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Integrated non-destructive assessment of relevant structural elements of an Italian heritage site: the Carthusian monastery of Trisulti

C Rainieri¹, A Marra¹, G M Rainieri², D Gargaro¹, M Pepe² and G Fabbrocino¹

¹Structural and Geotechnical Dynamics Laboratory, University of Molise, Via Manzoni, 86100 Campobasso – Italy

email: carlo.rainieri@unimol.it, adriana.marra@unimol.it, daniilo.gargaro@unimol.it, giovanni.fabbrocino@unimol.it,

²S2X s.r.l., Via Duca degli Abruzzi, 86039 Termoli – Italy,
email: gianmaria.rainieri@s2x.it, michele.pepe@s2x.it

Abstract: The analysis of historical structures in need of preservation and restoration interventions is a very complex task due to the large uncertainties in the characterization of structural properties and detailing in view of the structural response. Moreover, the predictive performance of numerical analyses and simulations depend on the availability of information about the constructional properties of the architectural complex, crack patterns and active degradation phenomena. In particular, local changes in material properties or damage due to past events (such as earthquakes) can affect individual structural elements. They can be hardly detected as a result of the maintenance interventions carried out over the centuries and the possibility to carry out limited or even no destructive investigations due to the historical relevance of the structure. Thus, non-destructive investigations play a fundamental role in the assessment of historical structures minimizing, at the same time, the invasiveness of interventions. The present paper deals with an explanatory case study concerning the structural investigations carried out in view of the seismic assessment of an Italian historical monument, the Carthusian monastery of Trisulti in Collepardo, erected in 1204 under Pope Innocenzo III. The relevance of the case study is due to the application, in combination, of different NDT methods, such as sonic tests, and active and passive infrared thermography, in order to characterize relevant masonry elements. Moreover, an advanced system for the in-situ non-destructive vibration-based estimation of the tensile loads in ancient tie-rods is described and the main results obtained from its application for the characterization of the tie-rods of the cloister are presented.

1. Introduction

The seismic vulnerability assessment of historical masonry structures is a challenging task due to the uncertainties affecting material properties and structural schemes, as well as to the structural modifications and interventions occurred over the centuries and hidden defects or damage. Type of masonry (e.g., regular brick or rubble stone), material properties, construction techniques and effectiveness of connections among structural elements play a fundamental role in defining the structural response. As a result, the seismic vulnerability assessment of historical masonry buildings requires a detailed knowledge of the traditional construction techniques to set appropriate models and the identification of existing damage and degradation phenomena [1].

Non Destructive Testing (NDT) can give a relevant contribution to the analysis of the constructional properties of the architectural complex as well as of individual structural components to identify, for instance, masonry texture, connections among different elements, mechanical properties



of materials or stresses in operational conditions, eventual damage or degradation phenomena. In particular, attention is focused on the integration between historical and iconographic research and the on-site experimental assessment of the actual conditions of the architectural complex. It is a crucial phase of the knowledge path of the historical asset that is sometimes adopted to support questionable invasive techniques aimed at evaluating local mechanical parameters, i.e. elastic moduli or compressive/shear strength of selected masonry panels, even though the latter could be not really relevant for the results of the analysis. Herein, these aspects are analyzed with reference to a very interesting explanatory case study: the Library and the Cloister of the Carthusian Monastery of Trisulti in Colleparado [2]. It represents a unique site for the experimentation of the integrated application of different NDT techniques to collect relevant information for the setting of an appropriate model, representative of the actual structural behavior. The Carthusian monastery of Trisulti (Figure 1) is a monumental site lying on the Ernici mountains in the Lazio Apennines (Central Italy). The erection of the primitive monastery is attributed to Saint Dominic by Sora, but the risk of landslides and the need for a rearrangement of the existing complex to fit the rules of the different monastic organization (in 1204 Pope Innocenzo III entrusted to the Carthusian order what remains of the former Benedictine monastery) led to the erection of another Carthusian monastery in a more suitable place. The construction of the new monastery was completed in 1211; thereafter, the complex was further enlarged and remodeled in the Baroque Age and later in the Eighteenth Century [3]. In order to minimize the uncertainties in the evaluation of the structural behavior of the most relevant buildings in the Monastery and identify past restoration interventions [3], extensive NDT has been carried out by means of different and often complementary methods. The results of investigations have been also compared with information collected from historical archives and detailed analysis of bibliographic sources such as historical documents and manuals on the construction techniques in the 13th century.



