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Diagnostic Campaign Aimed at Assessing the Seismic Vulnerability of Existing Buildings Applied to Strategic Buildings in Trentino Alto Adige (Northern Italy)

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Abstract
In order to assess the seismic vulnerability of existing buildings, the Italian structural codes require that the geometric characteristics of the structural elements and the mechanical characteristics of the materials shall be determined through diagnostic investigations. The Level of Knowledge (LK) achieved depends from the level of deepening of the investigations carried out; on this basis it is determined a Confidence Factor (CF) which have to be applied in the subsequent verification calculations to reduce the mechanical characteristics determined for the materials in the diagnostic mode. The legislation states also that for the buildings that are considered as "strategic" because of the effects consequent the seismic events, the vulnerability assessment is mandatory.
The paper describes the diagnostic activities carried out, on behalf of the Italian State Property Office, on some buildings located in Predazzo (Trentino Alto Adige Region - Northern Italy) built along the 20th c., which were originally intended as barracks and currently hosts the Alpine School of the Financial Police. These are very common situations in Italy: historic buildings, built with different construction techniques (both masonry and Reinforced Concrete and mixed techniques) and subject to multiple functional transformations over time.
The analysis carried out involved the geometric and material survey, the historical analysis of the events and interventions undergone, the mechanical characterization of the materials, foundations and soil. In particular, given the architectural interest of some of the buildings and the need to minimize disturbance to users, the tests that nevertheless have a limited impact on the construction (e.g. sampling on the concrete and tests with flat jacks on the masonry) were matched with Non-Destructive Tests (endoscopies, sonic and ultrasonic tests, penetrometric tests on mortars, sclerometric tests and magnetometric investigations) in order to extend the results and guarantee their representativeness. It was thus possible to reach the higher expected Level of Knowledge and to apply the minimum value of the Confidence Factor, so operating with the best compliance with the real state of the building. It is of particular interest also the building up of a Building Information Model (BIM), implemented from the laser scanner survey and developed up to the appropriate Level of Development, that constitutes a relational data base that allowed to embed all the acquired structural diagnostic information and to develop the following static and seismic assessment.

Keywords: Strategic buildings, seismic assessment, Masonry, Reinforced Concrete, Diagnostic test

1 Introduction

The State Property Office *(Agenzia del Demanio)* is the Italian administration responsible for the management and administration of a public real estate portfolio which currently amounts to approximately 43,000 assets, distributed throughout the Italian national territory, for an overall value of 62 billion euros. It promotes the valorization of public real estate and identifies innovative strategies and tools to activate urban regeneration operations and to stimulate the recovery of abandoned or underused public buildings.
Starting from 2018, with an address from the Ministry of Economy and Finance, the Agency also assumes the role of coordinator of a seismic and energy retrofitting plan for existing buildings, progressively involving the entire property assets entrusted to it. Particular attention is paid to the buildings used by public administrations, in order to improve their seismic safety

as well as to reduce the management costs. The recovery of this immense building stock and the goal of net-zero land consumption play an essential role both in the national strategic political choices and in the current ethics towards the natural environment.

The implementation of the building retrofitting plan foresees in its preliminary phase the execution of surveys of all the constituent components of the assets, seismic vulnerability analysis, and energy audits. The surveys are implemented following a broader investigative campaign that has to be developed in order to deepen the level of knowledge of the architectural, structural, material, and MEP characteristics of the buildings, as well as their state of conservation. The investigations have to be planned from each single case in order to obtain a high degree of knowledge, with the aid of methods and devices suitable for guaranteeing the conservation of the current state of the buildings. A proper selection of Non-Destructive Tests (NDTs) is necessary due to the many structural and administrative constraints to which the assets are subject. In most cases, these tests have to be carried out during the ordinary use of the buildings that are mainly used as offices by public administrations.

