A STUDY ON THE STRUCTURAL STABILITY OF THE SANVITALE CASTLE OF FONTANELLATO, ITALY

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SUMMARY

In the present paper, the main results of a structural analysis on the Sanvitale Castle of Fontanellato (Parma), Italy are presented. Firstly in-situ and laboratory tests for the mechanical and geometrical characterisation of subsoil, foundations and masonry structures have been carried out. Then the use of a monitoring system to control the evolution of deterioration phenomena together with the calibration of numerical models for stress analysis has allowed us to express a grounded judgement on the structural stability of this important monumental building.

1. GENERAL DESCRIPTION OF THE BUILDING

1.1 Historical notes

The present structure of the Sanvitale Castle of Fontanellato (Fig. 1a) is the result of several extensions, modifications and demolitions since the construction of its oldest part, the *mastio*, in the Thirteenth century [1]. The majority of the subsequent construction works were executed in the Fifteenth century, yielding to the formation of the four main bodies of the building surrounding a courtyard and of the overhanging tower located on a side of the *mastio*. In 1524, Francesco Mazzola called *Il Parmigianino* (1503-1540) painted the precious room of Paola Gonzaga Sanvitale, where the myth of Diana and Atteone taken from Ovidio's *Metamorfosi* is described (Fig. 2). Around the half of the Nineteenth century, a whole storey on the west side of the Castle was demolished in order to create an hanging garden. The demolitions of some vaults in the south body are dated from the same period.

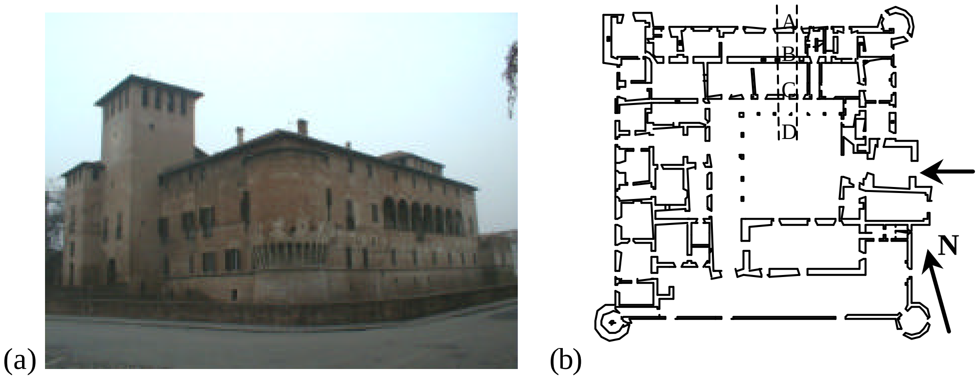


Figure 1: a) North-east view of the Castle; b) plan of the structure with the tested and monitored zone (light grey) and of the cross section analysed (dark grey)

Figure 2: Diana and Atteone's Room painted by *Il Parmigianino*: detail of Diana's bath

1.2 Subsoil survey

In Fig. 3, a lithostratigraphic section of subsoil, obtained from the results of static penetrometric tests and cognitive drilling, is reported. The section indicates the presence of alternating clay and lime deposits up to a depth of about 30 m where a gravel deposit was found. The first water-bearing stratum is located at a depth of about 28 m, in the gravel deposit. Such a stratum is characterised by a pressurised condition with a static level at about -4.5 m.

1.3 Structure and material description

The building has a square plan of about 50 m in side with a courtyard of about 18 m, and it is surrounded by a permanently water-filled moat (of about 18 m in width). Four main bodies along the sides of the courtyard can be identified. Three circular conical towers with a maximum diameter of about 6 m and a 8 m-square tower (on the north-west vertex) are located at the external vertices of the Castle.
The structure is characterised by vertical elements (walls and columns) and horizontal

elements (vaults, arches and wooden floors). The identification of simple and modular static schemes appears to be difficult, also because of the modifications and extensions undergone by the building. The vertical walls are constituted generally of rubble masonry having external leaves of bricks (with a regular texture and lime mortar) and internal leaf of a sort of conglomerate of lime mortar and stones. The columns of the internal portico and of the second-floor loggia in the north wing are made with brick, while the columns of the two first-floor loggias, again located in the north wing, are made with sandstone. The horizontal elements are as follows: on the ground floor, barrel and *a padiglione* brick vaults; on the first and second floors, thin barrel, *a padiglione* and cross vaults. On the higher levels, wooden structures of floors and roof are present. Foundation structures are not present along the central as well as the internal (toward the courtyard) walls (Fig. 4), whose foundation level is then that of the basement.

