beams (B2, B4, B6 and B8) (b).

The role of reinforcement in resisting the seismic actions was investigated. It was found that at failure, the steel reached its yield strength as shown in Figs. 19 and 20 for the cases 2 and 3. The highest stresses were noticed at the beams corners, i.e. at the connections with the columns.

6. Wind Analysis

The wind loads were estimated using the Eurocode 1 [11]. The total wind load was estimated as 60 tons. Full details are found in [15]. The ideal softening model was employed in the nonlinear static analysis under wind loads. The same phased analysis used for the earthquake analysis was also followed here. The load-displacement diagram is presented in Fig. 21 for the top point of the spire. The spire was able to resist the wind loads with a maximum displacement at failure of about 4.2 cm.

The damage at collapse is plotted in Fig. 22. It can be noticed that it is quiet similar to that found for the cases 1 and 2 of the seismic analysis. The stress in the reinforcement is depicted in Fig. 23. Again for the wind analysis, the steel ties were found to resist high values of stresses at failure that were near to its yield strength, Fig. 23.

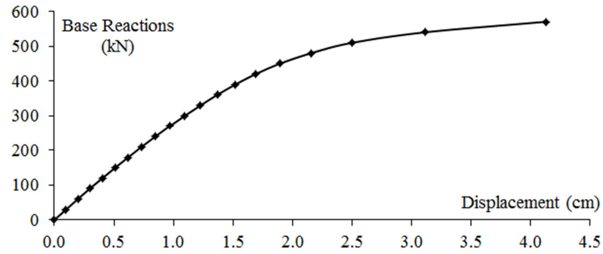


Figure 21. Load-displacement curve for wind analysis.

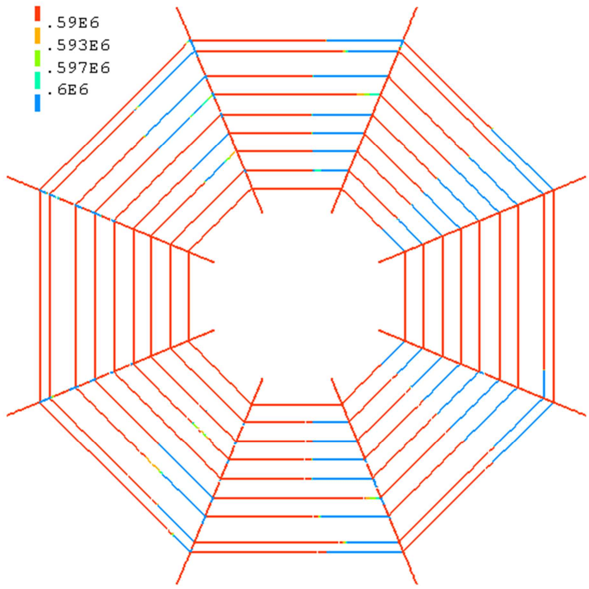
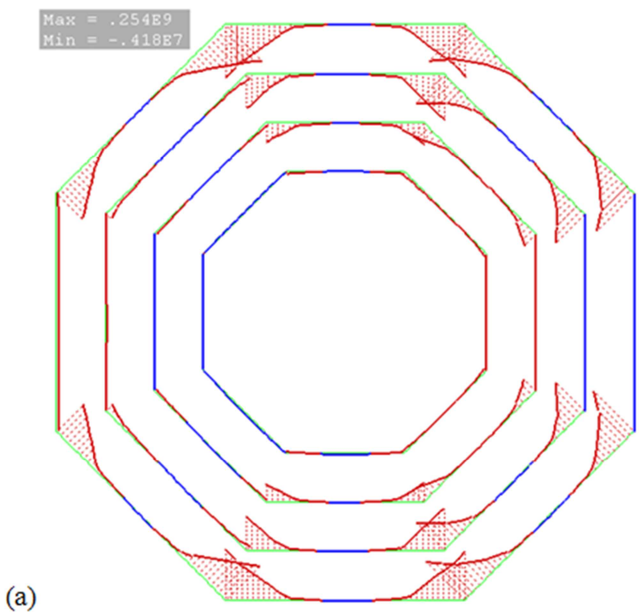


Figure 22. Spire in plan showing damage for wind analysis at collapse (locations in blue with stresses (MPa) higher than masonry tensile strength).



