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NUMERICAL MODELLING, ANALYSIS AND RETROFIT OF THE HISTORICAL MASONRY BUILDING "LA SAPIENZA"

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Abstract. *The evaluation of the structural safety and seismic vulnerability of historical masonry buildings represents one of the most important problems affecting countries, like Italy, characterized by a wide cultural heritage whose original configuration shall be preserved against unexpected seismic events or insufficient maintenance. Recent earthquakes in the Italian regions (Umbria-Marche 1997, Molise 2002, L'Aquila 2009 and Emilia-Romagna 2012) evidenced the high vulnerability of historical masonry buildings, severely damaged in both their structural and not-structural components (i.e. walls, vaults, domes, arches, ornaments and others) and the following significant economic effort required for the execution of retrofit interventions. According to the actual Italian Standard for Constructions (D.M. 14/01/2008) and to the Guidelines provided by the Italian Ministry for Infrastructures for the evaluation and reduction of seismic risk on historical heritage (2010), a multi-level approach is generally adopted for the assessment of the structural safety and seismic vulnerability of ancient masonry buildings and for the design of retrofit interventions. In the present work, the above mentioned multi-level approach is applied to "La Sapienza" Palace in Pisa (Italy). The building, ancient seat of the University of Pisa, was subjected to a wide in situ structural survey and to experimental testing campaigns (including geotechnical analyses, mechanical characterization of materials, structural monitoring and other) allowing the elaboration of a reliable FEM model used for the execution of structural verifications and for the individuation of the main retrofit techniques able to preserve its original nature providing, at the same time, a sufficient margin of structural safety.*

1 INTRODUCTION

The evaluation of the static safety and seismic vulnerability of existing buildings represents one of the most important topics in Italy, country characterized by a wide architectural heritage made up of buildings realized without the adoption of suitable measures against horizontal actions, following different and overlapping construction techniques and frequently characterized by the lack of adequate maintenance. Recent seismic events (such as L'Aquila 2009, Umbria-Marche 1997 and Emilia-Romagna 2012) evidenced the high vulnerability of the existing masonry heritage, as well as the need to define suitable strategies for modifying, improving or locally reinforcing structures (or portions of them), without altering their original architectural characteristics but providing, at the same time, a sufficient margin of structural safety.

During the centuries, historical masonry buildings often underwent severe modifications, expansions, enlargements and super-elevations that transformed their original configuration of "*single buildings*" into "*structural aggregates*", made up of different parts connected together without specific devices and not necessarily working in a global way, with the possible following activation of local mechanisms especially in presence of dynamic actions, such as overturning of facades, tilting of corners and others. As a consequence of what above presented, there is a clear and pressing need to execute extensive static safety and seismic vulnerability evaluations, with particular attention to buildings of historical-architectural importance, in order to organize suitable retrofit operations.

Current Italian and international standards for constructions [1, 2, 3] provide a codified procedure for the vulnerability analysis and the planning of readjustment/improvement operations for existing buildings. Such procedure is based on the definition of a *"Level of Knowledge"* of the structure, achieved through structural and geometrical surveys, critical historical analyses and determinations of the material mechanical properties. According to this level, a specific degree of uncertainty is attributed to the execution of safety checks and to the organization of the retrofit proposals. The aforesaid approach, commonly adopted for 'ordinary' structures (both masonry or r.c. ones), can be extended to historical-monumental buildings by accounting for their greater complexity and the following need of a very deep level of knowledge.

A number of examples of evaluations of the seismic behaviour of monumental buildings are presented in the current scientific literature [4, 5, 6]. Within the framework of the European project "Perpetuate" [7, 8, 9], a displacement-based approach for the vulnerability analysis of existing monumental buildings was provided. Wide-scale analyses of historical villages (or portion thereof), to be executed in parallel with the adoption of macroseismic intensity maps in order to assess the behaviour of buildings, to define vulnerability curves and to finally identify the most vulnerable constructions for which the organization of retrofit interventions can be considered a priority, were also proposed [10, 11].

Oliveira [12] strongly discussed the problem of the numerical modelling of complex buildings, evidencing the possibility to adopt many different possible approaches (linear and nonlinear one-dimensional models for individual elements, 2-D and 3-D models for entire building complexes, etc.), as well as the difficulty of determining the most appropriate methodology for each specific case. Despite the ever-more refined and accurate numerical models made possible by modern calculation software, significant uncertainties remain regarding the correct representation of the materials' mechanical properties and the dynamic behaviour of the entire building or portions thereof.

In this context, Italian Technical Regulations for Constructions [1], together with the "Guidelines of the Ministry of Culture and Heritage" [13], underlines the necessity to analyze, in parallel to the global behaviour of such structural aggregates, the possible activation of local collapse mechanisms of significant structural portions, identified on the base of the critical points and of the cracking scenario revealed during the in situ survey. According to the proposed approach, different evaluation levels of seismic safety, associated to different degrees of investigation/knowledge of the building, can be related to different safety checks, ranging from large-scale evaluations, to the formulation of macroelement models for structurally independent portions of the complex under study and to the execution of safety checks on specific global models of the individual buildings.

