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SAN NICCOLO'S TOWER-GATE, FLORENCE – ITALY: MASONRY CHARACTERISATION AND STRUCTURAL ANALYSIS

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Abstract

This San Niccolò's tower-gate stands up for 40 m on the Southern bank of the Arno River at Florence (Italy) as witness of the III Medieval ring of the city-wall erected in the XIV century. The Florence Municipality, for conservation purposes, planned to acquire knowledges on the Tower-Gate structure and masonry to leave hand down and perform seismic vulnerability assessment for that outstanding historical monumental building. The studies had been developed in three stages: 1) geometric survey by means of laser scanner and photogrammetry by drone and ground, with HBIM implementation. 2) NDT and LDT investigations performed according to the rule in force, namely the "MIBACT 2011 Guide Lines" for historical buildings. 3) seismic parametrization of the ground and tower-gate's masonry, and analysis of the seismic vulnerability of the tower-gate. The geological background implies that the tower's foundations are a few meters deep and rooted in hard quartz-calcareous turbidites bedrock. The seismic survey and the microseismic zoning of the Florentine area led to define the seismic parameters for the ground and the Towe-Gate. We conclude that the state of conservation of the Tower-Gate satisfies the principle of Integrity and Authenticity and the seismic performances are verified.

Keywords: masonry, dynamic behavior, geological setting, seismic vulnerability, cultural heritage.

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1 INTRODUCTION

This research has been developed in the frame of a general agreement protocol between the Firenze Municipality and the Department of Earth Science (DST) of the Florence University**.** Goal of the research is updating the knowledge on the City Walls and Tower-Gate structures and masonries for planning correct conservative interventions; the San Niccolò Tower-Gate is the first building analyzed for this project, and had been done in cooperation with the Department of Architecture.

This research is in line with the prevision of the rules in force [1, 2, 3]; in situ investigations had been performed according to [4] and with the permit of the local competent Conservation Authority.

2 THE SAN NICCOLO' TOWER-GATE

The San Niccolò Tower-Gate (Fig.1) was built in the year 1328 under the direction of Andrea dell'Orcagna, as a stronghold where the city wall meets the Arno River on the foot of the San Miniato hill. Many historical pictures shows that until the XVIII century the Tower stand up directly on the left Arno riverbank, rooted on the outcropping bedrock.

Figure 1. The San Niccolò Tower-Gate standing up for 45 m on the left bank of the Arno River at the foot of the San Miniato hill, as stronghold safeguarding *Fiorenza*.

During XIX century the Arno River had been narrowed for adding the along river avenue, and the city wall destroyed, so isolating the Tower-Gate that now represent a witness of the medieval times and is the only one preserving its original features and highness (45 m). For those items, the San Niccolò Tower-Gate can be considered as an out-of-scheme statue placed in the landscape.

Structurally the San Niccolò Tower-Gate consists of two lateral pylons (approximately 10.4x3.7 m) frontally connected by a curtain (1.75 m thick) with windows for archers and with three inner planes sustained by arches.

3 THE INVESTIGATIONS

The studies performed followed the knowledge road map defined by [4] (Fig.2) and consisted into: documental researches, geological and seismic studies, in situ No Destructive Tests (NDT) and Low Destructive Tests (LDT), and seismic stability analysis.

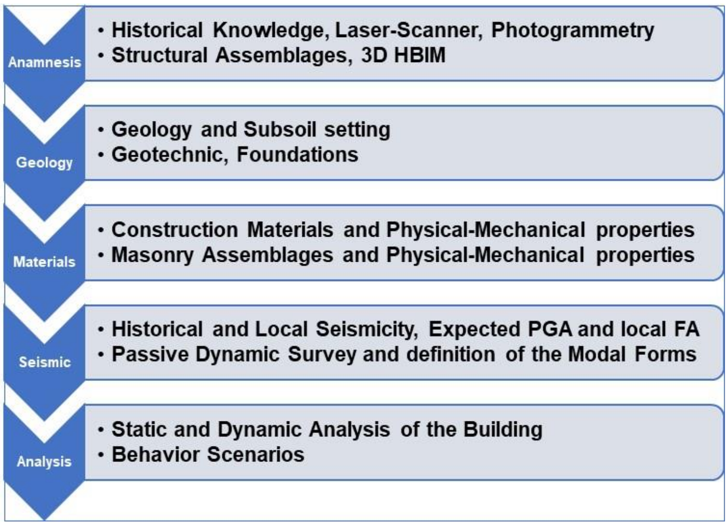


Figure 2. Knowledge road map as defined by the rule in force [4].