Figure 1. Overview of the Carthusian Monastery of Trisulti

2. Integrated NDT of the Library of the Carthusian Monastery of Trisulti

Extensive non-destructive investigations by means of a number of complementary NDT techniques have been carried out at the Library of the Carthusian Monastery to identify texture and hidden features of the masonry, presence of voids and other internal defects, degree of connection of the walls. Merging the results of experimental tests with information collected from a number of bibliographical sources, an accurate knowledge of the structure was achieved, including information and details about past interventions and hidden defects. The use of different, complementary in nature, NDT techniques allowed the accurate investigation of the structural elements without damaging paintings and decorations on the walls.

The following tests, alone or in combination, were performed and they are briefly reviewed in the following:

- *Passive and active thermography*, in order to gain information about the origin and historical evolution of the building, identify the type of masonry and investigate the connections between the walls;
- *Endoscopic tests*, in order to check and complement the basic information obtained from thermography at locations characterized by absence of artistic heritage;
- *Sonic tests*, in order to confirm the similarity between different masonry panels and to detect macroscopic voids, cracks or portions of masonry with different characteristics.

2.1. Infrared thermography

Infrared thermography can support geometric survey and investigations on materials and structural details, as well as the analysis of the historical evolution of the building [4]. By means of a thermal imaging camera the temperature distribution on the investigated objects surface can be detected. In fact this device provides a color map of the temperature field by exploiting the correlation between the intensity of the infrared rays, that a body emits, and its temperature.

Depending on the environmental conditions (outdoor, indoor) and the test objectives, passive as well as active thermography has been performed. Passive tests took advantage of the effect of the daily temperature variations. The main feature of the thermal imaging camera used for tests are: 320x240 pixels IR image resolution; 7.5-13 μm spectral range; thermal sensitivity <0.045 $^{\circ}\text{C}$; 60 Hz frame rate.

The infrared thermography has provided interesting information about the evolution of the building. In fact, it showed that some openings (Figure 2) were closed after interventions (probably in 1958, as resulting from the analysis of the literature) aimed at restoring the original configuration of the building. Such interventions could not be easily recognized by exterior visual inspections.

