Monitoring and strengthening interventions on the stone tomb of Cansignorio della Scala, Verona, Italy

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ABSTRACT: The “Arche Scaligere” is the gothic monumental funerary complex of the illustrious Veronese “Scaligeri” family. Between these monuments, the “Arca” (stone tomb) of Cansignorio della Scala is the most sumptuously decorated. In 2005 the “Soprintendenza per i Beni Architettonici e per il Paesaggio di Verona, Vicenza e Rovigo” (the local administrative body in charge of the conservation of the landscape, monuments and historical structures), with the aim of studying the stone tomb of Cansignorio and in the framework of a wider research, gave the task of designing and installing a structural monitoring system, besides the implementation of a detailed FE numerical model, to the University of Padova. In parallel with these studies, a light strengthening intervention was carried out in order to stabilize some critic points of the structure and to intervene in deteriorated parts or elements, to integrate the original materials. The paper describes the different activities carried out.

1 FOREWORD

1.1 Historical notes and description

The “Scaligeri” or “della Scala” family was a dynasty that ruled Verona, in Italy, for over a century, from 1262 to 1387. Cansignorio della Scala (1340–1375) managed the city in a relatively peaceful period, and adorned Verona in a way to make it call “marmorina” (marbled) for the abundant use of ancient marbles and roman statues.

The stone tomb of Cansignorio della Scala was built between 1374 and 1376, by will of the same Cansignorio, when he was still alive. The tomb was erected close by the St. Maria Antica church, where the tombs of Cangrande and Mastino the 2nd (his grandfather and father respectively) were already built by local workers. Differing from his ancestors, Cansignorio desired a monumental tomb, where the architectural aspect was more important than the decorative. The work was then commissioned to Bonino da Campione, a famous master of gothic sculpture. The monument, based on a hexagonal plan, is adorned with sculptures and spired tabernacles, with the overhanging equestrian statue of Cansignorio. The tomb is surrounded by an hexagonal wrought iron fence, at whose corners rise six pillars.

Figure 1. The stone tomb of Cansignorio (on the right) and Mastino the 2nd (rear left), near the St. Maria Antica church.
sustaining gothic tabernacles, containing statues of the saint-warriors (St. George, St. Martin, St. Quirinus, St. Sigismund, St. Valentine and St. Louis, king of France). The tomb starts with six columns sustaining a red marble slab on which finds place the white marble sarcophagus, sustained by eight pillars and decorated with bas-reliefs representing Gospel scenes. The cover of the sarcophagus hosts a lying statue of Cansignorio, watched over by angels.

At the second level, six further spiral columns sustain the canopy with polylobed arches. Above these finds place a cornice sustaining six gablets with allegorical figures representing the virtues. At the corners are positioned six further tabernacles with statues of angels. The roof, corresponding to an hexagonal pyramid made of white marble, finally supports the massive equestrian statue of Cansignorio (Fig. 2).

The stones used for the erection of the tomb are the “Candoglia” white marble, the same employed in the Milan’s cathedral, and the “Rosso di Verona” (Verona’s red marble), besides the Pietra Gallina (a soft limestone from Vicenza). The inner part of the roof (above the crossed vault and behind the stone facing of the canopy) is composed by solid brickwork masonry.

1.2 Past restoration works

Throughout the centuries, several repair interventions were necessary to preserve the delicate structure of the stone tomb, such as those carried out in the XVII, XIX and XX centuries. In 1676 the Verona municipality adopted a resolution to execute restoration works on the tomb, comporting strengthening interventions and substitutions on the upper part of the monument, without however intervening on the supporting elements. Between 1827 and 1829 other restoration works were carried out, raising arguments on the type of marble to be used in substitutions of the deteriorated parts. Between 1838 and 1844 the fence was restored, and on the 24th of July 1840 a portion of the southern gablet fell down, being subsequently restored (1846) and lodged back in the original position. Substitutions comported the use of Candoglia marble elements, secured with iron clamps fixed with melted lead. The sealing of the cracks was performed with filler. Main interventions carried out were: the reconstruction of the spires of some tabernacles; the positioning of steel reinforcing elements on two columns of a tabernacle; the complete reconstruction of a column and capital of a tabernacle, and of some gablets between the spires; the reconstruction of the tail and the left rear leg of the horse in the equestrian statue; the substitution of the copper tie beams of the tabernacles with saint-warriors with new ones in iron; the sealing of the vault’s groins.

