American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-4, Issue-9, pp-108-119
www.ajer.org
Research Paper Open Access

# Quali-quantitative evaluation for the definition of antiseismic recovery interventions in historical buildings.

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***ABSTRACT:*** *The evaluation of the seismic vulnerability in historical buildings represents an area of recent interest in relation to the need to define appropriate interventions to improve the quality, compatibility with the historical-architectural characters, as well as with the static behaviour. The present work shows a completion of an operational methodology for the definition and evaluation of effectiveness of antiseismic recovery interventions in historical buildings defined qualitative-quantitative approach. The methodology allows you to define a coordinated system of structural interventions, appropriate in relation to the specific historical-architectural and technical-constructive characters of these structures giving a higher degree of security. The articulation operates as to take into account both the qualitative aspects, related to the technology of construction and to the rule of the art, and the quantitative aspects of the numerical analysis of the characteristics of resistance of the structural elements. The methodological approach has found a specific validation with reference to a masonry and concrete structure: a public housing complex called "Gruppo Piave – ex Gondar" in the city of Bari (Italy).*

***Keywords -****historic masonry building, qualitative-quantitative approach, linear and nonlinear analysis, seismic vulnerability, index of elastic-seismic improvement.*

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## I. INTRODUCTION

It is known that earthquakes have always represented the main cause of damage and losses to the architectural heritage [1]. Historical buildings are characterized by an inherent vulnerability to seismic action, because anyhow masonry is not very resistant to states of traction, especially on the horizontal planes of the courses, normally compressed [2, 3]. On these, in the case of an earthquake, the horizontal action causes the weak resistance of the material to exceed for the states of tangential stress and tension, causing damages because of the sliding or the detachment of the elements [4]. In addition, the history of these buildings, marked by different construction phases, accentuates that behavior which is already inherent in the material. The growths, the superfoetations, extensions that are planimetric, determine the presence of many facilities within the same building. In this way the behavior is strongly influenced by the action that strikes them. In the case of an earthquake, the horizontal inertial forces are capable of causing the loss of balance of these elements especially if slim or not properly connected to the rest of the building. This intrinsic vulnerability is extremely fed, in some cases, by the lack of assessment of effectiveness of some new construction techniques [5] that increase the propensity on the part of historical structures to be damaged; solutions such as the remake of a reinforced concrete roof, the inclusion of curbs that are too for walls, the use of seams armed as an alternative to traditional metal tie rods, have caused higher damage in most of the cases compared to those that the original structure would probably have presented. Therefore, there is a problem of seismic safety for the historical buildings, in other words we need to assure that the structure have a capacity of resistance comparable to that required of the new constructions, both for the protection of the public safety, and for the upkeep of the property; the intervention of earthquake recovery can certainly not be a compromise between conservation of architectural building and protection of the public safety, but neither should it be the optimal synthesis [6, 7]. All this requires a proper understanding of the structure in its whole, in order to identify elements of weakness with respect to the Rule of the Art. In other words it wants to permeate the concept of structural safety of the historic buildings with all the aspects that are unlikely to be integrated within a mechanical model, even if it is refined. In this way the intervention, that comes from it, is certainly appropriate, because it poses as not a distortion of the "logic" (formal and spatial-material) of the pre-existent and in continuity with the "modal logic" (procedural) that it approves.

## II. OBJECTIVE OF THE STUDY AND METHOD

The following work presents a methodology for defining and assessing the effectiveness of interventions of earthquake recovery, defined quali-quantitative, through which improve the security level of an existing building, through a respect for its historicity. The approach selects quantitatively, as a result of dynamic analysis, combinations of interventions, adequately defined qualitatively related to conservative aspects of the product. In this way the need for conservation is not an obstacle but rather a guide to planning really effective antiseismic interventions. In other words, ways of knowledge and analysis are proposed in which the judgment on the suitability of an intervention emerges from the comparison between the ability of the structure, evaluated following a qualitative and quantitative knowledge of construction, and the seismic action. This comparison is not to be understood as binding occurs between strength of the structure and demand; on the contrary, it is attested, for each intervention, a quantitative parameter to bring into account, in conjunction with others, in a qualitative assessment that contemplates the desire to preserve the product from damage with seismic safety requirements about the enjoyment and the function [8]. The objective is to avoid unnecessary works, thus favoring the criterion of minimum intervention, but also by highlighting the cases in which it is appropriate to act more decisively. This study wants tohighlight only which can be made in full compliance with the historical nature of the construction and excluding the rest.

## III. QUALI-QUANTITATIVE METHODOLOGICAL APPROACH

The methodological approach starts from the knowledge of the structure according to three levels of different deepening, necessary both for the purposes of a reliable evaluation of the seismic safety current, and for the choice of an effective intervention to improve seismic behaviour [9]. The purpose is certainly to put in place a model that allows a qualitative interpretation of the mechanism of structural operation, as many as the real structural analysis, for a quantitative assessment. Problems are those related to the recognition of geometric data, the changes occurred in the course of time, due to the phenomena of damage, resulting from anthropic transformations, aging of materials and by natural disasters. The first level unfolds therefore in an analysis of the building, showing the data collected in appropriate forms mostly cataloguing, suitably designed, in order of:

1.1 identification of building organism in its organic structure;

1.2 characterization of the spatial and functional relationships with respect to the bordering territories;

1.3 recognition of individual building block;

1.4 understanding of evolution of transformative structure in correlation to the successive uses in the course of time, through extensive historical-archival investigations;

Of course for the purposes of proper identification of the structural system, the reconstruction of the entire building history, the construction process and the subsequent transformations, play a decisive role. Historical analysis allows both to limit the number of investigations in historically homogeneous areas, and to focus on those parts that are less known or to possible solutions of continuity, identifying simultaneously previous consolidation interventions. However, the study of the historical evolution of the building cannot be separated from knowledge of the sequence of earthquakes [10] that have involved the same product in the past; it shows a real testing from which emerges awareness on the state of seismic stress which has been subjected. A second level of analysis is oriented towards complete spatial identification and diagnostics of the organism itself, through operations both of geometric survey, strain behavior, and of study of geomorphologic and structural plan. The knowledge and characterization of these latter aspects is of great importance in the prediction of seismic behavior due to the interaction ground - foundation – structure.

In this way, the approach facilitates the next step of input of the seismic model, completed by material constructive relief of the various elements that make up the structure. It represents a cognitive framework of third level, through which acquire a detailed morphology intrinsic in the same [11]. Performed a mechanical modeling of the structure, if the analysis-verification (linear or non-linear) shows an inability of the building in order to confront the seismic acceleration while waiting for the reference site, the approach requires the definition of one or more combinations of interventions of earthquake recovery. Modeled each combination of intervention, rather than perform for each a numerical evaluation of efficacy, such as to require a significant computational burden, the approach proposes a simplification of the problem, limiting the post tests of detail to the really effective combination. More precisely, after obtaining the modal forms of each combination of intervention and state of pre-consolidation, the approach requires the formulation of an index of elastic-seismic improvement, appropriately introduced therein in order to select the combinations in terms of effectiveness, calculating it and distinguishing between two cases that require two different formulations of this index. The two cases concern buildings regular in plan and elevation and buildings that instead have geometrical and / or construction material irregularities in plan and / or elevation.