This in-depth knowledge gathering phase provides the basis for the progressive implementation of specific projects for the prevention of seismic risk, through design choices and construction site organization with the aim not to interrupt the ordinary work activities during the interventions. The use of high-performance materials and advanced technologies is furthermore promoted and solutions aimed at guaranteeing functional efficiency and maintainability over time are sought. The planning of the design phases and the consequent interventions of seismic improvement / adaptation that may be necessary are defined taking into account priority criteria, such as the level of seismicity of the areas where the assets are located, the type of use, and/or the "strategic" (for the effects consequent the seismic events) nature of the property. Of course, this plan has to be pursued with the constraint of the financial resources progressively made available by the Italian State Budget.

These activities are integrated with the implementation of the digitization of acquired information through the introduction of the Building Information Modeling (BIM) methodology in the different phases of the life cycle of each asset, from the survey, to the design, and to the restitution of the building post operam. This allows for optimization of the knowledge process, to improve the quality of the design and execution phases, to reduce diseconomies in terms of construction times and costs. The goal is to make available to all Italian public administrations the information necessary for the management, maintenance, and valorization of their heterogeneous (and often also artistically relevant) real estate portfolio.

2 Path of Knowledge

The evaluation of the safety and structural performance of an existing building requires that the structural complexity of the building is reduced to a model that can be somehow represented numerically. Knowledge of the construction is therefore a fundamental prerequisite both to carry out a reliable assessment of the current safety and to plan effective seismic improvement and adaptation interventions. Pursuing a proper Level of Knowledge (LK) allows one to properly choose the calculation parameters and to highlight the structural deficiencies, thus orienting the subsequent choice of any necessary structural interventions to be carried out.

The current Italian structural legislation [1] [2] highlights in particular the fact that, from the structural point of view, it is not possible to achieve complete knowledge of a building; for this reason, it traces a path of knowledge that can be developed at different levels of depth in relation to the level reached by the diagnostic analyses.

This path is aimed at defining an interpretative model of the structure that allows both a qualitative interpretation of the structural behaviour and a quantitative evaluation following the execution of a proper structural analysis. Particular attention has to be paid to the fact that it is necessary to understand the behaviour of the building by the comparison of the results found on site and always to be able to provide an intuitive justification of the expected phenomena. Otherwise, the mere result of arithmetic calculations, may not adequately represent the real physical behaviour of the building. A properly detailed global knowledge of the building is therefore essential, not only to have an overall picture of the current state of the structure, but also to validate, from a qualitative point of view, the results obtained from the numerical model.
The path of knowledge is divided [3] into the following activities:

- historical analysis of the construction phases, events occurred, and retrofitting interventions;
- geometric survey including the rendering of the crack and deformation patterns;
- survey of constructive details and state of conservation of materials and structures;
- mechanical characterization of materials;
- characterization of the soil-foundation behaviour.

Depending on the accuracy of the results obtained from the aforementioned activities, different LKs of the parameters involved in the model are identified and the related Confidence Factors (CF) are determinate [4]. These are defined as coefficients which reduce the characteristics of the materials and they vary from 1.00 to 1.35. In the case history and since these buildings are classified as “strategic”, in all the cases, the maximum Level of Knowledge defined by the standard (LK3) was reached, and consequently the minimum possible value of the Confidence Factor (CF = 1.00) was obtained.

3 Outline & Historical Analysis

The structural study of a building first requires the analysis of the documentation available in the historical archives which provides fundamental information relating to the construction phases and methodologies. Furthermore, it allows for the identification of which aspects need to be explored in the subsequent structural inspection and diagnostic activities.
In the case study, the research was carried out in the archives of different public bodies: State of Trento, *Agenzia del Demanio*, *Guardia di Finanza* (Financial Police), Superintendency at Public Works, as well as directly interviewing professionals who were involved in past interventions performed on the various structures. The many documents collected during this phase were then digitally logged and subsequently analysed.
The Alpine School of Predazzo, a complex made up of ten buildings, was built starting from 1910. The first buildings, the *Macchi* barrack and the *Berard* pavilion were built in 1913 (Fig. 1). After the 1st World War, the barracks were used as the seat for a detachment of skiers of the Royal *Guardia di Finanza*. Then it was decided to set up a school that had the task of training the financial policemen assigned to the companies located along the Alpine state border: thus, in 1920, the Royal Alpine School of the *Guardia di Finanza* was established.
In the following decades, new pavilions were built, and the existing ones were gradually refurbished, up to the current conformation of the school. The last enlargement dates back to the 1980s, when the *Fausto Musto* pavilion was built in conjunction with a general reorganization of the functions of the existing buildings. A detachment of the school is located at Passo Rolle and it also includes the *Sass Maor* mountain refuge, the *Colbricon Cimone* barracks, and the *Garage-Canile*, all built between 1963 and 1999.