Other interventions, similar to those executed at the half of the XIX century, were carried out between 1910 and 1914. The monument was then protected against bombing during the two world wars. In 1919, after the removal of the shields, some light restorations were carried out. Then, during the positioning of the shields of the 2nd world war, an analysis of the conditions of the tombs was carried out, with successive light restoration works.

2 THE INVESTIGATION ACTIVITIES

2.1 Dynamic identification

Between different Non Destructive techniques that may be profitably used for the achievement of an advanced knowledge of the structural layout of a historic masonry building, dynamic identification proved to be a very effective tool (Modena et al., 2001; Gentile et al., 2004; Ramos et al., 2006), being actually the only method able to experimentally define parameters related to the global structural behavior. Prior to the installation of a Structural Health Monitoring (SHM) System, a dynamic investigation campaign took place in August 2006. Tests were aimed at the definition of the optimal SHM system sensors’ positioning, and at the characterization of the dynamic properties of the monument for FE modelling calibration purposes.
Following the mode shapes emerged from the FE numerical model, sensors were placed at the first level (in the stone slab where the sarcophagus stands), at the second level (on the cornice above the pointed arches) and at the top of the monument (at the foot of the equestrian statue). A total of six sensors was employed, considering three test setups for a total of 6 acquisition points, recording the acceleration in orthogonal (and parallel to the ground) directions.

The acquisition system was composed by a compact unit provided with 24-bit digital acquisition cards, connected to piezoelectric mono axial acceleration transducers. Once fixed the transducers to the structure in the selected positions, tests consisted in acquiring data over a predetermined period, at a determinate sample rate. Each test setup consisted in recording the signal two times (65,536 points each) with a sampling frequency of 100 SPS (samples per second), with an overall setup signal recording duration of 21'51''.

For the identification of the modal parameters (natural frequencies and corresponding mode shapes), output only identification techniques were used (Operational Modal Analysis). In particular, the recorded ambient vibrations were related to the wind excitation and urban traffic.

The modal parameter extraction method selected was the FDD – Frequency Domain Decomposition – technique (Brincker et al. 2000) which estimates the modes, with the assumption that the excitation is reasonably random in time and in the physical space of the structure, using a Singular Value Decomposition (SVD) of each of the spectral density matrices. The data series acquired at 100 SPS were processed by a decimation of 2 (Nyquist frequency of 25 Hz), with segment length of 2048 points and 66.67% window overlap. Several peaks related to structural frequencies were detected in the frequency domain and the corresponding mode shapes defined (Fig. 3).

2.2 Monitoring

The Structural Health Monitoring System (installed in December 2006) is aimed at the control of static
and dynamic parameters related to the structural functioning of the monument. The system is composed by an acquisition unit connected to six piezoelectric accelerometers, two potentiometric displacement transducers and a temperature and relative humidity sensor. The central unit, located at the base of the tomb, is provided with a WiFi router for remote data transmission.

The monitoring strategy is conceived both to collect data at predetermined time-intervals (periodic monitoring, i.e. cracks opening, changes in the dynamic response) and to automatically start to save data in case of significant external events (such as seismic events). Such controls will permit to appreciate possible variations in the assessed structural functioning with the passing of time and to have a record of the dynamic behavior of the stone tomb during severe events.

The acceleration transducers are placed in suitable positions in relation to the mode shapes of the structure, as shown by the numerical modeling/dynamic identification (Fig. 4, left). Four sensors are placed on two levels for the evaluation of the vibration in the NS and EW direction (bending modes) and in the horizontal planes (torsion modes).

A couple of reference sensors is fixed at the base for the record of the ground acceleration both in operational conditions (i.e. evaluation of the traffic induced vibrations) and during seismic events. A temperature/relative humidity sensor is fixed at the intrados of the marble slab (first level). The displacement transducers are positioned across significant cracks (Fig. 4, right, see also Fig. 14). The temperature, relative humidity and displacement of the selected points (crack mouth opening) are recorded each 6 hours, corresponding to 4 daily readings. Dynamic data are collected both at fixed time intervals (each 48 hours, approximately 22’ of recording at a sample rate of 100 Hz) and on a trigger basis (shorter records, signals are recorded when the vibration exceeds a predefined threshold).