For buildings regular in plan and elevation this operator, Eq. (1) is configured for each combination of intervention, such as normalized ratio between total pseudo- acceleration of consolidation and pre-consolidation. Both pseudo - accelerations derive from the elastic response spectrum, specific of the reference site, by a combination of partial values of accelerations, corresponding to periods relating to vibration modes with participating mass more than 1 %.

$$I_{mes} = \frac{A_{cons}}{A_{prec\,.}} = \frac{\left(\left(\sum_{i=1}^{n}\left((a_i)\cdot(m_i^*)\right)^2\right)\cdot(n_m)\right)_{cons\,.}}{\left(\left(\sum_{i=1}^{n}\left((a_i)\cdot(m_i^*)\right)^2\right)\cdot(n_m)\right)_{prec\,.}} \quad (1)$$

With: mi* = mass normalized modal, nm = number of modes involved, ai = modal pseudo-acceleration.

Instead in buildings with irregularities in plan and elevation, and wherein the second mode of vibration result of torsional type index of elastic-seismic improvement is defined as follows:

$$I_{mes} = \frac{A_{cons}}{A_{prec\,.}} = \frac{\left(\left(\sum_{i=1}^{n}\left((a_i)\cdot(m_i^*)\right)^2\right)\cdot(n_m)\cdot\beta_t^{0.65}\right)_{cons\,.}}{\left(\left(\sum_{i=1}^{n}\left((a_i)\cdot(m_i^*)\right)^2\right)\cdot(n_m)\cdot\beta_t^{0.65}\right)_{prec\,.}} \qquad (2)$$

With: $\beta t = \frac{\max\,\{MPMx';MPy'\}}{\min\,\{MPMx';MPy'\}'}.$

MPx'(%)= percentage of participating mass in the direction X 'of the torsional mode of vibration; MPy'(%)= percentage of participating mass in the direction Y 'of the torsional mode of vibration.

In equation (2) is introduced the torsional factor β_t^0.65. This factor, obtained as a result of several experimental evaluations and interpolations of statistical data, refines the estimate of the index of elastic-seismic improvement evaluating the contribution due to the torsional motion.

In both equations, with the increase of the index of elastic-seismic improvement, induced by an increase in overall elasticity with respect to the pre-consolidated condition, building attenuates its vulnerability, in other words its propensity to suffer damage. The structure dissipates part of energy into the elastic phase and leaves the remaining contribution to plastic phase. Whether working on buildings of high historical and architectural interest or on solutions with lower value but still of undeniable interest, the approach provides an opportunity to recognize the combination of effective interventions quantitatively and qualitatively consistent with the history of artifact, promoting reduced invasiveness and reversibility of the same.

## IV. REAL APPLICATION OF THE METHODOLOGICAL APPROACH

### IV.I Case of study

The methodological approach has found a specific validation with reference to a public housing complex dating back to the late thirties of the twentieth century (built between 1937 and 1940) called “Gruppo Piave – ex Gondar” in the city of Bari (Italy)(Fig.1). It is formed by two C-shaped symmetrical bodies and is isolated from other adjacent buildings. The buildings are spread over four levels above ground and one basement and show irregularities in plan and elevation. The complex has a mixed construction type with presence of load-bearing masonry and vertical and horizontal elements in reinforced concrete (floor slabs, beams, pillars, curbs) and the building is of gallery type, unusual for the city of Bari, which was chosen for economic reasons. During the war, the complex has not been damaged or modified in any way; in subsequent years, until today, the building structure has not undergone substantial changes to anything, nor the structural parts; the few interventions concern a lacking and low end maintenance and numerous accretions. Concerning the seismic history the building has undergone during its existence a series of earthquakes including some quite significant to the local context in question, with peaks of intensity at the site of the 6th degree of the MCS scale, which suggests that it has been somehow stressed, though not seriously, from the seismic action over time.

### IV.II Knowledge of the historical building

The cognitive framework of the building have been organized in three levels with increasing depth as expected from the approach and has been systematized in the drawings and schedule graphs forms. For the first level (Figs.2, 3) we proceeded with the location, general analysis and registry and relationship identification, using data from the maps, and in particular identifying the relationship and the distances to the surrounding buildings, important to assess the seismic behaviour. Extensive documentary researches were also carried out at the State Archive of Bari and at the home of the “Autonomous Institute of Public Housing of the province of Bari” and further literature searches from which have emerged a number of important documents and technical papers with which were reconstructed the story of the building and identified the structural macro - elements. In the second level (Fig.4) has been gained a complete geometric, spatial, and state of preservation identification through the historical technical drawings and the direct in situ survey. In the third level (Figs.5, 6, 7) have been examined the material - structural and mechanical properties of each structural macro – element using both parameters provided by the legislation and data obtained from diagnostic tests performed on the artifact (cover meter and thermographic tests) and the archival documents. The mechanical values [7] have been appropriately scaled by applying the confidence factors related to the masonry and the reinforced concrete that are both equal to the level of knowledge and LC2 that is corresponding to a value of Fc equal to 1.20, based on the level of detail achieved, according to the Italian regulations [4].

### IV.III Mechanical modeling and analysis

The modeling of the building under study was made according to the method SAM II (Simplified Analysis of Masonry buildings) based on a macro-elements modeling (pier elements, spandrel beam elements, joint elements) of the masonry structure, such as to enable analysis of entire buildings with a reduced computational analysis. The method idealizes a masonry wall by means of an equivalent frame constituted by pier elements (vertical axis), spandrel beam elements (horizontal axis), modeled with the introduction of rigid offsets at the ends. In order to avoid the processing of redundant data, modeling was made by considering one of the two buildings that constitute the complex "Gondar", in particular the one willing to south on Via Bruno Buozzi, this was possible given the symmetry and the complete correspondence of the geometric and material - constructive parameters of the two buildings(Fig.8). For more caution in the modeling were not considered masonry spandrel beam elements present above and below the openings, as deemed low resistance. For modeling and subsequent analysis the software CDMA Win (Computer Design of Masonries) of the STS s.r.l. which implements the method SAM II extending the three-dimensional case was used. The program is interfaced with the calculation engine Opensees (Open System for Earthquake Engineering Simulation), developed at the University of California at Berkeley, having high computing power and reliability. It follows a three-dimensional equivalent frame configuration of the various macroelements with elements, diversified according to the type of wall or element in reinforced concrete, but all linked together in joints, and solicited by the loads transmitted from the floor slabs, so as to obtain a complete and proper description of the structure together with a convenient method of modeling (for one-dimensional beam-column elements) and sufficiently suitable for the description of the behavior of masonry and reinforced concrete elements which make up the building object of study. The analysis, carried out in accordance with the regulations [1], were kind of dynamic modal and nonlinear static (pushover analysis). The verification of resistance of individual pier elements was carried out for the vertical loads and horizontal ones. For the static analysis was performed the calculation of slenderness and eccentricity of each wall. Were taken into account both the bending and the shear failure modes with the respective values of limit shifts laid down in the seismic regulations. For the seismic response analysis of the building have been used the response spectrum parameters of the area where the artifact is. The results of the analysis showed an inability of the structure to ensure the resistance to seismic action pending in the site at Limit State of Preservation of Life (SLV). In particular, the structural deficiencies are highlighted in the tabulation of data on the pushover curves generated by the software due to non-linear static analysis of the structure [12], in which are not verified at the SLV the curves corresponding to the numbers: 1, 2, 9, 10 as the demand structure displacement exceeds the capacity of the same determining the collapse. The curves in question (Figs.9, 10) correspond to a seismic action in the X direction according to the reference system established in the modeling with the software. Given the insufficient resistance to seismic action of the building a seismic recovery intervention was determined and then modeled and evaluated according to the quali - quantitative approach.