In the present paper the methodology developed and refined for assessing the static safety and seismic vulnerability of the Pisa "*Palazzo della Sapienza*", historical site of the University since the 14th century, is presented. Moreover, some general proposals for the retrofit interventions are provided. The verification of the structural safety of a building as complex as the one considered cannot be performed simply based on traditional approaches based on global numerical modelling: methods specifically developed for the particular construction, based on an extensive knowledge of the structure's current state acquired through a multidisciplinary approach that combines historical studies of the building's evolution, morphological-structural-geotechnical surveys, experimental determinations of materials' properties and structural monitoring, are then needed. More in detail, accurate critical historical studies and detailed architectural surveys through both direct and indirect techniques allows the determination of the structural units and of their connections in the whole building. The information obtained through the morphological-structural surveys allow the elaboration of reliable numerical models (both at local and global level) for evaluating the static and seismic behaviour of the entire building and portions thereof, and the following determination of the suitable retrofit techniques to be used for the whole building, for its portion of it or for single structural elements. Figure 1 shows the general scheme adopted for the assessment and retrofit of Palazzo La Sapienza in Pisa.

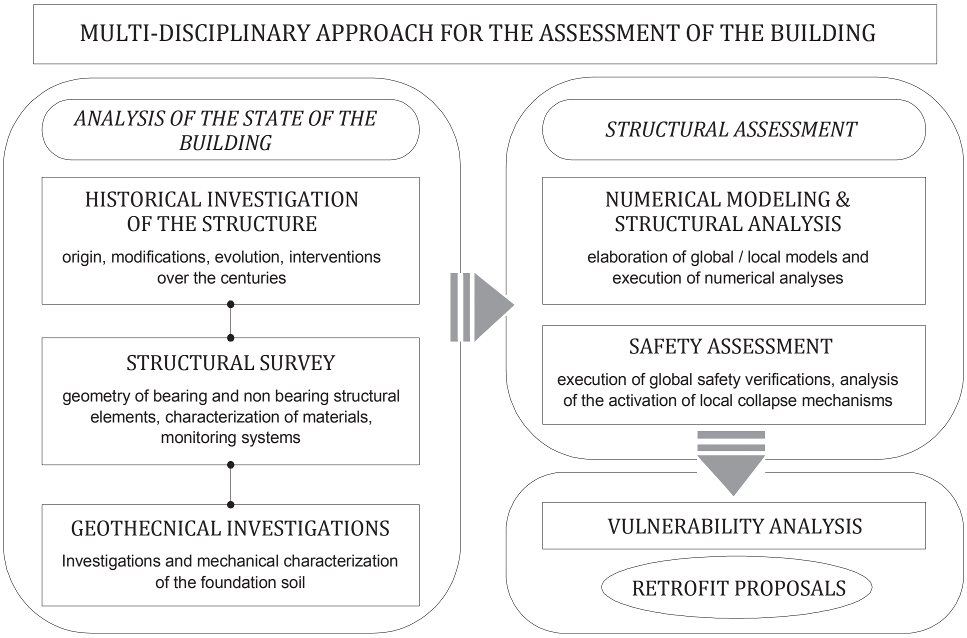


Figure 1: Scheme of the adopted methodology − integrated approach.

2 PALAZZO LA SAPIENZA: ORIGIN AND STATE OF ART

The building, originated from the medieval structures of *Piazza del Grano* and of *Dogana del Sale* adsorbing the adjacent single masonry units and ancient tower houses, was progressively extended, during the XV century, to house the seat of the University of Pisa and all the connected services. A significant modification in the original structure of the Palace was applied at the beginning of the XIX century, with the necessity to increase the available place for the books owned by the University Library (about 30.000 volumes). The works necessary for the enlargement of the building, including the demolition of many internal bearing walls, the super-elevation of the west part of the building of about 3.0 m, the modification of shape and dimensions of doors and windows, the realization of new storey slabs and others, started in 1819 and continued for about three years, immediately leading to structural diseases in several parts of the building: a wide cracking scenario was revealed in correspondence of the north and south-eastern parts of the building. The progressive deterioration of the building, as widely described in the ancient literature, was the direct consequence of the executed structural interventions, that neglected the original configuration of the Palace and its incapability to sustain higher loads respect to the design ones.