The compound of the school is currently made by the following pavilions (Fig. 1): *Macchi* (A), *Berard* (B), *Autorimessa* (C), *Nicolauchich* (D), *Latemar* (E), *Sass Maor* (F), *Monte Cimone* (G), *Corpo di Guardia* (H), *Poligono* (I), *Fausto Musto* (L), *Colbricon Cimon* (M) e *Canile* (N). Their relevant characteristics are listed in Tab.1.
The Olympic Village which will host the athletes of the 2026 Winter Olympic Games will be built within the compound of the Alpine School.

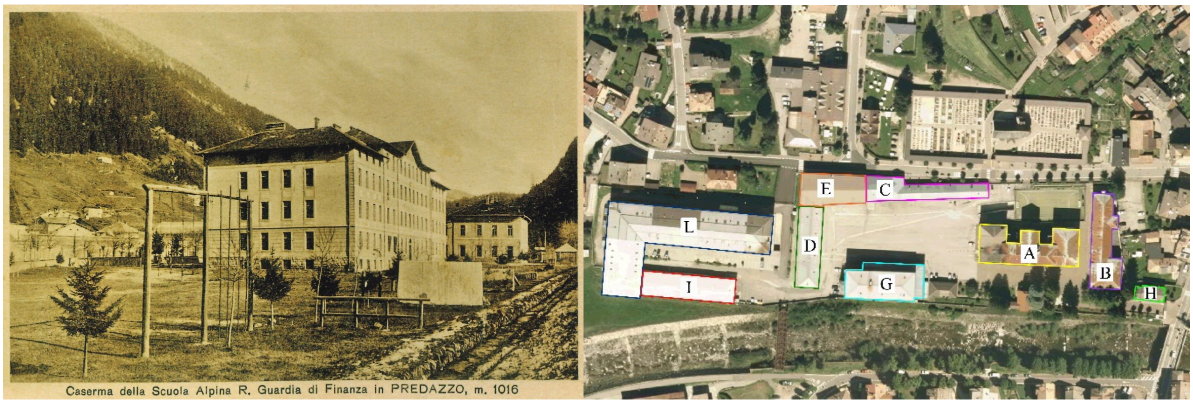


Figure 1: Postcard dating back to the 1920s showing the first two pavilions (*Macchi* and *Berard*) and current aerial view of the area with the location of the pavilions

Table 1: List of the buildings of the *Predazzo* Alpine School compound
(M = masonry RC = Reinforced Concrete MT = Mixed Technique)

Building	A	B	C	D	E	F	G	H	I	L	M	N
Year of construction	1913	1913	1936	1950	1961	1963	1971	1978	1980	1980	1988	1999
Construction technique	M	M	M	M	MT	M	RC	M	RC	RC	RC	RC

The interest of this case history is evident as these buildings were built over a century with different construction technologies ranging from masonry and reinforced concrete to mixed techniques.