### IV.IV Evaluation of the efficacy

The analysis performed showed that the inability of the building in facing an earthquake is due to insufficient strength of the masonry elements of the same, then the intervention should be aimed at strengthening the walls. In addition, given that the unmet SLV conditions refer to seismic actions agents in the X direction according to the reference system associated with the structural model (roughly coinciding with the direction north – south in the real building) it was decided to intervene solely on the load-bearing walls with this lying posture, in order to avoid unnecessary intervention with a further stiffening of the structure and a waste of economic resources, as well as a greater impact on the artifact. The intervention chosen (Fig.11) is the traditional consolidation through the application of reinforced plaster with the use of glass fiber reinforced plastic (GFRP) nets and connectors applied on both faces of the concerned walls, selected for its reliability and effectiveness widely proven, low cost, ease of execution even for unskilled labor, the relatively small impact because of the absence of decorative and valuable historical - artistic elements in this building. The dynamic modal analysis, performed on the consolidated model, has shown an increase in resistance of the elements affected by cracking mechanisms for bending or overturning in the plane of the wall. From the analysis data on total pseudo - accelerations in the X consolidated direction necessary for the calculation of the elastic - seismic improvement index and then the qualitative evaluation of effectiveness of the intervention (Table 1) have been obtained. In addition was also made a pushover analysis in the adopted consolidated state that has further confirmed the fulfillment of the seismic demand in terms of moving for the site where the artifact is.

### IV.V Results

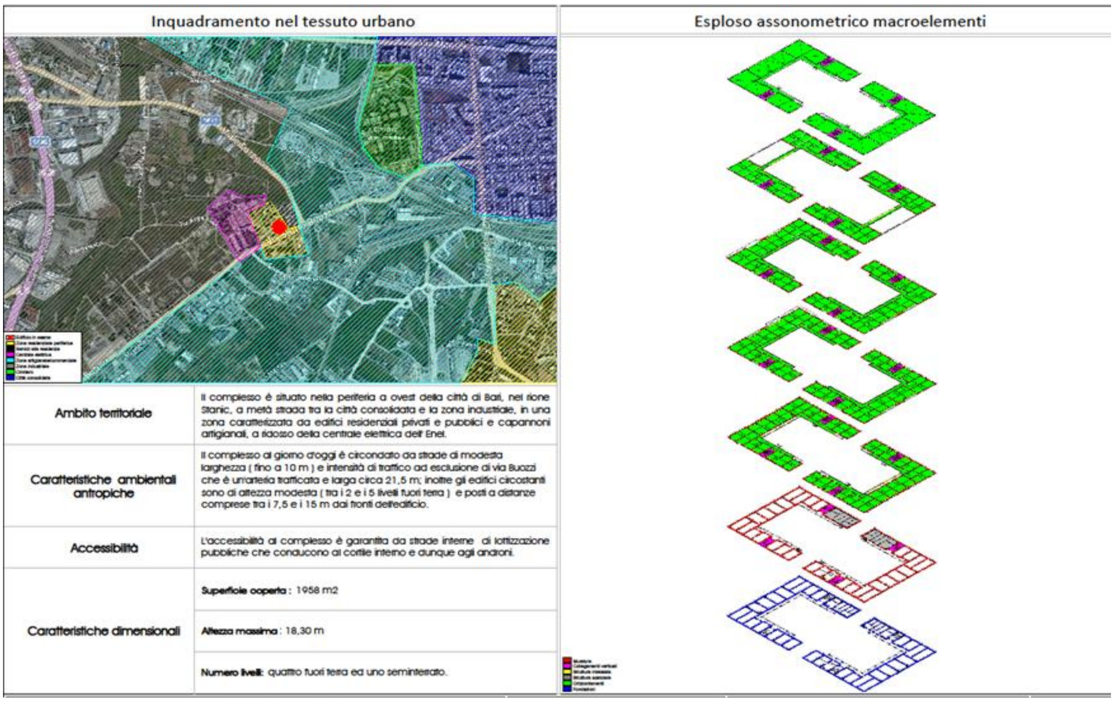
For the effectiveness assessment of the proposed intervention the elastic - seismic improvement index has been calculated according to the formulation proposed in this paper. Firstly the data of the pre – consolidated state, obtained by modal analysis, have been defined as summarized in table 2. These were compared with the consolidated state data. The results of the modal analysis of the building showed that, despite irregularities in plan and elevation, the first two modes of vibration are of bending, singular condition due to the nearly coincidence between the center of mass and center of rigidity of the structure, therefore it was possible to use the equation 1 for the definition of the index. So it is derived the elasto - seismic improvement index. Afterwards the value of the index was compared with the values of the SDOF (single degree of freedom) elastic stiffness obtained from the bilinearization of the 8 pushover curves of the investigated direction (X) in the pre- and post-intervention (Table 3). The average values of the coefficients (K *) in the two conditions were defined, then it is considered the ratio between the SDOF stiffness coefficient (K) pre and post consolidation for each pushover curve and it is compared with the ratio between the average values of the coefficients (K *) and the value of the elasto - seismic improvement index (Table 4) (Fig.12). Finally, the standard deviation between these values that is equal to approximately 1.77% has been calculated.

## V. FIGURES AND TABLES

Figure 1. Public housing complex “Gruppo Piave – ex Gondar” in Bari.

| | |
|---|---|
| Denominazione | Gruppo " Piave " - ex " Gondar ". |
| Localizzazione | Bari, rione " Stanic ", isolato compreso tra le vie Bruno Buozzi, Cassala e Cheren. |
| Coordinate geografiche | Latitudine: 41.1177582° Nord; Longitudine: 16.8378121° Est. |
| Proprietario | In parte proprietà dello IACP della Provincia di Bari, in parte dei singoli residenti. |
| Periodo di costruzione | 1937 - 1940 |
| Destinazione d'uso | Prevalente destinazione residenziale, in parte commerciale. |

Figure 2. Example module I cognitive level.



| | |
|---|---|
| Ambito territoriale | Il complesso è situato nella periferia a ovest della città di Bari, nel rione Stanic, a metà strada tra la città consolidata e la zona industriale, in una zona caratterizzata da edifici residenziali privati e pubblici e capannoni artigianali, a ridosso della centrale elettrica dell' Enel. |
| Caratteristiche ambientali antropiche | Il complesso al giorno d'oggi è circondato da strade di modesta larghezza ( fino a 10 m ) e intensità di traffico ad esclusione di via Buozzi che è un'arteria trafficata e larga circa 21,5 m; inoltre gli edifici circostanti sono di altezza modesta ( tra i 2 e i 5 livelli fuori terra ) e posti a distanze comprese tra i 7,5 e i 15 m dai fronti dell'edificio. |
| Accessibilità | L'accessibilità al complesso è garantita da strade interne di lottizzazione pubbliche che conducono al cortile interno e dunque agli androni. |
| Caratteristiche dimensionali | **Superficie coperta** : 1958 m2 |
| | **Altezza massima** : 18,30 m |
| | **Numero livelli**: quattro fuori terra ed uno seminterrato. |

Figure 3. Example module I cognitive level.