Documental researchers were made in the municipality archives, on historian texts and by historical paintings and pictures and led to accurately define the interventions executed during the times on the tower, mainly regarding the rebuilding of the battlements and frontal corbels in the XX century, as the installation of 7 transversal iron chains.

A 3D HBIM model of the tower had been done by means of laser-scanner and photogrammetric (by ground and by drone) surveys (Fig.3).


Figure 3. San Niccolò Tower-Gate: 3D laserscanner survey; 3D HBIM model.

3.1 Geology

The geological setting, at the ground and underground, of the Firenze area, as it is for the geotechnic of the local soils, is well known thank to a series of detailed studies developed in the last twenty years by the DST in cooperation with the Firenze Municipality [5, 6, 7].

In the site of the San Niccolò Tower-Gate, field geology survey and 6 drillholes outline a few meters of anthropic debris laying onto a quartz-calcareous sandstone bedrock, on which the tower is directly rooted (Fig.4), as well displayed by a picture of the XVII century.

Pietraforte sandstone has very good physical-mechanical properties [8, 9, 10, 11, 12, 13]: UCS = 130 MPa, $\gamma = 26.25$ kN/m^3, E = 16.8 GPa, $\nu = 0.194$, Vp = 4,900 m/s.

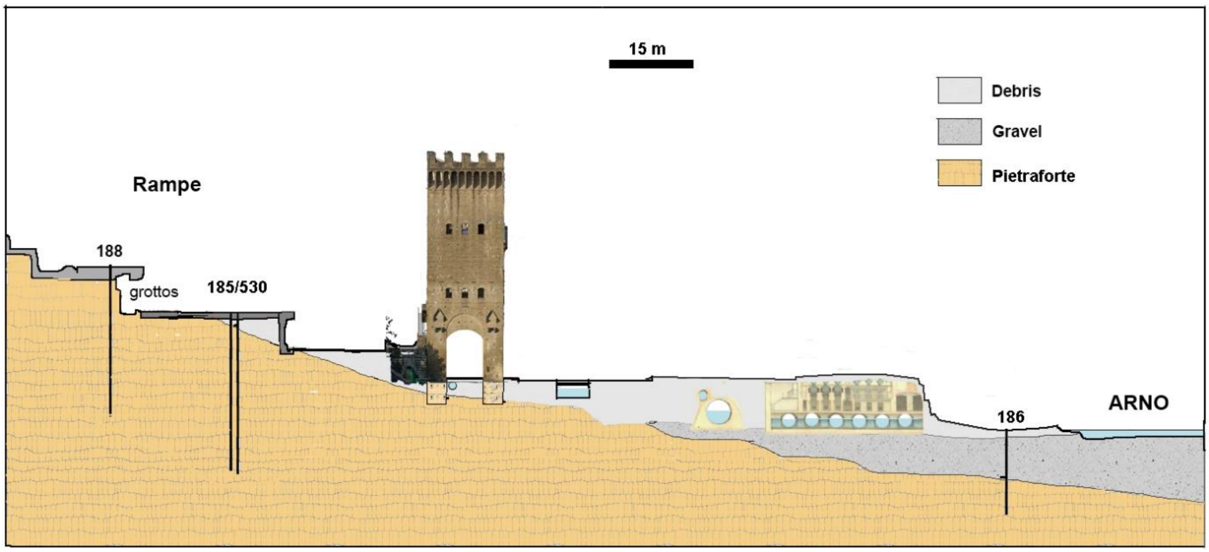


Figure 4. Geological cross-section of the San Niccolò Tower-Gate slope; numbers refer to drill-holes; along the Arno River the sewer and water systems.

3.2 Materials and masonry

Materials constituting the masonry of the tower had been defined by expert evaluation; they consist of stone (Piertraforte) and mortar. Façade vestments, about 50 cm thick, are in *facciavista* quoins, for East and West sides, and in stone-blocks and mortar, for North and South sides. Inside, the masonry consists in a full masonry of stone blocks and mortar well assembled.

Pietraforte stone was exploited in situ by the bedrock and in the near quarries; at those time quarries were opened in the north slope of the San Miniato hill [14,15].

Stone-blocks and quoins are assembled in regular rows and bounded by a very good mortar, as use in Firenze in the XIV century [9], which has these technical data: UCS = 20 MPa, γ = 17.5 kN/m^3, E = 7.9 GPa, $\nu = 0.27$.