Nevertheless, and also despite singular interventions executed during the XIX century (i.e. the application of steel ties to reduce the horizontal thrusts due to vaults, arches and to avoid overturning mechanisms of single and multiple walls), the enlargement of the building, with the following increase of vertical loads, continued during the XX century, once again due to the increase of the University Library. Between 1928 and 1929, the western part of the building was raised up reaching the height of the adjacent parts: this intervention finally transformed the original Renaissance structure of the Palace, made up of a relative small volume of two storeys into the actual massive three storey building (Figure 2). Several additional modifications (for example the reconstruction of the vault of the new Aula Magna) were then executed as a consequence of the damages of the second world war. The detailed description of the morphological development of the building is presented in [14].

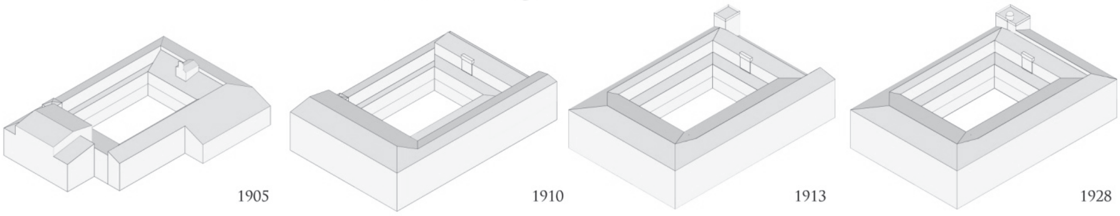
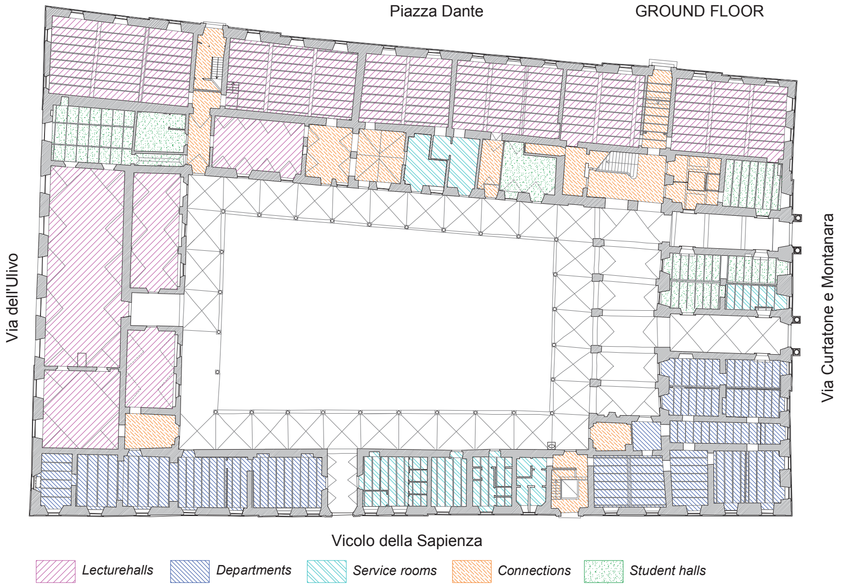


Figure 2: Structural modification of Palazzo La Sapienza during the first two decades of XIX century.

Nowadays, the building presents a trapezoidal plan with three floors above ground, with a gable roof whose garret accessible only for inspection and maintenance. The plan dimensions are 80.0 m by 53.7 m, while the central courtyard, surrounded by a ground-level colonnade and a first-floor arcade running parallel to the ground floor sides, has maximum dimensions of 35.5 m by 21.2 m. Different vaulted surfaces (i.e. cross and cloister vaults, some of them with lunettes) and various types of floor slabs (steel elements with different profiles) are present; the useful height of the ground floor varies from 4.30 m to 5.50 m. The situations are similar on the first and second floors, where the maximum heights attained are respectively equal to 5.60 m and 5.20 m, as measured during the in situ surveys.

The ground floor of the building actually houses several university classrooms, university department offices and the historical "Aula Magna". The first floor, besides more department offices and the double volume of the "Aula Magna Nuova" (not aligned with the one at ground floor), houses the University Library, which takes up the entire surface area of two sides of the building (along Piazza Dante square and Vicolo dell'Ulivo). The University Library also covers nearly the entire second floor, in part overlying the first floor sections, in part along the opposite side (along Via della Sapienza). Mezzanine floors and loft structures are, moreover, present in correspondence of the first and second floor of the library. The general plans of the building, with the indication of the different activities carried out, are presented in the Figure 3.