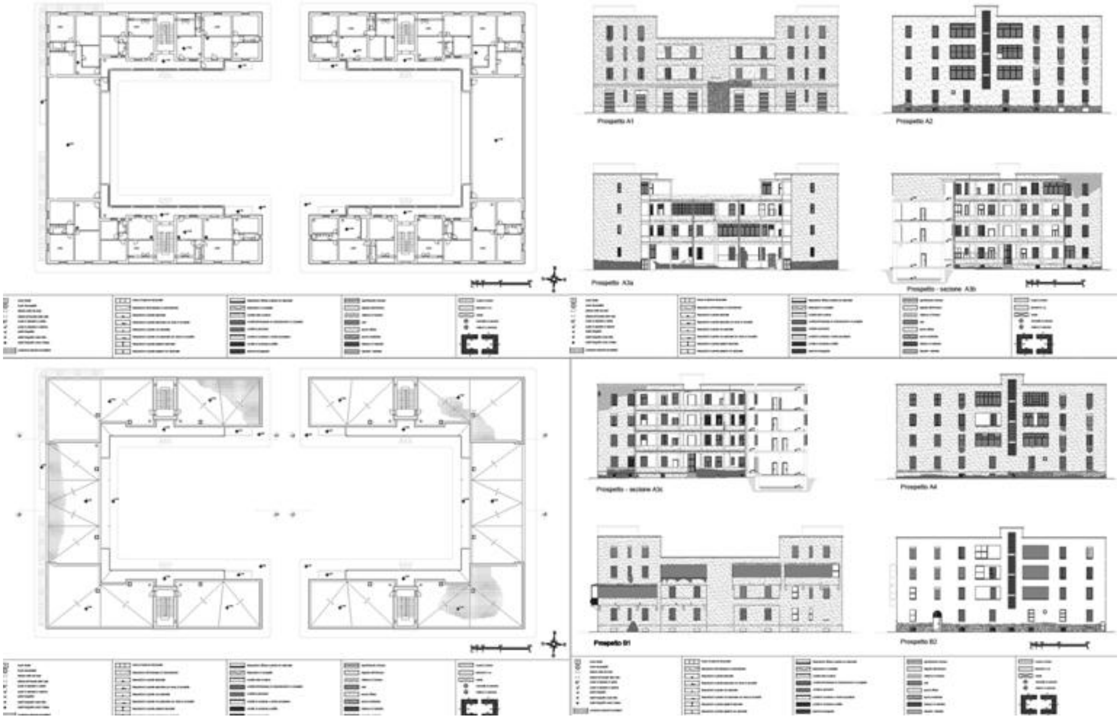
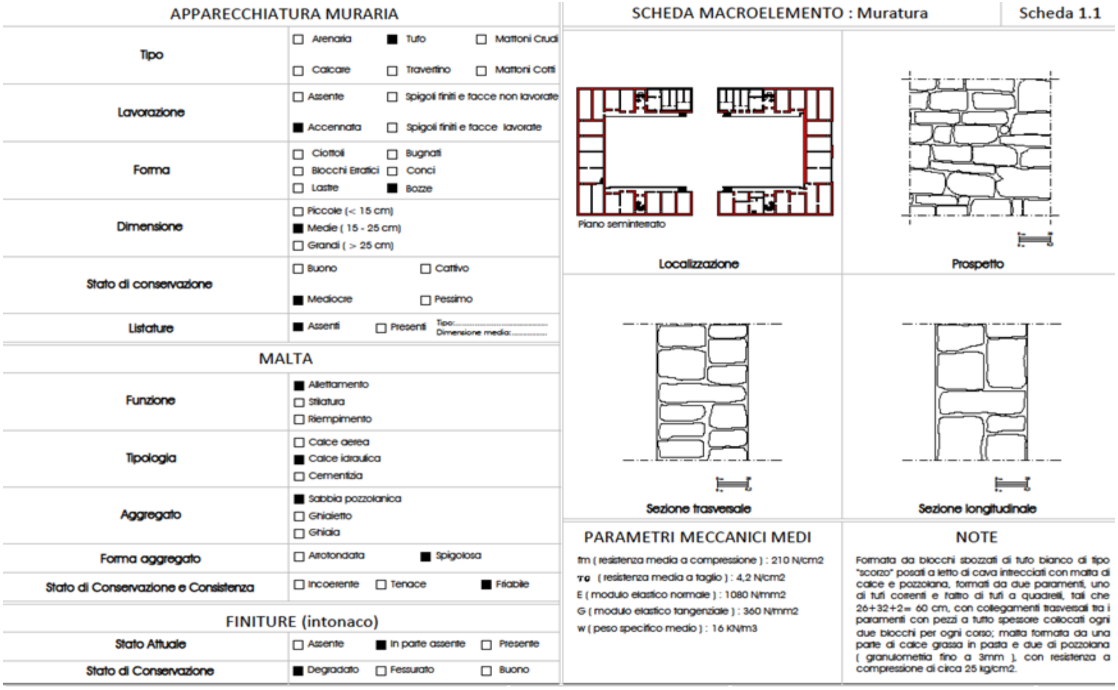


Figure 4. Example module II cognitive level.



| APPARECCHIATURA MURARIA | |
|---|---|
| **Tipo** | ☐ Arenaria ■ Tufo ☐ Mattoni Crudi<br>☐ Calcare ☐ Travertino ☐ Mattoni Cotti |
| **Lavorazione** | ☐ Assente ☐ Spigoli finiti e facce non lavorate<br>■ Accennata ☐ Spigoli finiti e facce lavorate |
| **Forma** | ☐ Ciottoli ☐ Bugnati<br>☐ Blocchi Erratici ☐ Conci<br>☐ Lastre ■ Bozze |
| **Dimensione** | ☐ Piccole (< 15 cm)<br>■ Medie ( 15 - 25 cm)<br>☐ Grandi ( > 25 cm) |
| **Stato di conservazione** | ☐ Buono ☐ Cattivo<br>■ Mediocre ☐ Pessimo |
| **Listature** | ■ Assenti ☐ Presenti Tipo:......................<br>Dimensione media:.............. |

| MALTA | |
|---|---|
| **Funzione** | ■ Allettamento<br>☐ Stilatura<br>☐ Riempimento |
| **Tipologia** | ☐ Calce aerea<br>■ Calce idraulica<br>☐ Cementizia |
| **Aggregato** | ■ Sabbia pozzolanica<br>☐ Ghiaietto<br>☐ Ghiaia |
| **Forma aggregato** | ☐ Arrotondata ■ Spigolosa |
| **Stato di Conservazione e Consistenza** | ☐ Incoerente ☐ Tenace ■ Friabile |

| FINITURE (intonaco) | |
|---|---|
| **Stato Attuale** | ☐ Assente ■ In parte assente ☐ Presente |
| **Stato di Conservazione** | ■ Degradato ☐ Fessurato ☐ Buono |