The masonry assemblages of the tower have been investigated by means of georadar (GPR) survey (Stream T and C thrue types - by IDS-GeoRadar, part of Hexagon), DAC-Tests and endoscopies, sonic velocity determinations, Schmidt hammer tests, mortar penetrometric tests; the tension of the chains had been also determined.

In particular, we would like to emphasize the first use of the Stream T, a new generation GPS system consisting of an array of 6 antennas working contactless for strips 1 m wide. Stream T, mounted on a lifting basket, had been used for a full scan of all the sides of the Tower-Gate (Fig.5); the tomographic results were very fruitful well depicting the inside structure of the masonry.

DAC-Tests, endoscopies and sonic velocity investigations led to evaluate a mortar/stone ratio for the two pylons from the ground to the second floor of approximately 70% stones and 30% mortar and from the second floor to the top approximately 55% stones and 45% mortar, with γ = 23.6 kN/m^3 and γ = 22.3 kN/m^3, respectively, with Vs = 2.800 m/s for both; the frontal curtain has a mortar/stone ratio of about 50%, with γ = 21.9 kN/m^3

Figure 5. – Left: georadar Stream T antenna mounted on a lifting basket; right: a moment of acquisition along one side of the tower.

The investigation results outline that in the context of the types of historic Tuscan masonry, this masonry equipment belongs to the "stonemason techniques with quarried blocks placed on horizontal rows", an evolved typology in use starting from the XII century and connected to the supply of stone materials from newly opened quarries.

According to [16] it is a masonry of Type a2 "Masonry in rough stone", to [17] can be referred to category C "Masonry of rough-hewn stone in the presence of irregularities", and to Table C8.5.I of [3] it owns to Class III "Masonry in split stones with good texture".

3.3 Seismicity and dynamic survey

The recent studies for the Seismic Microzoning of the Firenze area [18] highlight an historical seismicity a MCS Imax = VIII with M = 5.4. For the site of the tower the expected PGA calculated as by law [2], for a set of 7 accelerograms spectrum-compatible for the site for both return periods of 712 (SLV) and 75 (SLD) years, respectively equal to 0.151g and 0.065g.

For defining the Tower-Gate seismic dynamic behavior, 13 seismic stations record were used for 2 hours for recording the behavior of the tower under ambient noise vibrations., The stations wer located on four different levels from the ground up to the roof. In particular, one station was installed at the basement of the Tower-Gate and four stations were installed at the corners of the first, second and third level. Each seismic station was equipped with 3-component seismometers Lennartz 3D/1s (sensitivity 800 V/m/s and with a 1 s eigen period). Seismic data were digitized using a 24-bit Guralp CMG24 Digitizer at 500 Hz, and time synchronization between stations was achieved using GPS.

The seismic data were analyzed using the Enhanced Frequency Domain Decomposition (EFDD) which is a frequency domain technique for operational modal analysis of structure. In the present study, we performed and automatic EFDD method [19] to extract automatically the modal parameters of the structure.

The first five modes of the Niccolo's Tower gate, with natural frequency at 1.552 Hz, 1.666 Hz, 3.275 Hz, 5.612 Hz, 8.080 Hz (Fig.6) were detected. The first modal shape is char-acterized by a motion trending in North-South direction with a frequency of 1.552 Hz, where-as the second modal shape is transversal and trends in East-West direction with a frequency of 1.666 Hz. The third mode is torsional with a frequency of 3.275 Hz. The fourth and fifth modes are instead bending modal shapes at 5.612 and 3.156 Hz, respectively.

3.4 Stability analysis

In this work, a simplified LV1 analysis was conducted with reference to the requirements contained in the "Guidelines for the assessment and reduction of the seismic risk of cultural heritage - alignment with the new technical standards for buildings" [4]. With regard to "Towers, bell towers and other structures with mainly vertical development" the Guidelines in the case of the first level of assessment define a specific simplified calculation scheme, which refers to collapse due to bending (Fig. 7).

The verification is performed considering the horizontal action in the direction of the two main directions of inertia of the section, in both directions.