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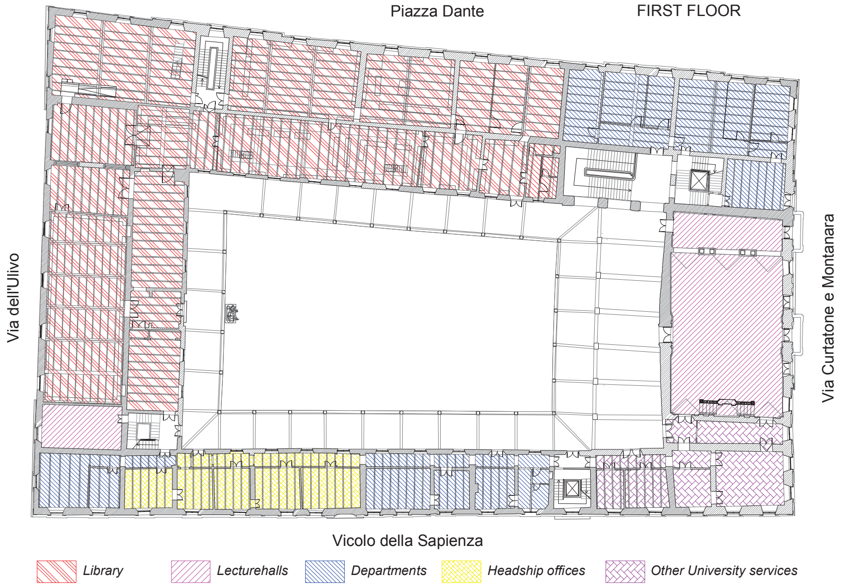

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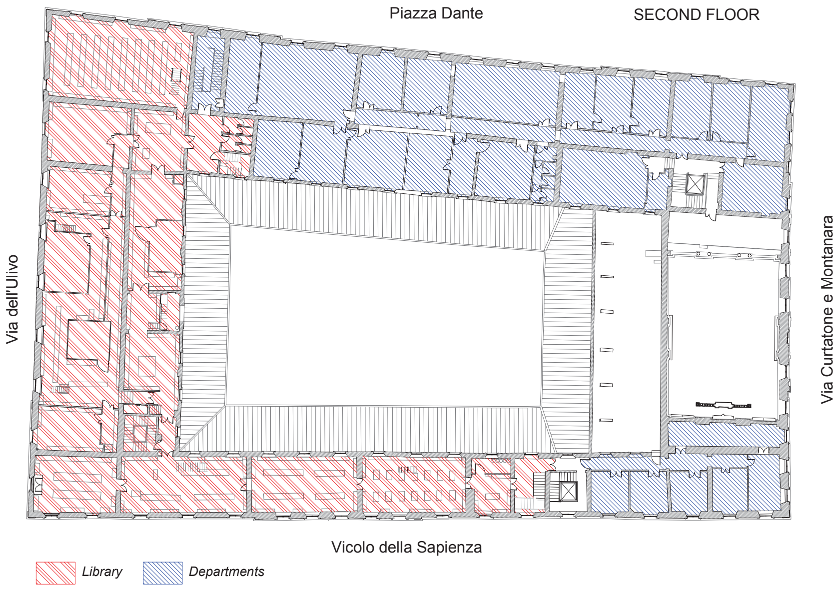

c)

Figure 3: Plans of a) ground floor, b) first and c) second floor with indication of the activities housed.

3 MORPHOLOGICAL-STRUCTURAL SURVEY OF THE BUILDING

The historical analysis of the building evidenced a series of critical structural issues affecting Palazzo della Sapienza, mainly due to the changes and transformations to which the building was subjected during the centuries, nowadays visible through widespread cracks in different portions of the construction. An extensive in situ survey campaign was executed, in order to deeply investigate the current structural condition of the building, with attention to the masonry patterns, horizontal storeys and vaults, roofing system, foundations, mechanical properties of materials and geotechnical properties of the soil.

The masonry patterns were investigated by removing 50x50 cm plaster surface with following endoscopic examinations (Figure 4), necessary to determine the presence of air spaces or adjacent facings of different thickness and type. The studies revealed the presence of 5 different types of masonry patterns (i.e. full brick, full brick and split stone, stone with brick courses, etc.) and the absence of suitable connections between perpendicular walls. The distribution of the different masonry typologies present in the building's various floors was reconstructed bearing in mind the results of the historical analysis (Figure 5). In general, the different types of masonry corresponded to the different historical stages of the building's construction and modification; for example, the area at the corner between Via Curtatone e Montanara and Via della Sapienza, originated from the building's medieval walls and tower-houses, revealed greater complexity and heterogeneity, as well as already evidenced during the historical analysis. Three experimental flat jacks tests were then executed on three different masonry typologies to determine the compressive strength of the material and to estimate the effective actual stress state on vertical elements.

Similar investigations (removal of plaster and endoscopic analyses) were also executed on vaulted surfaces, in order to define the masonry typology, the disposition of blocks and the total thickness of the filling materials. The direct in situ survey of horizontal storeys allowed the determination of the steel profiles' dimensions and of the thickness of the slabs and flooring, necessary to estimate of the effective dead load (Figure 6).