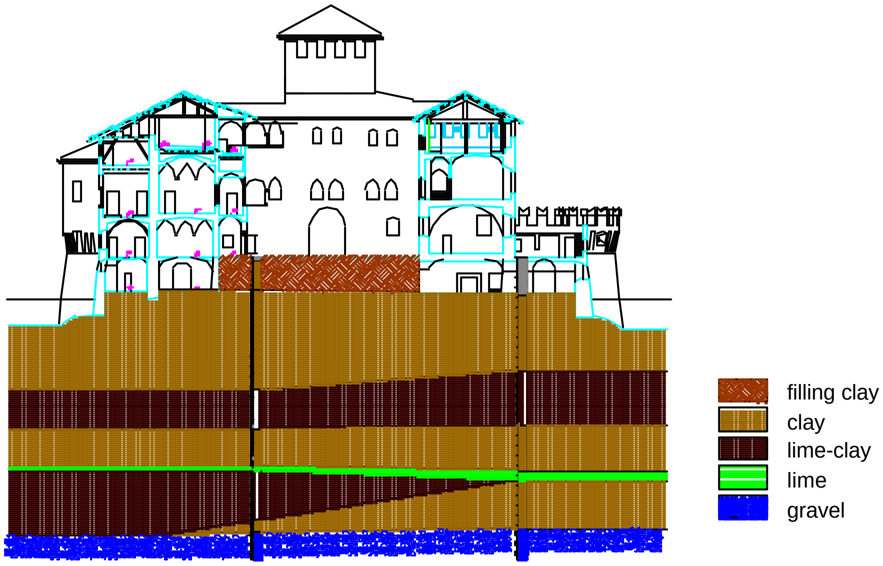


Figure 3: North-south lithostratigraphic section

1.4 Main deterioration phenomena

Although the Castle does not present in general worrisome deterioration conditions, some local phenomena deserve a thorough attention. For instance, in the basement of the north wing, diffuse cracking is present, with some longitudinal main cracks with respect to the longest side of the wing, indicating a separation between barrel vaults and the external supporting wall on the moat side. Moreover, masonry columns of the internal portico on the ground floor show vertical cracks due to crushing of the material. In some wooden floors, in the North wing, the principal beams exhibit a diffuse degradation near supports.

2. TESTING CAMPAIGN

2.1 Geognostic investigation

The geotechnical characterisation of the Sanvitale Castle's subsoil was performed on the basis of in-situ and laboratory tests. The former consisted of cognitive drilling and static penetrometric tests. For the latter, soil classification, oedometric and triaxial tests were carried out in order to determine the loading history of the deposit and the mechanical characteristics of soil. The results of penetrometric tests shown a normal-consolidated condition of subsoil, as confirmed by the three oedometric tests. Two consolidated drained standard triaxial tests were performed in order to determine shear resistance of soil and its stiffness parameters under drained conditions. These parameters can be used in a subsoil model to estimate settlements of the structure. As a matter of fact, from the results of geotechnical tests an elastic modulus for the subsoil was determined [2]. Moreover, the bearing capacity of foundations was calculated for the existing typologies through shear resistance.

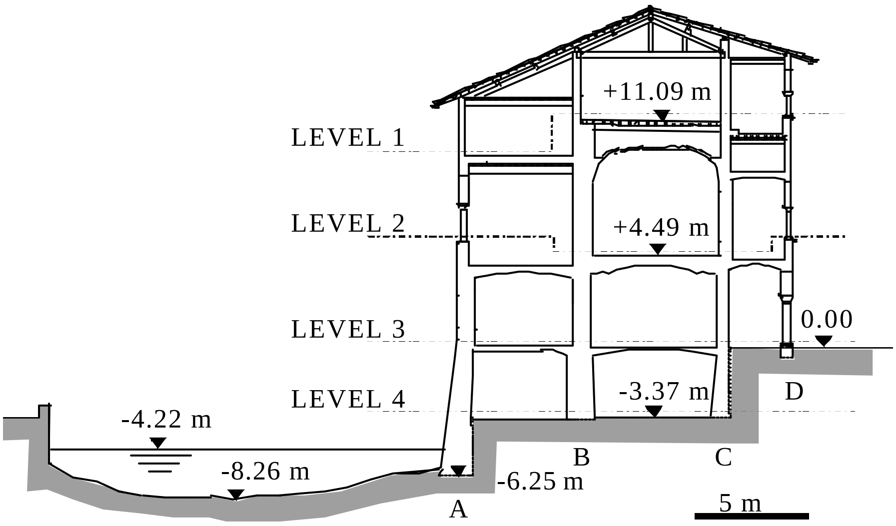


Figure 4: Typical cross-section of the north wing

2.2 In-situ tests on masonry structures

The testing campaign on masonry structures was mainly focused on the north wing of the Castle (Fig. 1b). The following tests were performed: three single and one double flat-jack testing, three core testing of masonry structures, two sub-vertical drilling and three local cognitive digging of foundations, ultrasonic tests on 5 masonry columns and on 5 sandstone columns, three endoscopic testing on masonry columns. The results of the tests has allowed us to characterise the geometry of the structure and the mechanical properties of the materials, along with their stress state. Ultrasonic and endoscopic testing showed a regular through-the-thickness texture of solid bricks and the presence of some voids and cracks.