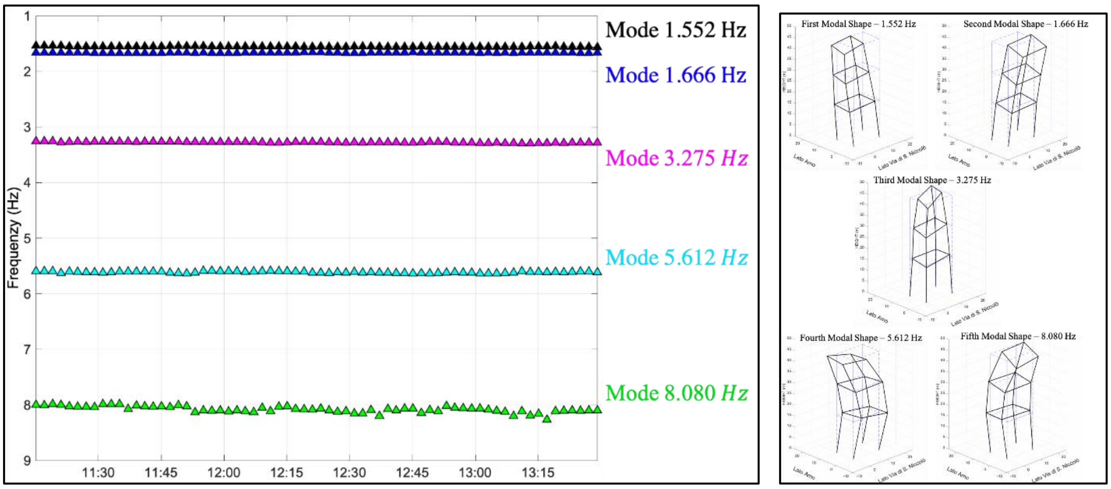
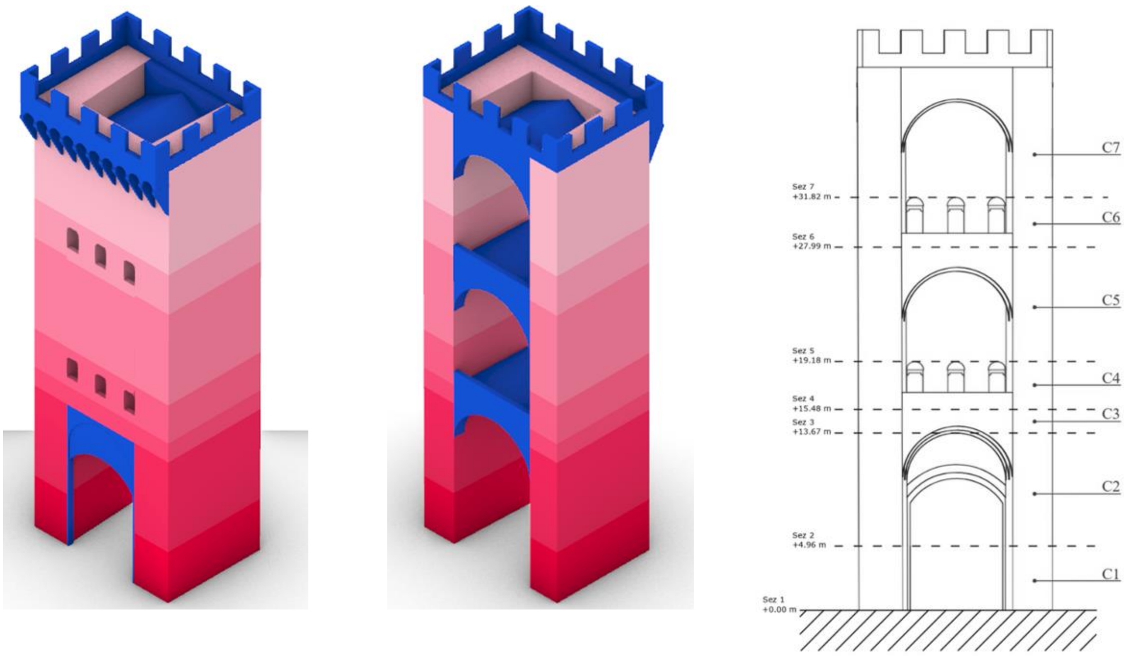


Figure 6. Left: time trend of the 5 structural frequencies with the average values for each structural mode for the 2 hours of measurements. Right: three-dimensional representation of the 5 modal shapes identified for the Tower of San Niccolò.



(a) (b) (c)

Figure 7. Division of the tower into sectors: In different shades of red, the sectors considered as resistant elements and in blue the parts considered overloaded on the adjacent sectors; a) and b) 3D views; c) section view.

The safety of the building is quantified through the seismic safety index I_S, given by the ratio between the return period T_{SL} (calculated through an iterative procedure, described in the appendix of the NTC2018) of the seismic action that leads to the generic limit state (in this case SLV) and the corresponding reference return period $T_{R,SL}$. Similarly to the safety index, it is possible to define an acceleration factor f_a, defined by the ratio between the acceleration on the ground which leads to the achievement of the SLV (a_{SLV}) and that corresponding to the reference return period ($a_{g,SLV}$), both referred to subsoil category A.