The roofing structure, consisting of trusses of different types and materials on which the secondary elements (longitudinal beams and joists) are placed to support the roof covering, is also the result of the modifications undergone by the building over the years. Steel Polonceau trusses, wooden trusses of different sizes and shapes, all presenting various degrees of deterioration in their elements are present in the different portions of the building. The poor state of maintenance, the manner in which supports between the various elements were fashioned, the presence of small full-brick walls to support the bearing elements, as well as the accumulations of construction debris and other factors evidenced the strong vulnerability of the roofing system.

Figure 4: Execution of in situ investigations on masonry walls.

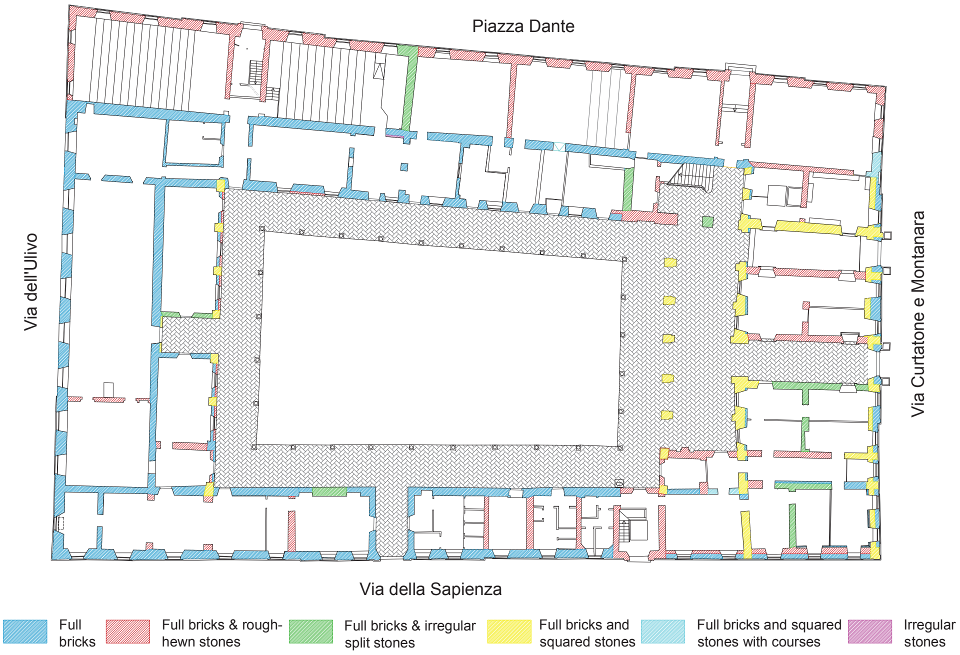

Figure 5: Plan of ground floor with indications of the various types of masonry

Figure 6: Execution of in situ investigations on horizontal floors with steel elements.

The historical analysis of the building evidenced, moreover, the instability and the non-homogeneity of the foundation soil; the continuous growth of the building highlighted the inadequacy of the foundation system in sustaining the increasing loads due to the progressive enlargements of the structure, visible through a well defined cracking scenario. In order to better analyze the state of art of the foundation system, a series of core samplings at different angles in the proximity of the masonry walls, at locations planned according to the evolutionary reconstruction of the building, were executed: different types of foundations, in terms of both size and depth, corresponded to the different stages of the building's construction. The investigations performed in correspondence to the interior colonnade revealed the absence of connections between columns, characterized by an isolated square foundation set at a depth of about 1.9 m from ground level, lower than that of the portico pillars, laid at a depth of 1.75 m below ground level. The foundation of the portico's interior walls reached different depths (ranging from 1.0 m and 1.5 m below ground level), with width varying between 1.50 and 2.40 m. The two investigations performed on the foundation structure on Vicolo dell'Ulivo provided analogous results, with foundation depths of 2.75 and 2.10 m, and widths of 1.75 and 1.60 m, respectively, while the Piazza Dante side foundation reached a depth of about 1.50 m below ground level, with a width of 0.90 m.

Based on the careful survey of the cracking scenario of both vertical walls and horizontal floors/vaults, two monitoring systems − periodic and continuous – were organized and installed in order to determine the possible evolution of the ongoing subsidence and disruptions (Figure 7). The periodic monitoring system involved fixed metal reference gauges straddling the cracks to enable measuring any further widening or narrowing of the cracks at time intervals of about 2 months. The continuous monitoring system, on the other hand, made up of electronic displacement transducers, provided a measurement for each considered point every 5 minutes, allowing the processing of collected data in graph form and the continuous checking of the ongoing cracking process. The analysis of the monitoring results enabled the identification of the areas characterized by differential displacements, such as, for instance, in correspondence to the vaults of the ground floor colonnade and first-floor arcade.