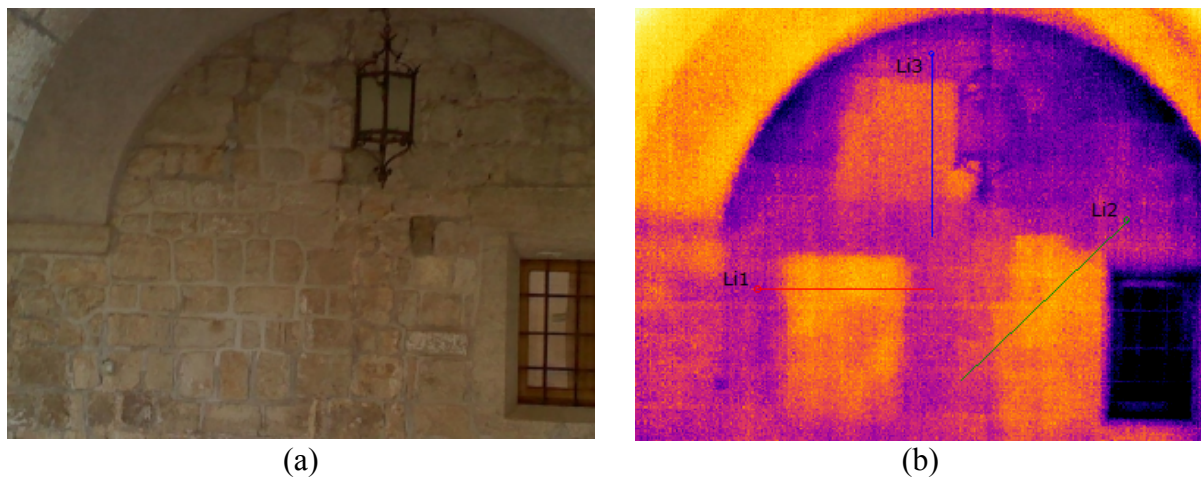


Figure 2. Digital (a) and infrared (b) image of the outer wall of the Library

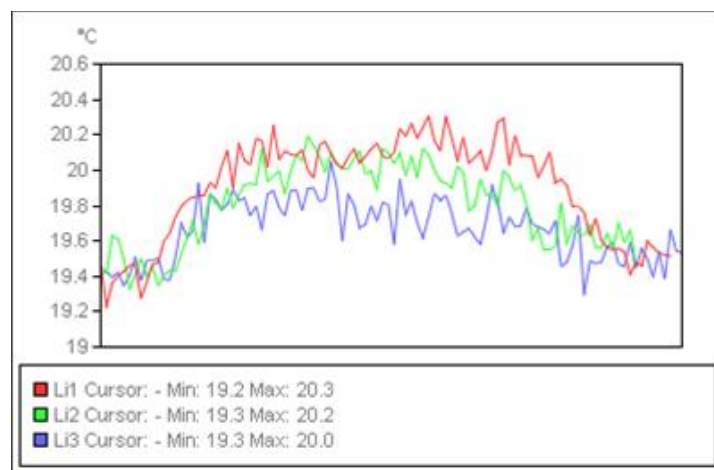


Figure 3. Temperature profile of the segments Li1, Li2, Li3 of Figure 2

The analysis of the infrared image highlights three portions of the wall characterized by a slightly higher temperature with respect to the rest. The analysis of the thermal profiles along three segments intercepting these areas shows that they are comparable (Figure 3), denoting common characteristics of the material in these areas.

2.2. Endoscopic tests

Endoscopy has been used, alone and in combination with thermography, to identify the types of masonry constituting the structure of the Library. By direct visual inspection of cavities the inside of walls has been analyzed, verifying the absence of voids or a core made of different and poor materials. Inspections have been carried out by means of a miniaturized digital camera with crystal clear output at the end of a 8.2 mm diameter probe with six adjustable LED lights; the system was completed by a 3.5" color LCD screen.

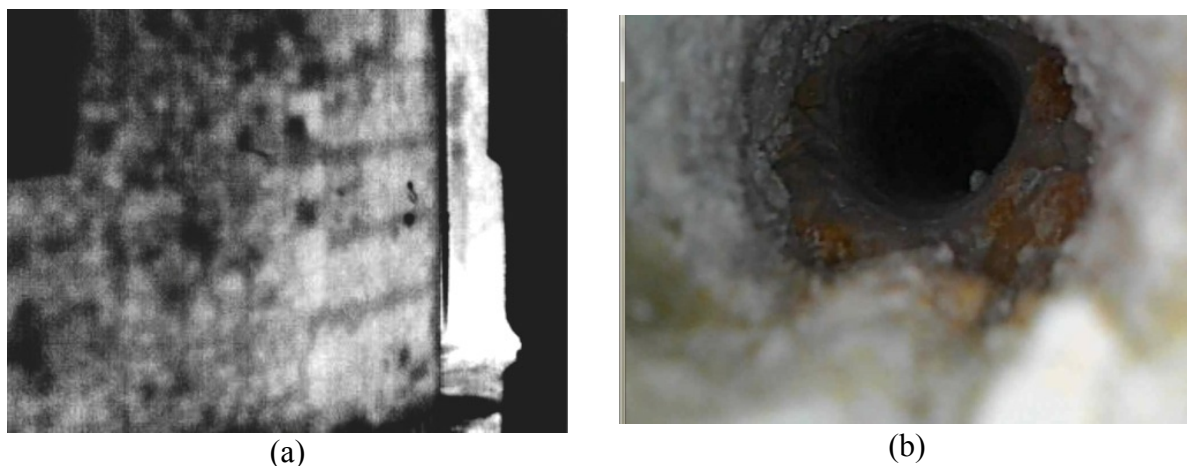


Figure 4. Masonry Class A1/II: infrared image (a), endoscopic image (b)



Figure 5. Masonry Class A3/I: infrared image (a), endoscopic image (b)

Endoscopic tests, in combination with thermography, allowed the identification of the following masonry typologies [5]:

- *Class A1 - Group II*: irregular masonry characterized by the presence of compact limestone and other materials (travertine and bricks), and corners made by large stone blocks (Figure 4).
- *Class A3 - Group I*: masonry made by compact limestone with lime mortar and aggregates; the texture is homogeneous and undifferentiated; this class of masonry is also characterized by the presence of adjustments of horizontality along the height (Figure 5).

The combination of thermography and endoscopy has revealed its potential in the analysis of the vaults (Figure 6) confirming some assumptions based on the historical research [3] and literature reviews [5].