2.3 Monitoring

Monitoring systems to record the evolution of degradation, for a sufficiently long period of time, are largely employed in the context of structural analysis of historical buildings [3]. The time history of the cracking pattern in the Sanvitale Castle is under monitoring for a number of key points (Fig. 1b). In particular, variations of crack opening for five significant cracks are recorded approximately monthly. Details of the results are reported elsewhere [4].

3. STRESS ANALYSIS

The stress state in the structures of the north wing of the Castle have been analysed in detail. In particular, a cross-section of the building with thickness equal to the column spacing in the ground floor internal portico (equal to 3 m) was examined (Fig. 1b). Such a section (Fig. 4) consists of vertical elements (external wall on the moat side containing loggia's columns, two central walls and three orders of columns on the courtyard side, termed as element A, B, C and D, respectively, in Fig. 1b) and horizontal elements (masonry arches and vaults, wooden floors). The wooden roof structure is supported by king trusses. Stress analysis has been performed for service conditions of the structure. The acting vertical loads are: self-weight, permanent loads and accidental loads.

The section of Fig. 4 was modelled through an accurate discretisation in finite elements. The geometry of the section was simplified by discarding the elements which have a marginal influence on the overall structural behaviour (e.g. trusses and wooden floors). Linear elastic analyses with either rigid subsoil or deformable subsoil were performed. The elastic deformability of subsoil was modelled via independent springs (Winkler's model). The elastic modulus of subsoil was determined on the basis of experimental results of laboratory soil testing. Masonry structures were discretised by means of a 4-node isoparametric plane stress plate elements. In total, 625 plate elements and 870 nodes, corresponding to 1728 degrees of freedom, were used in the model.

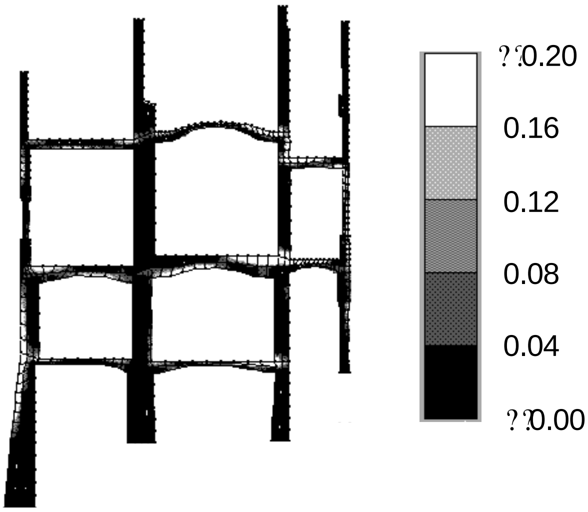
Some salient results of the analysis obtained from the deformable-subsoil model are reported in Fig. 5. The highest stresses occur within the sandstone columns on the first floor. The values of vertical stress undergo a general increment with respect to those relative to the rigid-subsoil model [4]. Moreover, the elements present higher bending stresses, characterised, in few cases, by tensile values. In particular, the A-wall at level 3 and the sandstone D-column at level 2 show the highest bending stresses, with tensile stresses up to 0.48 MPa in the masonry and 7.05 MPa in the sandstone. A non-symmetric stress distribution with respect to mid-span cross-section of vaults can be noted, owing to the differential settlements at their supports.

The results of the deformable-subsoil model indicate values of both compression and tensile stresses beyond the common average resistance of the materials [5]. In this respect, the approximation produced by linear elastic model, in describing the mechanical behaviour of soil and masonry materials, should be borne in mind. However, more complex analyses, which can better simulate the actual behaviour of the materials, were not performed, since the values of stresses were not excessively high.

4. CONCLUDING REMARKS

The results of a numerical analysis to study the stress-strain field and the structural stability of the Sanvitale Castle of Fontanellato have been presented. The geometry of the problem, the mechanical characteristics of masonry structures and subsoil, together with their stress state, were obtained through cognitive testing in some key points of the building and through geotechnical investigations. The numerical analysis was performed through a linear elastic finite element model for masonry structures and subsoil. Subsoil was modelled both as a rigid and a deformable medium. For the latter, a linear elastic behaviour according to Winkler’s model (the elastic modulus of subsoil was determined by using Vesic method [2] and by taking into account of the nonlinear behaviour of soil) was considered. In a nutshell, the results of the analysis have indicated an overall fairly good static state of the building with few provisos. For instance, the internal columns of the courtyard on the ground floor and those of the loggia on the first floor of the north wing exhibit high values of stresses. Note that these columns were already been repaired in the past; however, particular attention should be given to the future results of monitoring system, before undertaking any further strengthening action.

Figure 5: Maximum principal tensile stresses (MPa), for the deformable-soil model



5. ACKNOWLEDGEMENTS

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