No meaningful variations in terms of displacements were reported up to November 2007 (Fig. 5a). Variations remain limited and related to the environmental parameters, presenting maximum differences (corresponding to crack mouth opening) of about 1/10th of millimeter. No seismic events were recorded in the monitored period. Limited shifts (max 4%) were noted in all of the identified frequencies (see also Ramos et al., 2007), possibly related to environmental parameters, as reported in Figures 5b and c (slight decrease with the relative humidity, seasonal variations).

3 STRUCTURAL MODELS

3.1 Introduction

A detailed FE numerical model, based on a laser scanner geometrical survey of the monument previously carried out, was implemented in order to evaluate the static and dynamic behaviour of the monument. The evaluation of the initial results of the numerical model (linear static and natural frequency analyses) assisted the design phase of the strengthening intervention and indicated the most suitable places for the sensors’ positioning (dynamic identification and monitoring). The first model was calibrated on the basis of the results of the experimental activities, in order to be subsequently used to simulate the response of the monument to different external actions.

3.2 The FE model

As a first step, linear elastic constitutive laws were assigned to all materials in order to define the static load pattern (self weight) and the dynamic properties of the monument. The model is composed by approximately 49,000 brick elements and 53,600 nodes. Finite elements’ sides are comprised between 0.10–0.15 m. The mesh is more refined in the slender elements (columns) and in the junctions, rougher elsewhere. The decorative elements and statues were modelled as the structural parts: only areas too small to be considered significant were neglected (Fig. 6).

The linear static analysis (self weight) indicates that compressive stresses reach their maximum values in the columns, where stresses of about 1.0–1.5 MPa (lower order) are found. In small areas of the upper order of columns compressive stress peaks of 2.0 MPa are noted. Tensile stresses generally present very low values or close to zero. However, non negligible tensile
Figure 5. Monitoring results: (a) displacement transducers PZ1/PZ2 and environmental parameters, recorded data plotted vs. time; dynamic parameters, identified frequencies: (b) first two bending frequencies vs. time and (c) vs. relative humidity.

Table 1. Experimental vs. numerical frequencies.

<table>
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<th>Mode</th>
<th>Description</th>
<th>Exp. (Hz)</th>
<th>FE model (Hz)</th>
<th>diff. %</th>
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<tr>
<td>1</td>
<td>1st bending N-S</td>
<td>3.19</td>
<td>3.25</td>
<td>1.88</td>
</tr>
<tr>
<td>2</td>
<td>1st bending E-W</td>
<td>3.24</td>
<td>3.26</td>
<td>0.71</td>
</tr>
<tr>
<td>3</td>
<td>1st torsion</td>
<td>5.88</td>
<td>5.85</td>
<td>0.48</td>
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<tr>
<td>4</td>
<td>2nd bending N-S</td>
<td>12.55</td>
<td>12.90</td>
<td>2.79</td>
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<tr>
<td>5</td>
<td>2nd bending E-W</td>
<td>12.88</td>
<td>13.30</td>
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</tr>
<tr>
<td>6</td>
<td>2nd torsion</td>
<td>19.42</td>
<td>19.38</td>
<td>0.21</td>
</tr>
</tbody>
</table>

stresses localize at the crown of the pointed arches and on the above cornices.

The natural frequency analysis indicates the elastic dynamic characteristics of the structure (natural frequencies and mode shapes). In the calibrated FE model 8 sets of materials are considered, the Young’s modulus ranging from 40,000 (solid stone) to 4000 MPa (brickwork masonry), the corresponding densities from 2700 to 1900 kg/m³. Six principal modes emerged from the analysis (Fig. 7). A close match between the frequencies/mode shapes emerged from the calibrated numerical model and those emerged from the dynamic investigation was found (Table 1).

Figure 6. (a) Rendered view of the FE model, East side; (b) corresponding mesh. The positive Y axis corresponds to the North direction.
4 THE STRENGTHENING INTERVENTION

4.1 Introduction

In parallel with the studies previously reported, and benefitting from their outcomes, a light strengthening intervention was carried out. New structural elements were introduced as precautionary measures, e.g. by providing redundant confining systems, to collaborate with existing deteriorated elements and acting in case of sudden structural deficiency of the original material.