Figure 6. Vault in the portico of the Library: infrared image (a) and endoscopy (b)

The vaults were made of limestone with elements arranged in form of shell ("*in foglio*"). It was also recognized that the stone slabs have been put with the broader face along the intrados of the vault, then cemented with mortar.

2.3. Sonic tests

Sonic tests have been also carried out for the nondestructive characterization of the masonry walls of the Library. They are based on the analysis of wave propagation in the material. The time for the emitted impulse to cover the distance between the emitter and the receiver is related to the dynamic elastic modulus, the Poisson's ratio and the density in the case of homogeneous and isotropic material. However, in the case of masonry, the inherent heterogeneity and anisotropy prevents the correlation of wave velocity with the elastic properties of the material [6].

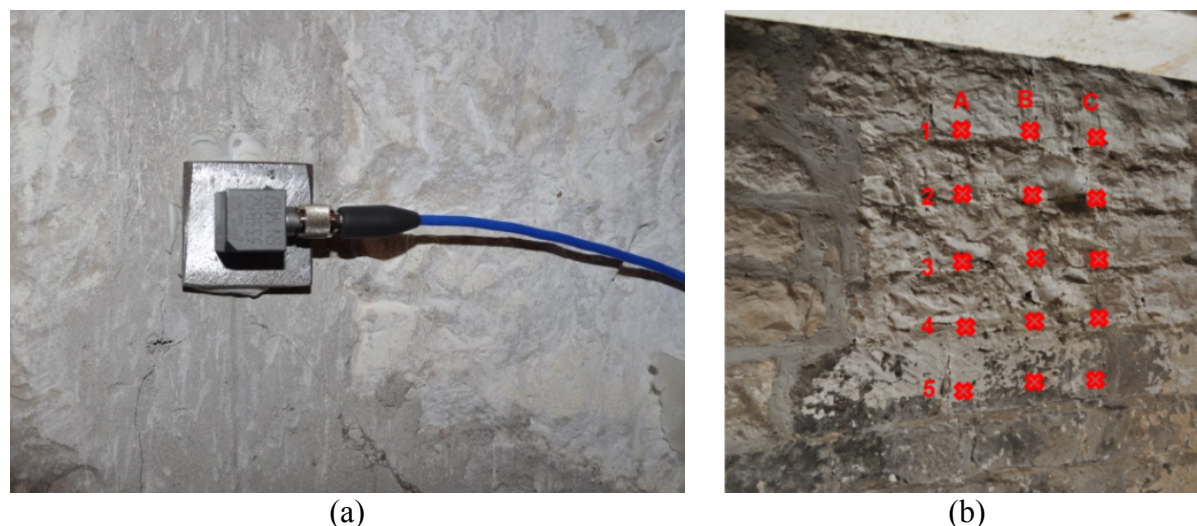


Figure 7. Sonic tests: sensor (a) and measurement mesh (b)

Direct sonic tests, aimed at obtaining qualitative information about texture and homogeneity of the walls, have been performed at the Library of the Carthusian Monastery of Trisulti. The sensors were arranged according to a regular mesh grid (20 cm spacing in both x and y direction) on the investigated wall surfaces (Figure 7).

The test equipment consisted of an impact hammer (22.240 kN full scale range, 0.23 mV/N sensitivity), IEPE accelerometers (1 V/g sensitivity, ± 5 g pk full scale range, 0.5-3000 Hz frequency range, 0,00005 g rms resolution), a data acquisition unit (24 bit resolution).

The sonic tests highlighted a discontinuity in the response of the masonry between the upper and lower part of one of the outer walls of the Library (Figure 8). It was probably due to the reconstruction of the upper part of the wall during the past. The discontinuity of material was visually detectable and also confirmed by the infrared thermography.