4 Laser-scanner Survey

In order to know the geometry of the buildings with a high level of precision, the survey was carried out with 3D laser scanner technology which allowed us to obtain a high density of metric information. This is necessary for the correct and timely three-dimensional modelling of the building which forms the basis of all subsequent study phases.
The building survey activity was articulated into four phases:
1. topographic survey carried out with total station and GNSS satellite antennas
2. laser-scanning
3. aerial photogrammetry from a drone
4. post-processing

The topographic survey phase, fundamental to the subsequent use of terrestrial laser scanners and drones, exploits the sub-centimetre measurement precision of traditional topographic instruments (total station and GNSS receivers) to materialize a network of targets with known coordinates around the building. Subsequently, a laser scanner is used; the device consists of an emitter / receiver of laser beams which, by rotating on itself, allows to acquire a three-dimensional point cloud useful for describing the objects surrounding the instrument. To integrate the data obtained by the laser scanner in areas non-directly detectable from the ground, balconies, or from accessible flat roofs, a photogrammetric survey was carried out with the use of a drone. Special "structure for motion" software allows one to obtain a three-dimensional point cloud from the aerial photos, similar to that produced by the laser scanner, thus completing the survey.

Figure 2: View of the point clouds from the survey of *Macchi* barrack

The acquired data are then post-processed through software that allows them to be verified for correctness, corrected for eventual problems, and merged in such a way as to create the digital model of the building (Fig. 2). The final product consists of a single geo-referenced point cloud that collects all the information acquired during the survey.
The number of scanning positions necessary for the description of the building depends on various factors related to the geometric complexity of the construction. As an example, for the survey of the whole compound presented in this study, 2197 scans were carried out.
The use of this survey methodology has also proved to be fundamental for the highlighting of anomalous behaviour of some structural elements (e.g. deformations or inflections) which have been precisely determined with the analysis of the point cloud.

5 Diagnostic Analysis

A preliminary visual survey made it possible to describe the state of conservation of the buildings, to detect the crack pattern and to identify the elements that require more in-depth investigations in order to achieve the best structural understanding of the building.
This survey also made it possible to evaluate the information necessary to define the quantity of subsequent investigations, those related to the LK that has to be reached. The codes and norms [2] in fact, based on the construction technology of the building, define the procedures necessary to achieve the various levels of knowledge. For example, the minimum level necessary to achieve level LK3 on the *Monte Cimone* pavilion (G - reinforced concrete building) is the following:

- geometry - complete survey with laser scanner technique integrated with the data obtained from the analysis of the drawings found in the historical research and of the information obtained during the visual inspection;

- construction details - execution of analysis quantified on the basis of the completeness of the available documentation; in the specific case, analysis of the rebars for 15% of the structural elements (taking into account the usual repetitiveness of the reinforced concrete structures);
- material properties - execution of tests at "extended" level consisting of specimens integrated with NDTs in order to extend the data and evaluate the homogeneity of the materials.

Table 2 summarizes the survey campaign carried out on the buildings of the compound.

Table 2: Diagnostic analysis performed on the buildings of the compound

Test	A	B	C	E	G	H	I	L	F	M	N	Tot
Magnetometric	1	7	6	12	25	2	14	56	10	27	6	**166**
Ultrasonic				8	20		1	26		14	5	**74**
Endoscopy	5	9	8	11	6	2	7	9	17	4	1	**79**
Cores	2	4		1	2	1			6			**16**
Single Flat Jack		2	2									**4**
Two Flat Jacks		2	2									**4**
Mortar Penetr.		2	2									**4**
Conc. sampling				2	6		7	22		7	2	**46**
Steel sampling				2	4		3	10		6	2	**27**
Carbonatation				2	6			20		7	2	**44**
Rebound H							11					**11**

The diagnostic campaign strictly related to the structural aspects of the buildings was also integrated through geo-gnostic investigations necessary for the characterization of the soil, which are fundamental, but which however are not described below as they are out of the scope of the present paper.
The magnetometric analyses made it possible to define the construction details of the reinforced concrete structures by locating the rebars and determining their geometric characteristics. The data obtained from the investigations were then compared with those that were available from the analyses of the historical documentation, allowing us to confirm the relevancy of the old design drawings (Fig. 3).