SCHEDA MACROELEMENTO : Muratura | Scheda 1.1

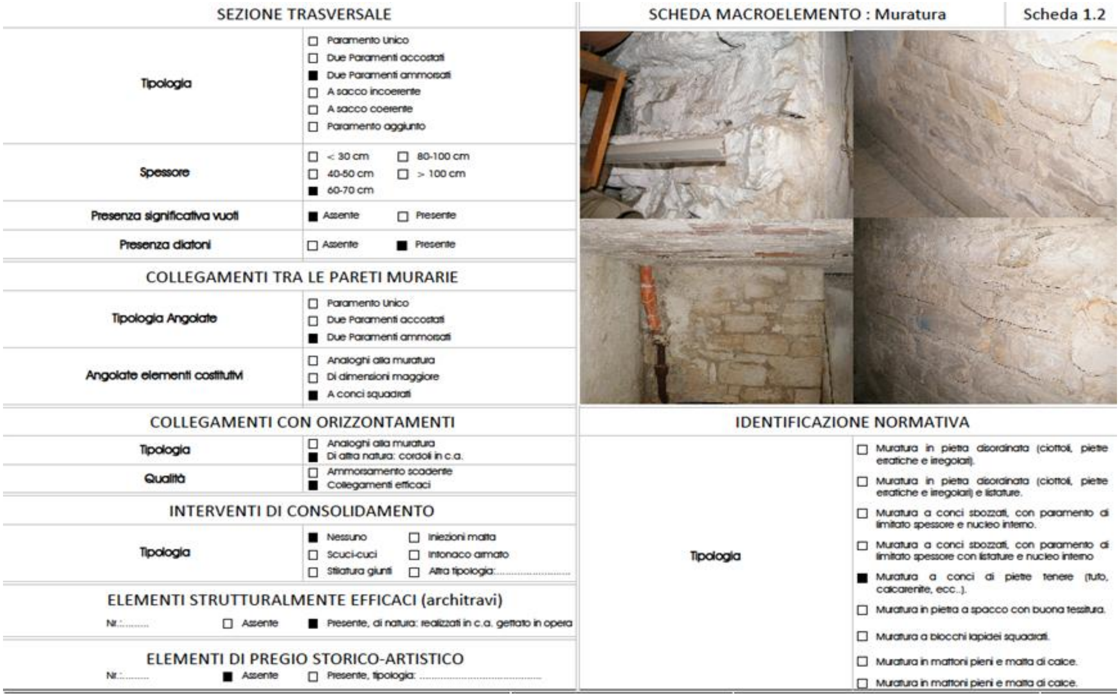
PARAMETRI MECCANICI MEDI

fm ( resistenza media a compressione ) : 210 N/cm2
τ0 ( resistenza media a taglio ) : 4,2 N/cm2
E ( modulo elastico normale ) : 1080 N/mm2
G ( modulo elastico tangenziale ) : 360 N/mm2
w ( peso specifico medio ) : 16 KN/m3

NOTE

Formata da blocchi sbozzati di tufo bianco di tipo "scorzo" posati a letto di cava intrecciati con malta di calce e pozzolana, formati da due paramenti, uno di tufi correnti e l'altro di tufi a quadrelli, tali che 26+32+2= 60 cm, con collegamenti trasversali tra i paramenti con pezzi a tutto spessore collocati ogni due blocchi per ogni corso; malta formata da una parte di calce grassa in pasta e due di pozzolana ( granulometria fino a 3mm ), con resistenza a compressione di circa 25 kg/cm2.

Figure 5. Example module III cognitive level.



| SEZIONE TRASVERSALE | |
|---|---|
| **Tipologia** | ☐ Paramento Unico<br>☐ Due Paramenti accostati<br>■ Due Paramenti ammorsati<br>☐ A sacco incoerente<br>☐ A sacco coerente<br>☐ Paramento aggiunto |
| **Spessore** | ☐ < 30 cm ☐ 80-100 cm<br>☐ 40-50 cm ☐ > 100 cm<br>■ 60-70 cm |
| **Presenza significativa vuoti** | ■ Assente ☐ Presente |
| **Presenza diatoni** | ☐ Assente ■ Presente |

| COLLEGAMENTI TRA LE PARETI MURARIE | |
|---|---|
| **Tipologia Angolate** | ☐ Paramento Unico<br>☐ Due Paramenti accostati<br>■ Due Paramenti ammorsati |
| **Angolate elementi costitutivi** | ☐ Analoghi alla muratura<br>☐ Di dimensioni maggiore<br>■ A conci squadrati |

| COLLEGAMENTI CON ORIZZONTAMENTI | |
|---|---|
| **Tipologia** | ☐ Analoghi alla muratura<br>■ Di altra natura: cordoli in c.a. |
| **Qualità** | ☐ Ammorsamento scadente<br>■ Collegamenti efficaci |

| INTERVENTI DI CONSOLIDAMENTO | |
|---|---|
| **Tipologia** | ■ Nessuno ☐ Iniezioni malta<br>☐ Scuci-cuci ☐ Intonaco armato<br>☐ Stilatura giunti ☐ Altra tipologia:.......................... |

ELEMENTI STRUTTURALMENTE EFFICACI (architravi)

Nr.:.......... ☐ Assente ■ Presente, di natura: realizzati in c.a. gettato in opera

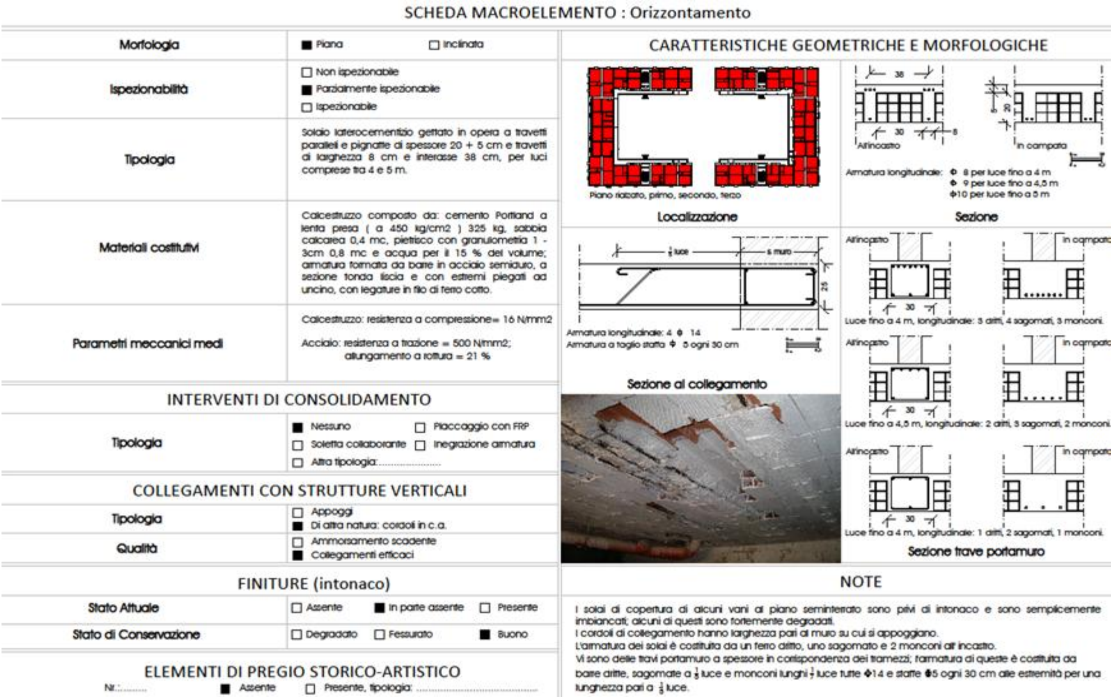
ELEMENTI DI PREGIO STORICO-ARTISTICO

Nr.:.......... ■ Assente ☐ Presente, tipologia: ..............................................

SCHEDA MACROELEMENTO : Muratura | Scheda 1.2

| IDENTIFICAZIONE NORMATIVA | |
|---|---|
| **Tipologia** | ☐ Muratura in pietra disordinata (ciottoli, pietre erratiche e irregolari).<br>☐ Muratura in pietra disordinata (ciottoli, pietre erratiche e irregolari) e listature.<br>☐ Muratura a conci sbozzati, con paramento di limitato spessore e nucleo interno.<br>☐ Muratura a conci sbozzati, con paramento di limitato spessore con listature e nucleo interno<br>■ Muratura a conci di pietre tenere (tufo, calcarenite, ecc..).<br>☐ Muratura in pietra a spacco con buona tessitura.<br>☐ Muratura a blocchi lapidei squadrati.<br>☐ Muratura in mattoni pieni e malta di calce.<br>☐ Muratura in mattoni pieni e malta di calce. |

Figure 6. Example module III cognitive level.