Since these are historic masonries of singular consistency and resistance, a sensitive analysis of the mechanical parameters was conducted for the first level of evaluation. The use of several values allows to evaluate the impact that the variation of the single parameters generates on the seismic safety of the structure; therefore, in relation to the seismic demand of the site.

In summary, the resistance values of the design compressive strength adopted in the bending checks of the first evaluation level are:

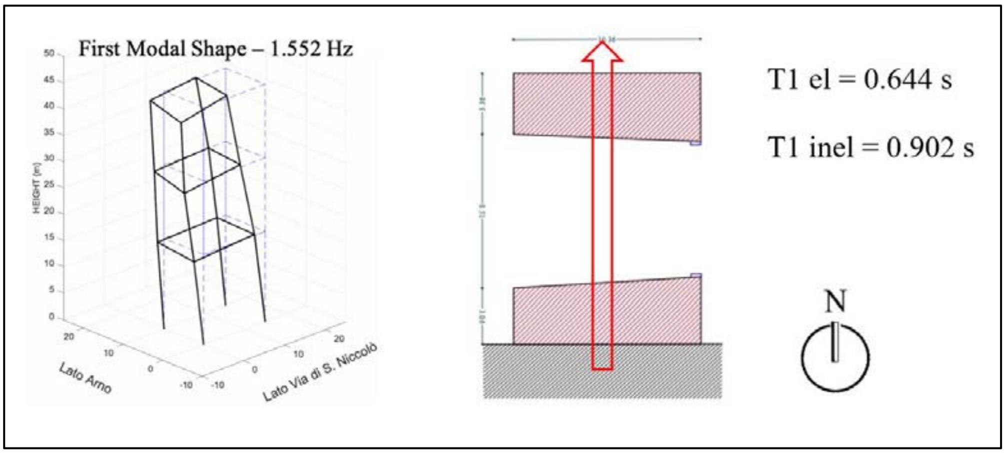
• 1.083 MPa: Considering the minimum value of the range of the "split stone masonry with good texture";
• 1.58 MPa: Considering the max value of the range of the "split stone masonry with good texture";
• 2.42 MPa: Considering the minimum value of the range of the "square stone block masonry".

Similarly, to the resistances, several values of the specific weight of the masonry have been hypothesized, both by referring to the values listed in the legislation and by considering various percentages of stone and mortar:

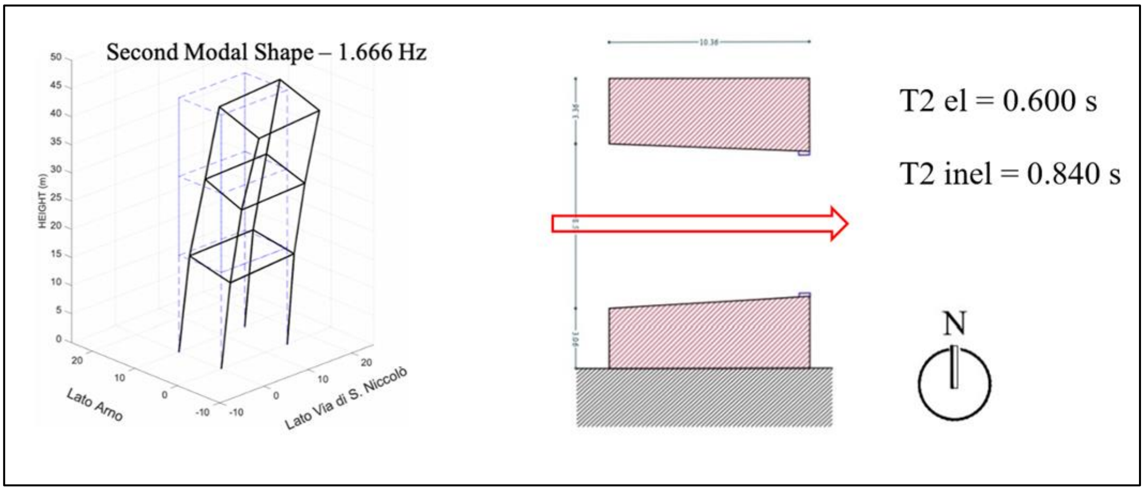
• 22.9 kN/m^3: considering a stone/mortar ratio of 60/40;
• 23.8 kN/m^3: considering a stone/mortar ratio of 70/30;
• 21 kN/m^3: considering the value relating to the family "split stone masonry with good texture".