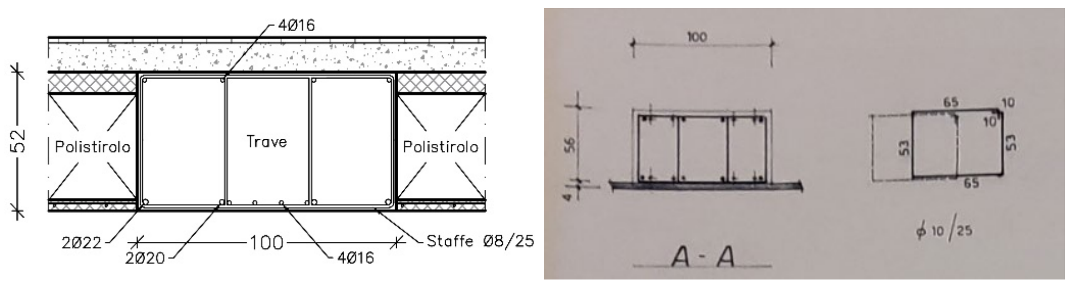


Figure 3: Comparison between rebars detected by magnetometric survey (at left) and the ones resulting from the analysis of the historical documents (at right)

The mechanical characteristics of the concrete and of the steel rebars were determined by combining the results of direct tests (compression and traction on samples) with non-destructive tests (e.g. ultrasonic, rebound hammer and durometric tests). This allowed us to extend in a non-destructive and cost-effective mode the results of the previous tests. The correlation curve that matches the values of V vs. Rc obtained from the tests carried out on two of the pavilions is plotted as an example (Fig. 4). The first correlation presents a good square correlation coefficient (R^2), the second, with a lower R^2 value, is therefore very similar to the previous one. The curve expressing the correlation Year of construction vs. Strength (Fig. 4), also of general interest, highlights that over time more resistant concrete has been used for the construction.

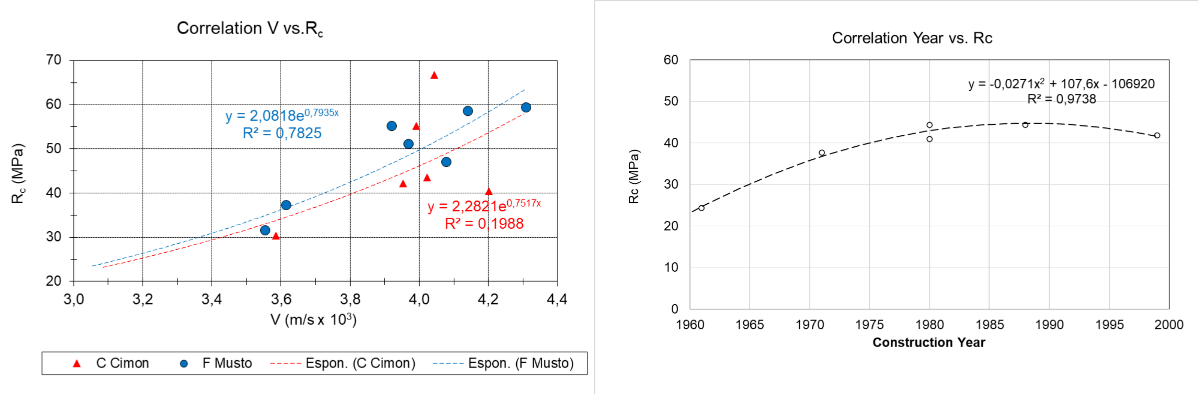
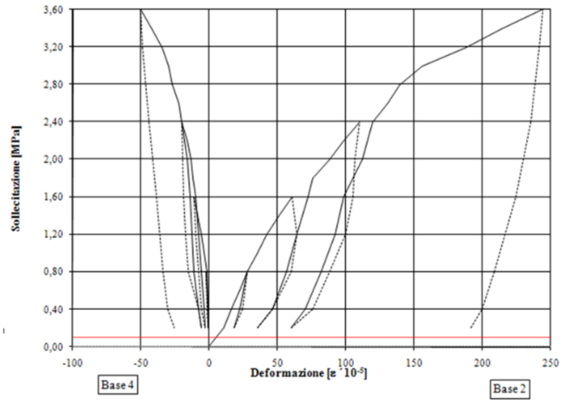