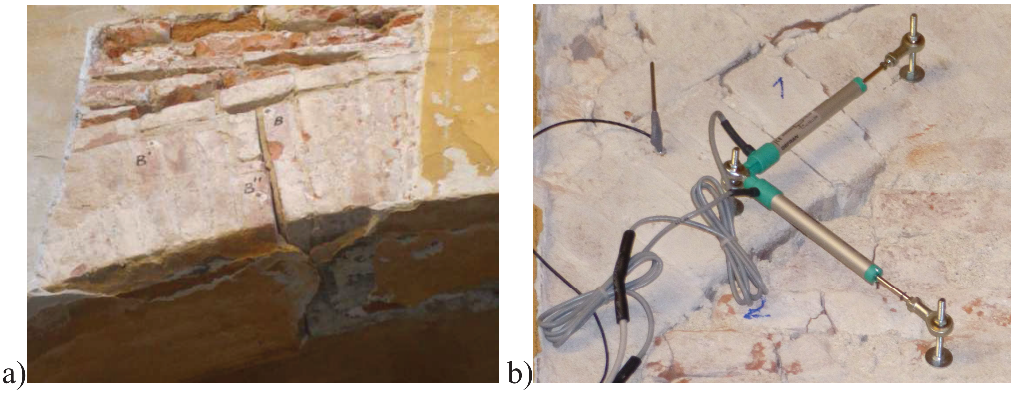

Figure 7: a) Periodic monitoring system, fixed metal reference; b) Continuous monitoring system.

4 NUMERICAL MODELLING AND ANALYSIS

4.1 Elaboration of FEM numerical model

A numerical three-dimensional model of the structure was realized in order to develop numerical analyses according to what prescribed by [1]. Such a complex building shall be considered more similar to a *"structural aggregate"* than to a single building, made up of different parts connected together during the centuries; the difficulty to model material discontinuities, disconnections between perpendicular walls, and other factors allowed the elaboration of a global numerical model that is representative of an "improved condition" of the structural system. The linear three-dimensional FEM model of the building (**Errore. L'origine riferimento non è stata trovata.**Figure 8) was realized using SAP 2000, with two-dimensional "shell" elements for the walls and one-dimensional "frame" elements for the profiles of the floor slabs, the roofing and the university library mezzanines. The vaulted surfaces were modelled with equivalent two-dimensional plane. The mechanical characteristics of the masonry material were selected according to the results of in situ flat-jack tests and to the indications contained in the Ministerial Memorandum Circ. 617/2009 [15], for the different types of masonry pattern (Table 1). The presence of cracking phenomena was conventionally taken into consideration through the reduction of the stiffness of the masonry walls [1, 16].

The interaction between the superstructure and the ground soil was represented through the Winkler model, with elastic three-directional springs calibrated according to the results of the geotechnical investigations. The horizontal stiffness (both in x and y directions) was assumed equal to the 25% of the vertical one. The stiffness of the Winkler springs was evaluated considering the effective dimension of the foundation structures and a spacing equal to 0.50 m, more or less corresponding to the discretization adopted in the model of masonry elements. The values of effective vertical stiffness (k_v) are presented in the Table 2 for the different portions of the building, being B the average width of the foundation, i the springs' spacing in the model and A the footprint of the foundation area for columns and pillars.

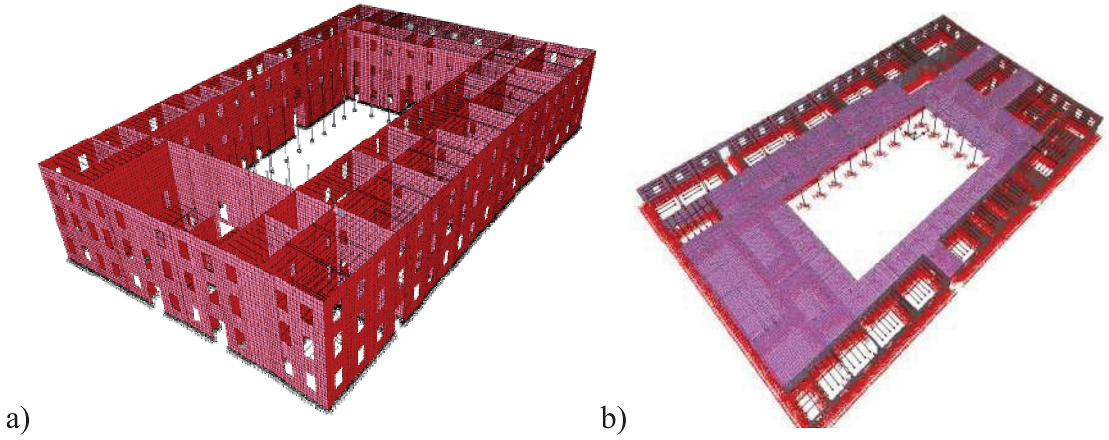

Figure 8: a) Global model, b) vaulted surfaces and frame elements of the storeys.