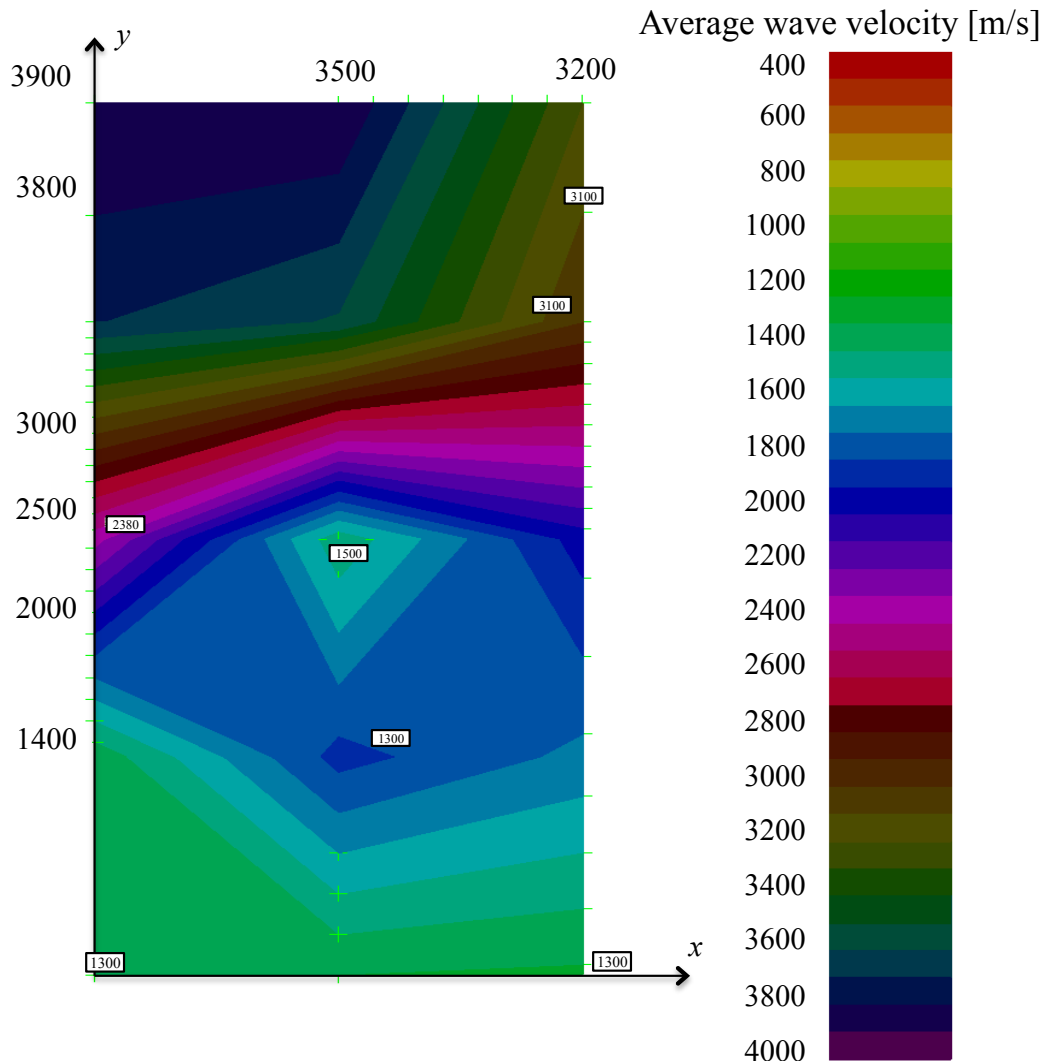


Figure 8. Mapping of average wave velocity

3. Vibration-based estimation of tensile loads in tie-rods

The analysis of documents collected in the Public Archive in Frosinone highlighted that, after the restoration interventions carried out in 1936, the tie-rods in the cloister of the Monastery were not tensioned, so that they could be activated by external loads such as the earthquake. Non-destructive vibration-based tests have been therefore carried out to estimate the tensile load [7] in four tie-rods of the cloister of the Carthusian Monastery (Figure 9) and assess their role in the current equilibrium condition of the structure.

For the vibration-based tensile load estimation, an innovative system developed by S2X s.r.l., a spin off company of the University of Molise, has been used. It is a compact system able to acquire

and automatically process the ambient vibration response of cables and tie-rods, providing estimates of the fundamental modal properties and the tensile load in operational conditions [7]. The portable system (Figure 10a) for in-situ evaluation of tensile loads in tie-rods consists of two boards working in parallel. The first board is dedicated to data acquisition and storage, while the second carries out the automated modal parameter identification and the estimation of the tensile load.