In general the stone tomb does not present indications of worrying structural problems. Interventions mainly consisted in hooping the monument at different levels. With reference to Figure 8, interventions included: A) hooping the base of the canopy with a stainless steel cable; B) hooping the capitals with a couple of stainless steel cables; C) repair of the junctions of existing tie beams; D) hooping the tabernacles with high resistance stainless steel cable. Local interventions consisted in: (1) binding the damaged supports (horse’s hooves) of the equestrian statue of Cansignorio by means of CFRP strips; (2) strengthening a cracked capital with hoopings in high resistance stainless steel cable.

4.2 Interventions description

Widespread cracks were noted in the cornice above the pointed arches, and in the same arches close by their keystones (Fig. 9a, b).

Parts of the cornices tended to separate, being this however not a recent damaging process, since iron clamps of previous interventions were found. A hooping device (hooping A) consisting in a stainless steel 7 mm diameter cable, connecting 6 corner steel plates and tensioned by turnbuckles, was positioned above the cornices. The size of the steel elements was minimized in order not to be invasive with respect to the monument (Fig. 9c, d).

The existing iron tie beams, spanning between the capitals of the upper order columns and locally damaged by oxidation (Fig. 10a), were complemented with a couple of 3 mm diameter stainless steel cables (hooping B). In fact, a strengthening intervention on the original tie beams was not feasible without heavily
intervening on the columns capitals. Cables were fixed to the capitals through stainless steel bushes, moulded following the shape of the capitals (Fig. 10c). An even contact between steel and stone was provided by means of lead sheets.

The iron tie beams connecting the tabernacles of the fence to the spiral columns, likely positioned during the XIX c. interventions, manifested marked decay at the connection with the original copper tie beams anchored to the stone. The tie beam strengthening intervention (C) aimed at the restoration of the original elements avoiding the onset of a new oxidation process on the copper anchoring elements. Two titanium studs were placed to join the existing iron and copper tie beams (Fig. 11a, b).

The deterioration or lack of the original iron tie beams in the same tabernacles required the introduction of new elements (high resistance stainless steel 1.6 mm diameter cables – hooping D) to restore the original layout (Fig. 11c, d). To minimize the dimensions of the clamps, the fixing methodology was tested (tensile strength of cable and connection) by means of laboratory experimental activities.

The removal of the copper “bandage” provided to the equestrian statue of Cansignorio during past interventions for the strengthening of the supports of the statue, highlighted the presence of material decay, with severe cracks and voids (Fig. 12a, b). Damaged supports were strengthened by the application of high resistance CFRP strips, subsequently covered with a plaster facing (Fig. 12c, d).
The expansion of the iron tie beams due to material oxidation caused the cracking of the capitals of the upper order columns, in some cases with severe effects (Fig. 13a). The strengthening intervention required the sealing of the crack and the positioning of hoopings on the capital, on 3 levels (1.6 mm diameter high resistance stainless steel cable). Purposely shaped titanium elements (Fig. 13b) were employed to allow the clamping of the cable.

5 CONCLUSIONS

Extensive studies were carried out on the Arca of Cansignorio della Scala, in Verona, in parallel with a light structural strengthening intervention and stone restoration activities. The research involved several aspects, some of them not reported in the paper (e.g. the laser scanner survey or stone characterization analyses), aimed at the achievement of a complete picture of the monument, for conservation purposes.

The investigation activities carried out (dynamic identification) proposed experimental evidences for the calibration of behavioral models of the monument.

Finite Elements models of the Arca were implemented on the basis of the laser scanner survey of the monument. Models were used to predict the static and dynamic behavior of the building and were successively tuned on the basis of the experimental activities. In a successive stage the models will be considered (with material non linear properties) to assess the response of the monument to seismic events.

The installation of a static and dynamic Structural Health Monitoring System gives the possibility to continuously evaluate the conditions of the monument by recording significant indicators (environmental parameters, dynamic response, cracks opening). The systems also allows to check the dynamic response of the structure to traffic or seismic events. An important aspect considered in the setup of the monitoring system was the reduced impact on the monument, given also the continuous attendance of tourists: sensors were minimized and "camouflaged" as much as possible (Fig. 14).

The design of the intervention was based on a almost complete removability of the new structural elements, positioned to compensate the lacks of the original material. Interventions, except the consolidation of heavily damaged parts (horse’s hooves), are based on a mechanical assembly of metallic elements, avoiding chemical connections with the original material. New materials and structural elements were chosen in order to maximally reduce their dimension (i.e. high resistance stainless steel cables).

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