Masonry	σ [MPa]	E [MPa]	Notes
1 Full bricks	2.25 (*)	1500	* flat jack tests (mean values)
2 Irregular split stones	1.40	870	
3 Full bricks and rough-hewn stones	2.20 (*)	1500	* from flat jack tests
4 Full bricks and irregular split stones	2.20 (*)	1500	* type similar to (3)
5 Full bricks and squared stones	2.20 (*)	2150	* type similar to (3)
5 Full bricks and squared stones with courses	2.64 (*)	1500	* (3) improved by courses

Table 1: Resistance and elastic moduli values adopted for the various types of masonry patterns

Foundation type	K [kPa/m]	i [m]	B [M]	A [m^2]	k [N/mm]
Colonnade	32560	-	-	1.21	39398
Portico pillars	25300	-	-	1.80	45540
Via Curtatone Montanara/della Sapienza	3200	0.5	2.4	-	3840
Piazza Dante/Via Curtatone e Montanara	7600	0.5	0.9	-	3420
Other	4500	0.5	1.6	-	3600

Table 2: Rigidity values of the springs modelling the ground-to-structure interactions.

Vertical loads were determined in relation to D.M. 14.01.2008; an accurate estimation of the effective weight of the books of the libraries was also executed in order to obtain more reliable evaluations and safety checks. For what concerns the evaluation of seismic action, due to the complexity of the building, a *local seismic response analysis* under free-field conditions (i.e. neglecting the presence of the building), aiming to evaluate the response spectrum to be used for the safety checks was executed. The definition of the seismic input was performed selecting seven spectrum-compatible accelerograms, scaled according to the site's reference design acceleration [17], and applying them directly to the representative model of the subsoil of the site on which the building rests. The subsoil model employed, made up of a finite number of parallel plane layers with infinite horizontal extension, was represented by an equivalent elastic medium set on a viscous-elastic half-space representing the bedrock. Each layer, assumed to be homogeneous and isotropic, was characterized by thickness h, density ρ, a transverse rigidity modulus G and damping factor D (Table 2). Applying this subsoil model to the seismic input to the bedrock enabled the determination of the specific response spectrum for the considered site. Analysis of the local seismic response was then conducted by calculating the average effects, in terms of acceleration over time at the depth of the foundation plane, of each of the seven accelerograms selected. Figure 9 shows the elastic response spectrum for the site under examination (soil type C) in comparison to the standard spectrum for return period T_R equal to 712 years. Linear dynamic analysis was then finally performed on the Palazzo della Sapienza using the response spectrum resulting from the foregoing determinations. A behaviour factor equal to 2.25 was adopted [15], minimum value allowable for masonry structures with irregular height, quite conservative respect to the value proposed by the Guidelines for cultural heritage [13], which specify a maximum value of 2.80.

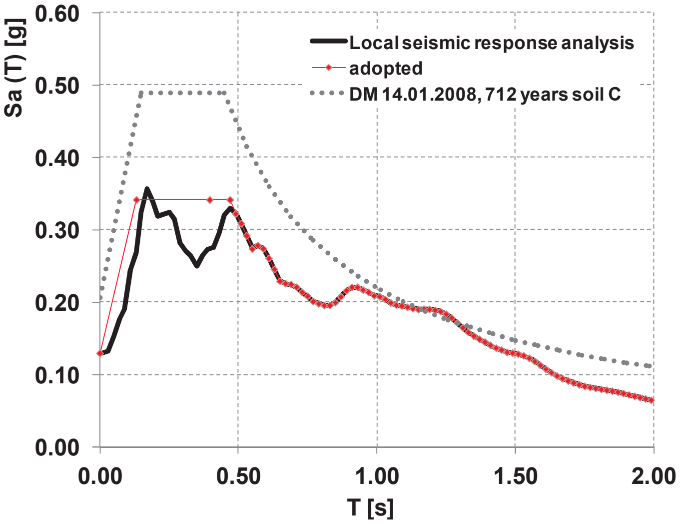

Figure 9: Elastic response spectrum results for the site in comparison to regulatory indications for type C soils.

4.2 Safety checks and evaluation of critical issues

Safety assessment was executed according to the indications provided by [1, 15]. The values of the design actions used to carry out the checks were derived from the global numerical model, which as stated, obviously cannot account for situations such as the lack of connections between perpendicular walls, discontinuities between adjacent walls or between walls and overlying vaults, the presence of air spaces, walled-off openings etc. The obtained results are therefore representative of an "enhanced" condition in comparison to the actual current state. The results of the global checks on the building are however indicative of the effective state of maintenance of the vertical walls, floors, vaults, and roofing and foundation structures.

The obtained results were combined with the ones coming from the investigations of the most significant local collapse mechanisms, allowing the attainment of a general overview of the state of art of the construction.