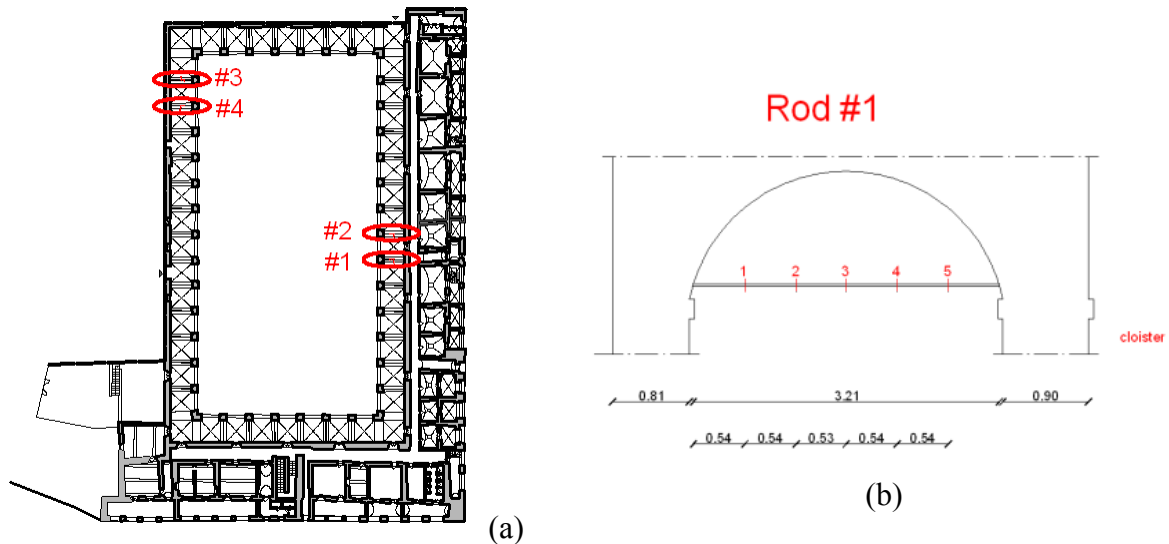


Figure 9. The tested tie-rods (a) and sample sensor layout (b)



Figure 10. Vibration-based testing of tie-rods: measurement system (a), installed sensor (b)

The system can acquire data from a maximum of eight IEPE accelerometers by means of the integrated NI PCI 4472b board. The system is complemented by a set of seismic, miniature (50 gm) IEPE accelerometers (Figure 10b). The characteristics of the sensors are: 10 V/g sensitivity, 0.7-450 Hz bandwidth, 0.5 g pk full-scale range. The data acquisition system is characterized by 24-bit Sigma-Delta ADCs for simultaneous sampling of the eight channels, analog antialiasing filters, 110 dB dynamic range, 102.4 kHz maximum sampling rate.

Reference values of 210 GPa and 7800 kg/m³ have been adopted for the Young's modulus and the density of the steel, respectively. Stable estimates of the tensile loads have been obtained, as reported in Table 1. The results point out that the investigated tie-rods are subjected to tensile loads in operational conditions.

Table 1. Results from in-situ tests at the Carthusian monastery of Trisulti.

Rod #	Base (mm)	Height (mm)	Net span (m)	Number of estimates	f_{av} (Hz)	N_{av} (kN)	σ_N (kN)	γ_N (%)
1	28.8	29.3	3.21	31	13.58	30.3	0.9	3.0
2	29.4	29.0	3.24	12	15.72	43.0	0.6	1.4
3	29.3	29.7	3.17	35	14.46	38.5	0.6	1.6
4	29.5	29.4	3.17	12	16.17	39.4	0.2	0.5

4. Conclusions

The application of different NDT methods, complementary in nature, allowed the accurate investigation of the characteristics of masonry elements (walls and vaults) of the Library of the Carthusian Monastery of Trisulti. The paper has shown how an integrated approach to NDT can provide relevant information for the structural assessment and makes the process more robust as a result of the cross validation of the results provided by the different testing methodologies. Moreover, an innovative vibration-based system for the estimation of the tensile load in tie-rods has been introduced and applied to evaluate the load in the tie-rods of the vaults belonging to the central cloister of the Monastery. Most of the test results confirmed the information obtained from extensive literature review and analysis of documents collected into historical archives. NDT, therefore, provides a valuable support to the enhancement of knowledge about the structural behavior of historical structures, when destructive tests have to be limited. Furthermore, the experience of the conducted research confirmed the effectiveness and reliability of the integrated use of historical and iconographic research and experimental evidences taken on site by means of different advanced NDT techniques.

5. Acknowledgments

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