Figure 4: Correlation V vs Rc from the tests performed on three pavilions
Correlation V vs Rc and Year vs Rc from the tests performed on R.C. pavilions

For masonry buildings, the mechanical characterization was carried out by means of tests with a single flat jack [5], which allow one to measure the state of local stress, and tests with two parallel flat jacks [6], which allow one to determine the characteristics of deformability of a representative structural sample of masonry (Fig. 6). In this case the results were further extended by means of non-destructive tests (e.g. sonic and penetrometric tests on mortar joints).



	B1	B2	C1	C2
σ_v	0.26	0.72	0.17	0.04
E_{04-08}	5882	4348	3333	5000
σ_{max}	3.20	4.00	3.60	2.40
f_m	1.15	0.89	1.15	1.07

Figure 5: Tests on masonry – stress, deformability, strength of masonry and mortar [MPa]

6 BIM Modelling

The modelling of the compound was carried out with the Building Information Modelling (BIM) methodology, that make it possible to implement a parametric relational database, which can be constantly updated and modified and to which all operators can refer for the entire life of use of the building. The BIM methodology applied to an existing building [7] uses 3D modelling of a Real-Based type, and therefore the implementation took place starting from the point cloud, which allows a detailed reconstruction of the architectural shape of the buildings (Fig. 7). The model was developed up to the appropriate Level of Development (LOD = 300) [8].

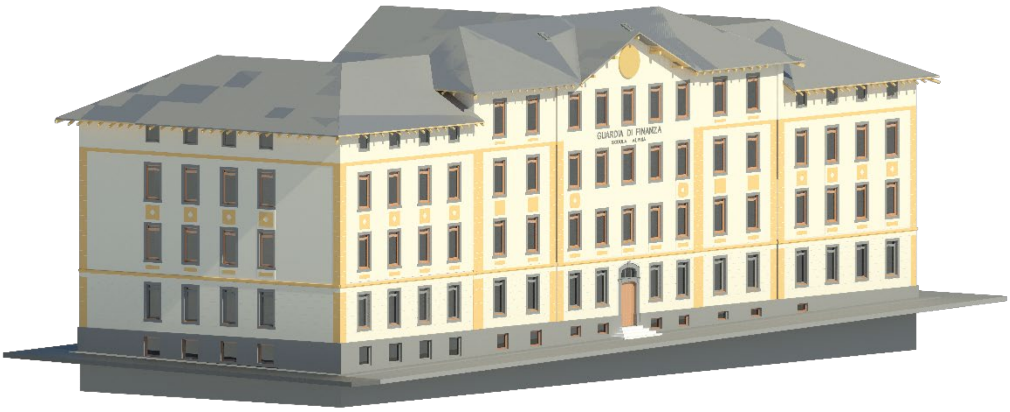


Figure 6: View of BIM model of *Macchi* barrack

The model was then integrated with the information provided by the diagnostic campaign. For example, the entire crack pattern detected was reproduced in the BIM model with the aid of systems of element adapted to the specific need, starting from families pre-existing in the software. The elements inserted in the real position of the crack simulation, its trend and the groups created by the union of the different elements have been associated with parameters that describe the peculiarities of the crack (coding, opening, severity, urgency, ..).
The BIM has to be intended as the basis of the subsequent structural modelling and of the seismic improvement / adaptation projects that have consequently been implemented.