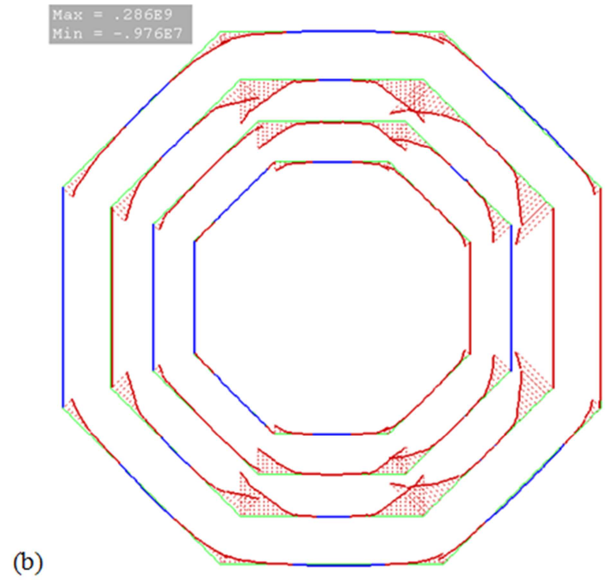


Figure 23. *Axial stresses (MPa) in reinforcement at failure for wind analysis. Odd beams (B3, B5, B7 and B9) (a) and even beams (B2, B4, B6 and B8) (b).*

7. Conclusions

The spire of Barcelona cathedral was subjected to a complete restoration project in which the spire was totally dismantled and reconstructed. This was due to the corrosion of the steel ties used to reinforce its stone masonry beams. The steel ties corrosion led to sever problems like the developing of wide visible cracks in the stone beams and detaching of large parts of the beams stones.

It was necessary for the restoration to understand the behavior of the spire under lateral loads and the role of the steel ties in resisting these loads.

The spire was modeled using the FE code DIANA and analyzed under the effect of earthquakes and wind. Different constitutive models and load patterns were tried. It was found that:

- The seismic capacity and the damage pattern depended significantly on the employed constitutive model.
- Using the same seismic action pattern, the ideal softening model in tension and compression gave about 35% higher capacity than the model of linear softening in tension and parabolic softening in compression. For the ideal softening model, the spire manifested more extended damage than the other softening model.
- Using the same constitutive model, lower seismic capacity was obtained when applying the seismic action in the form of prescribed displacements according to the first mode shape than that obtained one when applying forces proportional to mass.
- The steel ties were highly needed to resist both of the wind and the earthquakes. The stresses in the ties were found to be near to the steel yield strength.

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References

[1] Elyamani, A. "Integrated monitoring and structural analysis strategies for the study of large historical construction. Application to Mallorca cathedral", PhD Thesis, Technical University of Catalonia, Spain (2015).

[2] Lourenço, P. B. "Recommendations for restoration of ancient buildings and the survival of a masonry chimney", Construction and Building Materials, 20, no. 4 (2006): 239-251.

[3] Asteris, P. G. “On the structural analysis and seismic protection of historical masonry structures”, Open Construction and Building Technology Journal 2 (2008): 124-133.

[4] Ademovic, N., Mustafa H., and Oliveira, D. V. "Pushover analysis and failure pattern of a typical masonry residential building in Bosnia and Herzegovina." Engineering Structures 50 (2013): 13-29.

[5] Peña, F., Lourenço, P. B., Mendes, N., and Oliveira, D. V. "Numerical models for the seismic assessment of an old masonry tower." Engineering Structures (2010), 32 (5): 1466-1478.

[6] Akcay, C., Bozkurt, T. S., Sayin, B. and Yildizlar, B. "Seismic retrofitting of the historical masonry structures using numerical approach." Construction and Building Materials 113 (2016): 752-763.

[7] Caselles, O., Clapes, J., Roca, P. and Elyamani, A. "Approach to seismic behavior of Mallorca cathedral." 15th World Conference of Earthquake Engineering, Lisbon, Portugal, 24-28 September (2012).

[8] El-Derby, A. A. and Elyamani, A. "The adobe barrel vaulted structures in ancient Egypt: a study of two case studies for conservation purposes". Mediterranean Archaeology and Archaeometry, 16(1), pp.295-315, (2016).

[9] http://listas.20minutos.es/lista/catedrales-goticas-y-romanicas-en-europa-345380/. Visited on July, 2016.

[10] DIANA. Diana 9.4, user’s manual. The Netherlands: TNO Building and Construction Research. Available from www.diana.tno.nl. (2009).

[11] EN - Eurocode 1: Actions on structures, Part 1-4: General actions – Wind actions, (1991).

[12] EN - Eurocode 8: Design of structures for earthquake resistance, (1998).

[13] Canada, A. "Analisi d’estabilitat del cimbori de la cathedral de Barcelona", Graduation thesis, Technical University of Catalonia, Barcelona, Spain. (2010).

[14] Roca, P. and Molins, C. "Computer analysis of a Gothic cathedral", Engenharia Civil. UM, Numero 9, (2000).

[15] Elyamani, A. Wind and earthquake analysis of spire of cimborio of Barcelona cathedral. MSc thesis, Technical University of Catalonia, Barcelona, Spain. (2009).

[16] Murcia, J. "Seismic analysis of Santa Maria del Mar church in Barcelona". MSc thesis, Technical University of Catalonia, Barcelona, Spain. (2008).