The next step in the LV1 evaluation is the definition of the structure factor q and the confidence factor FC that depends on the level of knowledge achieved. In the case in question, the structure factor was defined through the procedure of the NTC 2018 and equal to 2.97, which however is included within the range envisaged by the Guidelines. While for the definition of the confidence factor, the guideline table was used and, through the sum of the partial factors, we arrived at a FC equal to 1.15.

The valuations prescribed by LV 1 were carried out considering the fundamental periods in the two main directions. In particular, the elastic period was considered as defined by the dynamic identification and an inelastic period obtained considering the approach of the Guideline, which considers the inelastic period 1.4 times the elastic period of the structure (Fig.8).



First Mode direction North-South



Second Mode direction East-West
Figure 8. Main modal forms and verification analysis results.

The results obtained show and confirm how sensitive these checks are to the resistance parameters used. In particular, for the San Niccolò Tower, the analysis highlighted a greater criticality in correspondence with the basement section, in particular in the WE direction parallel to the short side. Therefore, in the hypothesis of a good quality and high resistance masonry, the bending test had a positive result in all the sections and all the models analyzed, while, in the case of a less resistant masonry, the base section was not verified in any model, reaching very low security levels.

The trend of the acceleration factor has been verified in the most critical section (Fig.9); that of the basement considering a variation of the specific weight and of the compressive strength for all the cases analyzed with respect to the two directions and periods: elastic (non-cracked condition of the structure) and inelastic (cracked condition of the structure).

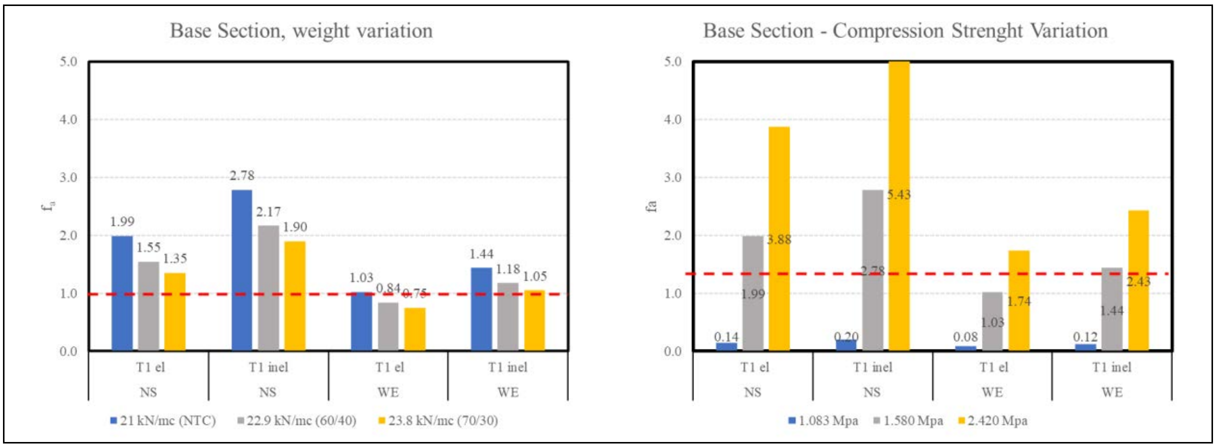


Figure 9. Trend of the acceleration factor in diverse configurations.

4 CONCLUSIONS

This project is an example of multidisciplinary research involving into a real integrated cooperation more public and private institutions all addressed to the common target constituted by the up-to-date knowledge of the San Niccolò Tower-Gate structure and conservation level.

The results of the research have made it possible to increase knowledge of the state of security and address the project of conservation, in full compliance with the principle of Integrity and Authenticity, driven to reduce Induced Vulnerability for elongation the Tower-Gate cycle of life.

The results obtained for the evaluation level LV1 show greater criticality in correspondence with the basement section, in particular in the NW direction parallel to the short side. However, considering the good quality and high strength masonry, the bending test was successful in all sections and in all models analyzed. Subsequent levels of assessments will make it possible to obtain indications on the structural behavior and safety of the tower affected by fewer uncertainties, thanks to the diagnostic campaign currently underway.

The results achieved in this first phase of the research have made it possible to define a workflow, which, upon completion of the subsequent evaluation steps, can be applied to other historic monumental buildings.

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