SCHEDA MACROELEMENTO : Orizzontamento

| | |
|---|---|
| **Morfologia** | ■ Piana ☐ Inclinata |
| **Ispezionabilità** | ☐ Non ispezionabile<br>■ Parzialmente ispezionabile<br>☐ Ispezionabile |
| **Tipologia** | Solaio laterocementizio gettato in opera a travetti paralleli e pignatte di spessore 20 + 5 cm e travetti di larghezza 8 cm e interasse 38 cm, per luci comprese tra 4 e 5 m. |
| **Materiali costitutivi** | Calcestruzzo composto da: cemento Portland a lenta presa ( a 450 kg/cm2 ) 325 kg, sabbia calcarea 0,4 mc, pietrisco con granulometria 1 - 3cm 0,8 mc e acqua per il 15 % del volume; armatura formata da barre in acciaio semiduro, a sezione tonda liscia e con estremi piegati ad uncino, con legature in filo di ferro cotto. |
| **Parametri meccanici medi** | Calcestruzzo: resistenza a compressione= 16 N/mm2<br>Acciaio: resistenza a trazione = 500 N/mm2; allungamento a rottura = 21 % |

INTERVENTI DI CONSOLIDAMENTO

| | |
|---|---|
| **Tipologia** | ■ Nessuno ☐ Placcaggio con FRP<br>☐ Soletta collaborante ☐ Inegrazione armatura<br>☐ Altra tipologia:...................... |

COLLEGAMENTI CON STRUTTURE VERTICALI

| | |
|---|---|
| **Tipologia** | ☐ Appoggi<br>■ Di altra natura: cordoli in c.a. |
| **Qualità** | ☐ Ammorsamento scadente<br>■ Collegamenti efficaci |

FINITURE (intonaco)

| | | | |
|---|---|---|---|
| **Stato Attuale** | ☐ Assente | ■ In parte assente | ☐ Presente |
| **Stato di Conservazione** | ☐ Degradato | ☐ Fessurato | ■ Buono |

ELEMENTI DI PREGIO STORICO-ARTISTICO

Nr.:.......... ■ Assente ☐ Presente, tipologia: ........................................

CARATTERISTICHE GEOMETRICHE E MORFOLOGICHE

Piano rialzato, primo, secondo, terzo

**Localizzazione**

Armatura longitudinale: Φ 8 per luce fino a 4 m
Φ 9 per luce fino a 4,5 m
Φ10 per luce fino a 5 m

**Sezione**

Armatura longitudinale: 4 Φ 14
Armatura a taglio staffa Φ 5 ogni 30 cm

**Sezione al collegamento**

Luce fino a 4 m, longitudinale: 3 dritti, 4 sagomati, 3 monconi.

Luce fino a 4,5 m, longitudinale: 2 dritti, 3 sagomati, 2 monconi.

Luce fino a 4 m, longitudinale: 1 dritti, 2 sagomati, 1 monconi.

**Sezione trave portamuro**

NOTE

I solai di copertura di alcuni vani al piano seminterrato sono privi di intonaco e sono semplicemente imbiancati; alcuni di questi sono fortemente degradati.
I cordoli di collegamento hanno larghezza pari al muro su cui si appoggiano.
L'armatura dei solai è costituita da un ferro dritto, uno sagomato e 2 monconi all'incastro.
Vi sono delle travi portamuro a spessore in corrispondenza dei tramezzi; l'armatura di queste è costituita da barre dritte, sagomate a $\frac{1}{5}$ luce e monconi lunghi $\frac{1}{7}$ luce tutte Φ14 e staffe Φ5 ogni 30 cm alle estremità per una lunghezza pari a $\frac{1}{5}$ luce.

Figure 7. Example module III cognitive level.

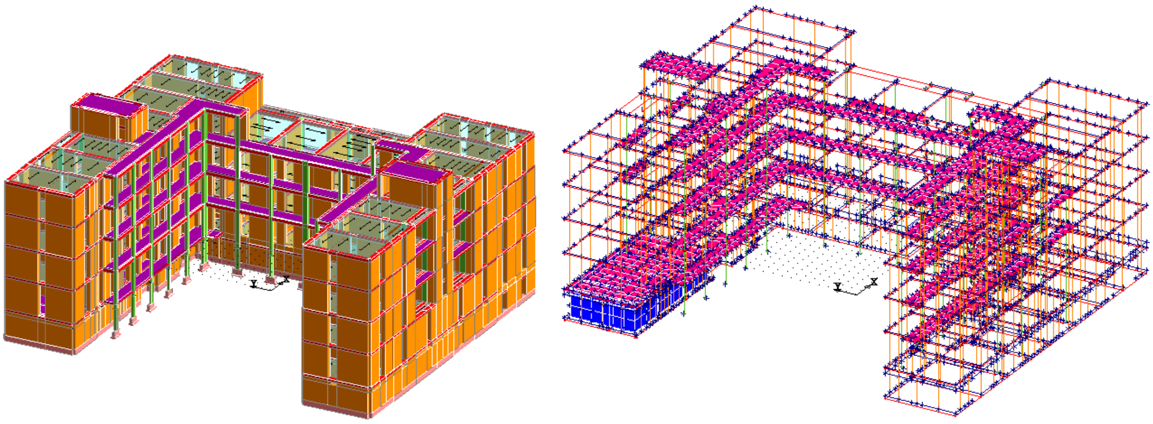


Figure 8. Three-dimensional mechanical modeling of the building.