7 Structural Modelling & Seismic Vulnerability Assessment

The structural vulnerability assessment with respect to the seismic load combinations was carried out in compliance with the current Italian Building Codes [1]. For each structural unit examined, the modeling and the analysis level were chosen in relation to the structural typology. For buildings made with reinforced concrete or concrete and masonry, the modeling was carried out with the Finite Elements Method (FEM) representing two-dimensional elements (reinforced concrete partitions and bearing walls) with "shell" elements and one-dimensional elements (beams and columns in reinforced concrete) with "beam" elements. For masonry buildings, on the other hand, two-dimensional elements (masonry walls and floor strips) were modeled through an Equivalent Frame. FEM modeling provides the distribution of internal stresses point by point, allowing to increase accuracy with the thickening of the mesh (thus requiring a greater computational burden). Equivalent Frame modeling does not provide information about the punctual stresses in the structural elements, but however guarantees a correct representation of the overall behavior of the structure.
The complexity of the model must also be appropriately correlated with the Level of Knowledge achieved: Italian legislation requires a simplified analysis in the case of a low Level of Knowledge and analyses of increasing complexity as the level of knowledge increases. In the current case history, the choice of analysis methodology was made between the following:

- dynamic linear analysis, applicable both for Equivalent Frame and for FEM modeling, for buildings mad with masonry or Reinforced Concrete; this method models a linear constitutive link for the materials and the behaviour of the structure is defined as a linear combination of the building's own vibration modes;
- static non-linear analysis, applicable only for Equivalent Frame; this method models a non-linear constitutive relationship of the materials used (difficult to define for two-dimensional elements) used only in the case of frame structures made with reinforced concrete as the modeling of the non-linear behavior of the masonry requires too complex definitions.

Whatever the type of analysis carried out, the seismic vulnerability assessment of a structure allows for the identification of its safety level by expressing the result of the analysis in terms of the Seismic Risk Indicator (SRI). It is defined [1] as the relationship between the maximum seismic action that the structure can support and the projected seismic action defined in compliance with the legislation. This indicator, tagged as ζ_E, is expressed in terms of the ratio of accelerations and have to be $\zeta_E \geq 1$ in order to consider the structure seismically adequate. Alternatively, it can be expressed in terms of the ratio of the return times that define the seismic action.

The different types of checks carried out for each structural unit under analysis, for masonry elements include: bending check in the wall panel plane, shear check by sliding, shear check by diagonal cracking and bending check in the orthogonal direction to the bearing walls.

In a similar way for Reinforced Concrete elements, they included: the verification of the potentially ductile mechanisms and the fragile mechanisms for the various structural elements (beams, pillars and partitions) and the verification of the unconfined nodes.

The global SRI of a structure equals the lower of the calculated ζ_E indicators. The buildings of the Alpine School compound provided results ranging from $\zeta_E = 0.218$ to $\zeta_E > 1.00$. It should be noted that for Reinforced Concrete structures the lower value of the SRI in almost all cases derives from the verification of un-confined nodes as the verification methods defined by the current standard are very restrictive for structures designed and built in the past, when the constructive details of the reinforcements at the nodes of the structural frames were less restrictive.

It is of extreme interest the observation that the results of the analyses highlighted how the reinforced concrete frame structures built during the 20th century according to non-seismic criteria are generally more vulnerable to seismic loads than the old masonry structures. On the other hand, for the masonry structures, low results were achieved in the case of buildings that have an irregular configuration both from the point of view of the structural geometry and from the point of view of the materials used in the construction.

8 Conclusions

The case history highlights that the Seismic Vulnerability Assessment of existing buildings does not require only tests on materials and structures, but it needs to pursue a wider path of knowledge that involves collecting more in depth historical and geometrical information. This path can be enhanced through the implementation of a BIM model, that is a parametric relational data base that collects all the information and that is very effective for the subsequent structural modelling and vulnerability assessment.

NDTs have a fundamental importance because they allow one to extend the information about constructive details and material properties and to reach, in a non-destructive and cost-effective

mode, a high Level of Knowledge (LK3 in compliance with the Italian legislation), thus reducing the Confidence Factor.
Finally it is relevant to underline that the analyses carried out in the compound allowed the design team to highlight how the Reinforced Concrete frame structures built during the 20th century according to non-seismic criteria are generally more vulnerable to seismic loads than the old masonry structures. On the other hand the masonry structures present high vulnerability specifically when they have irregular configuration both from the point of view of the geometry of the structure and of the materials used in the construction.

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