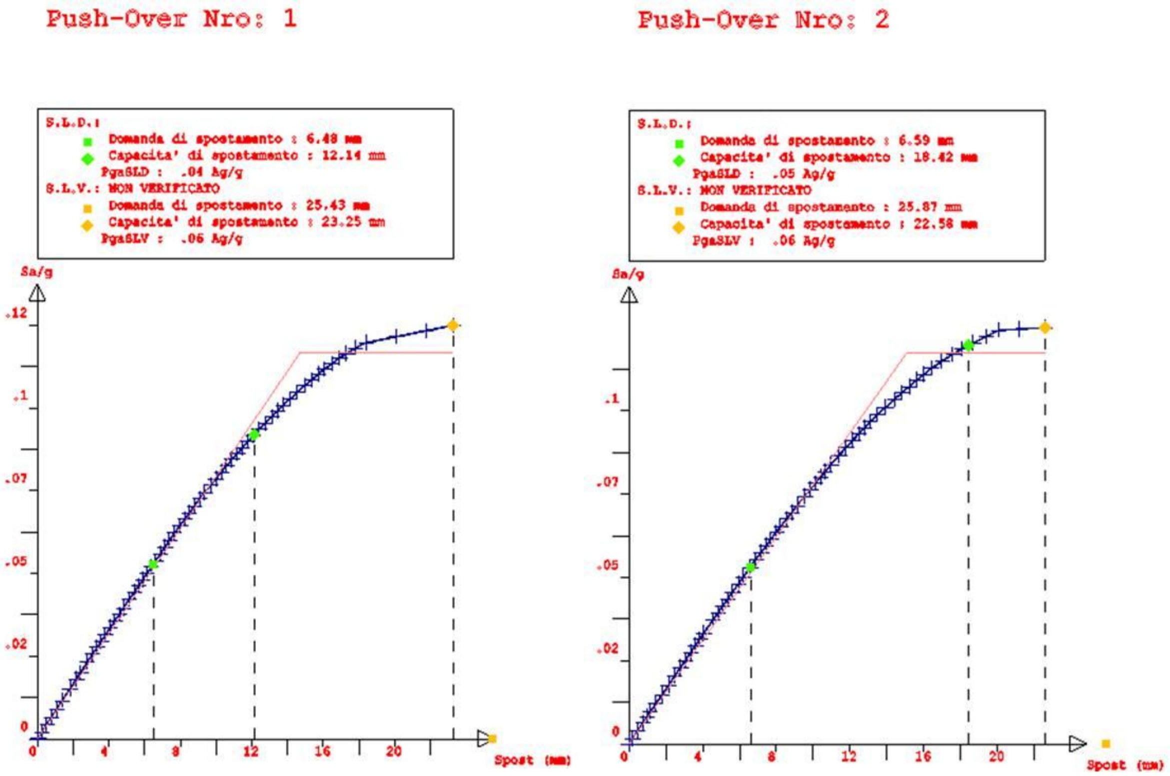


Figure 9. Unverified pushover curves, pre-consolidation state, X direction.

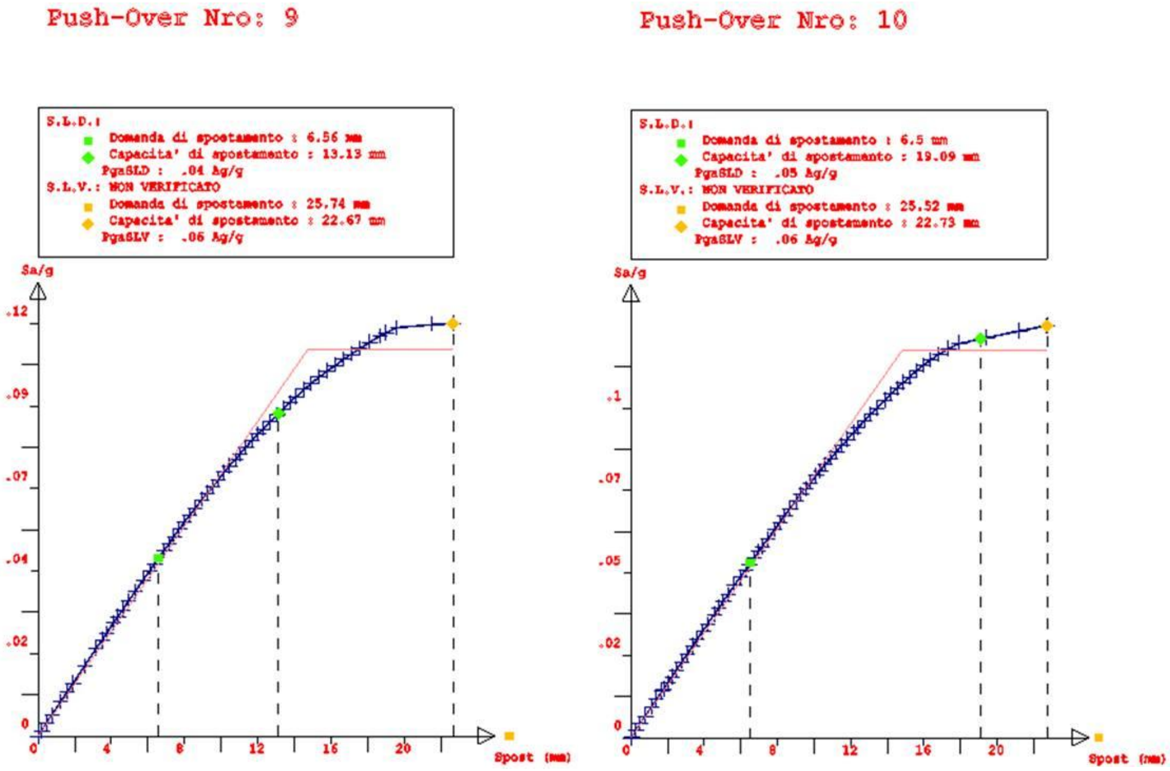


Figure 10. Unverified pushover curves, pre-consolidation state, X direction.

Figure 11. Localization of the seismic improvement intervention.

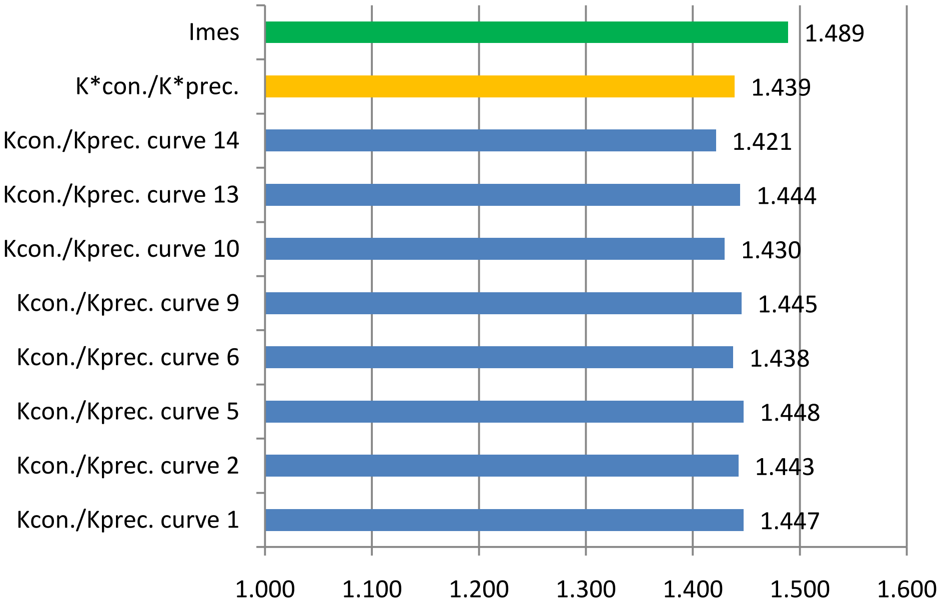
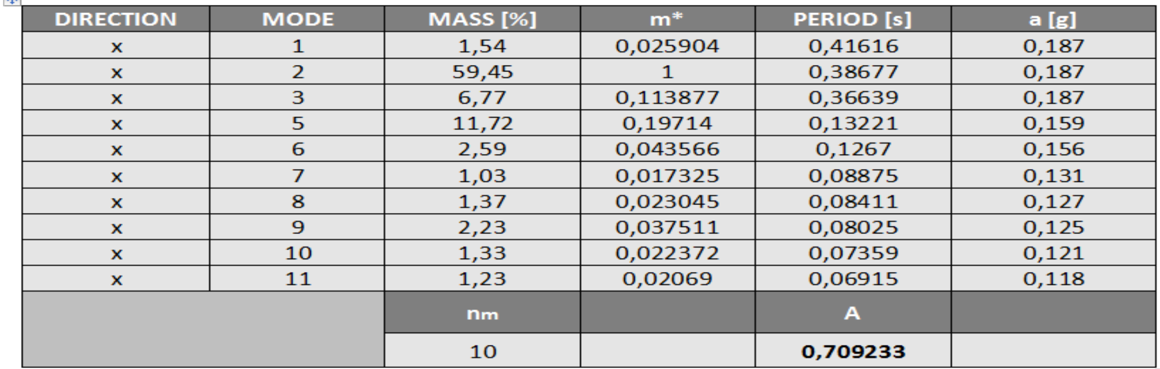
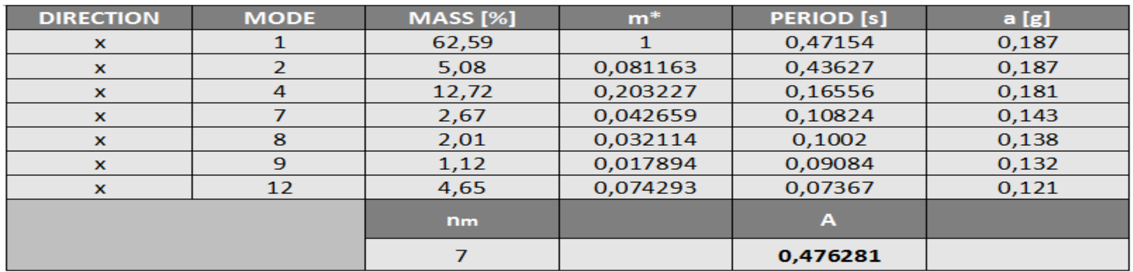


Figure 12. Graph comparing the values of the ratios between coefficients of elastic stiffness in pre and consolidated state for each pushover curve in the X direction and between their mean values and the elastic - seismic improvement index.



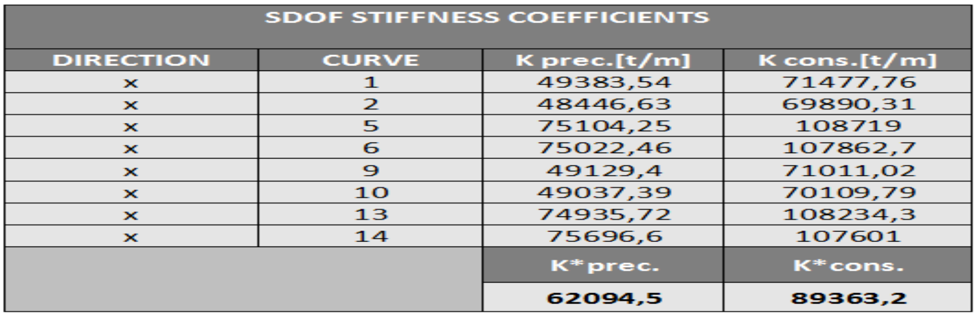
| DIRECTION | MODE | MASS [%] | m* | PERIOD [s] | a [g] |
|---|---|---|---|---|---|
| x | 1 | 1,54 | 0,025904 | 0,41616 | 0,187 |
| x | 2 | 59,45 | 1 | 0,38677 | 0,187 |
| x | 3 | 6,77 | 0,113877 | 0,36639 | 0,187 |
| x | 5 | 11,72 | 0,19714 | 0,13221 | 0,159 |
| x | 6 | 2,59 | 0,043566 | 0,1267 | 0,156 |
| x | 7 | 1,03 | 0,017325 | 0,08875 | 0,131 |
| x | 8 | 1,37 | 0,023045 | 0,08411 | 0,127 |
| x | 9 | 2,23 | 0,037511 | 0,08025 | 0,125 |
| x | 10 | 1,33 | 0,022372 | 0,07359 | 0,121 |
| x | 11 | 1,23 | 0,02069 | 0,06915 | 0,118 |
| | | nm | | A | |
| | | 10 | | **0,709233** | |

Table 1. Definition of total pseudo-acceleration of consolidation.



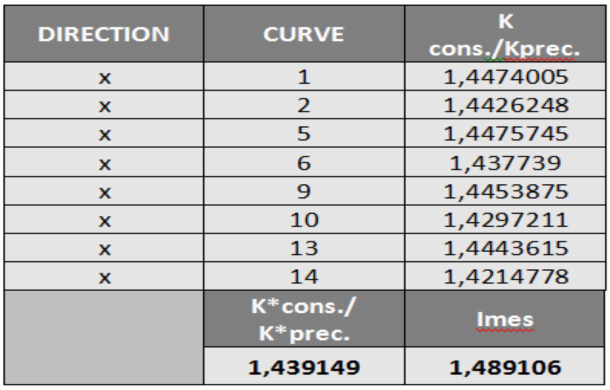
| DIRECTION | MODE | MASS [%] | m* | PERIOD [s] | a [g] |
|---|---|---|---|---|---|
| x | 1 | 62,59 | 1 | 0,47154 | 0,187 |
| x | 2 | 5,08 | 0,081163 | 0,43627 | 0,187 |
| x | 4 | 12,72 | 0,203227 | 0,16556 | 0,181 |
| x | 7 | 2,67 | 0,042659 | 0,10824 | 0,143 |
| x | 8 | 2,01 | 0,032114 | 0,1002 | 0,138 |
| x | 9 | 1,12 | 0,017894 | 0,09084 | 0,132 |
| x | 12 | 4,65 | 0,074293 | 0,07367 | 0,121 |
| | | nm | | A | |
| | | 7 | | **0,476281** | |

Table 2. Definition of total pseudo-acceleration of pre-consolidation.



| SDOF STIFFNESS COEFFICIENTS | | | |
|---|---|---|---|
| DIRECTION | CURVE | K prec.[t/m] | K cons.[t/m] |
| x | 1 | 49383,54 | 71477,76 |
| x | 2 | 48446,63 | 69890,31 |
| x | 5 | 75104,25 | 108719 |
| x | 6 | 75022,46 | 107862,7 |
| x | 9 | 49129,4 | 71011,02 |
| x | 10 | 49037,39 | 70109,79 |
| x | 13 | 74935,72 | 108234,3 |
| x | 14 | 75696,6 | 107601 |
| | | K* prec. | K* cons. |
| | | **62094,5** | **89363,2** |

Table 3. SDOF stiffness coefficients related to the pre-consolidated and consolidated state.



| DIRECTION | CURVE | K cons./Kprec. |
|---|---|---|
| x | 1 | 1,4474005 |
| x | 2 | 1,4426248 |
| x | 5 | 1,4475745 |
| x | 6 | 1,437739 |
| x | 9 | 1,4453875 |
| x | 10 | 1,4297211 |
| x | 13 | 1,4443615 |
| x | 14 | 1,4214778 |
| | K*cons./ K*prec. | Imes |
| | **1,439149** | **1,489106** |

Table 4. Ratio between the stiffness coefficients SDOF relating to the consolidated and pre-consolidated state and comparison with the ratio between their average values and the elastic - seismic improvement index.

## VI. CONCLUSION

The study has helped to develop and perfect a practice for the selection of seismic recovery interventions in the historical buildings, assuring simultaneously safety and conservation of the structure. The complexity of the buildings, which have been chosen for the analysis, together with further tests carried out on other equivalent structures, has allowed us to test the applicability of the approach as a tool to address in overcoming of seismic risk at the territorial level. The elastic-seismic improvement index has been validated through the pushover analysis, which confirmed that the increase of the index, represents the increase of the elastic stiffness and the decrease of the oscillation period of the structure, resulting in an attenuation of the request displacement expected for the site and therefore a reduction of the seismic vulnerability of the building. The study has also shown how the reliability of the evaluation approach is strongly influenced by the level of knowledge of the construction. The approach is therefore a tool able to grasp, with a reduced computational burden and an appropriate level of accuracy, the response in terms of improving the seismic vulnerability of the historical buildings, otherwise punishable by methodologies of much more complex analyses. For this way, it can be considered that the proposed approach, together with other practices for the assessment and mitigation of seismic risk, is capable to drive the design of interventions in existing buildings.

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