The global checks on masonry walls evidenced that the building essentially satisfies the safety requirements with regard to both static and seismic combinations, with the exception of extremely small-sized, slender elements characterized by a considerable heterogeneity in shape and materials and by extensive cracking due to the progressive structural layering and modifications made to the building. Relatively critical conditions were encountered in the area of the historical Aula Magna, where two of the original spaces of the colonnade were closed-up, and in the proximity of the double volume of the new Aula Magna.

Problems of out-of-plane overturning were found in correspondence to the interior wall of the 1st floor towards the arcade parallel to Piazza Dante, where the perpendicular masonry restraints were removed without taking into account their structural effects, as well as in correspondence to the wall of the double volume of the new Aula Magna.

The horizontal structures (floors), with the exception of one under-dimensioned slab on the building's second floor, did not evidence significant structural deficiencies in terms of either resistance or deformability, probably because they were realized relatively recently (during the post-war restructuring of the building). Analogous considerations can be executed for the vaulted structures, which, though presenting widespread cracking, especially in the colonnade area and in the proximity of the original Aula Magna, were able to sustain a load equal to 350 daN/m^3, as demonstrated by the in situ load tests executed.

The wooden roofing structures presented signs of widespread degradation due insect and mold damage, with consequent reduction of the resistant section of the bearing elements, with the following not satisfaction of the prescribed safety requirements. Other critical issues were linked to the presence of curtain walls supporting trusses, supports of varying shapes and types, and to the accumulation of construction debris in various areas of the garret.

Analysis and safety checks of the foundation structures, characterized by considerable geometric heterogeneity as previously presented (i.e., foundation depth and the width of the supporting base), revealed the substantial heterogeneity of the overall mechanical behaviour of the foundations, variable stiffness of the ground-foundation assemblage and different limit load values, minimal for ribbon foundations and higher in the case of isolated foundations. The unit load-subsidence diagrams for the foundation-ground assemblage for the various analyzed sections (Figure 10a) highlight the different responses of the various foundation elements as a function of the geometry, especially for unit load values below 1.0 MPa. A substantial difference in the behaviour was visible between the building's perimeter and its interior part (i.e. colonnade and pillars of the interior courtyard, Figure 10b); in the presence of either static or seismic loads, these local differences can expose the building to considerable damage in those areas with significant differences in rigidity characteristics or those subject to more heterogeneous loads.

Apart from these structural issues, many other intrinsic critical situations were identified as a consequence of the building's morphological conformation itself. Such problems were frequently aggravated by the modifications executed over the centuries in relation to the architectural and functional needs.

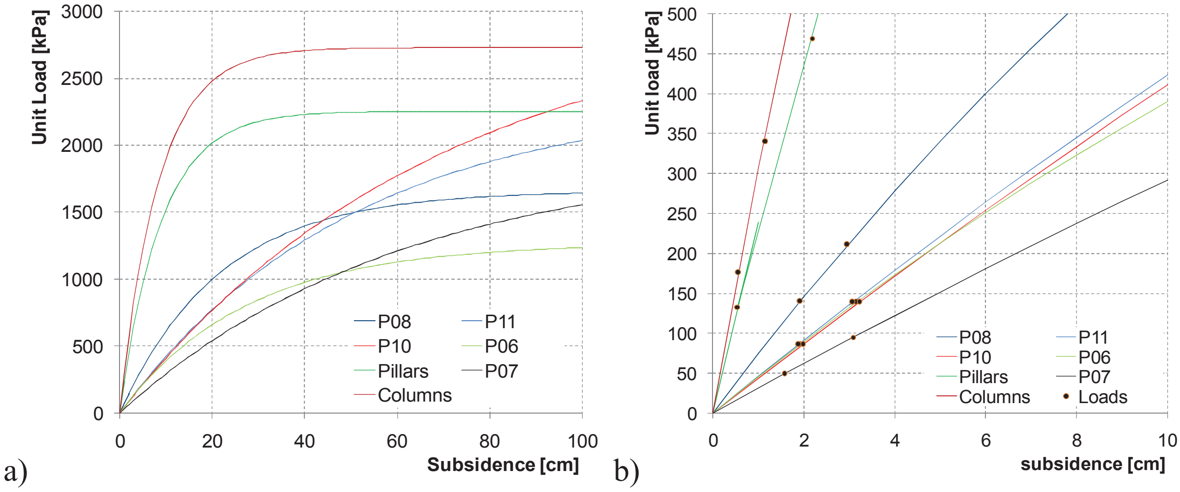

Figure 10: a) Unit load-subsidence curves for the different sections investigated, b) estimates of the subsidence of different building zones.

5 RETROFIT INTERVENTIONS

The organization of retrofit interventions on complex structural aggregates, such as the one presented in the previous paragraphs and, more generally, in the case of historical masonry structures, represents a very difficult engineering topic. The "traditional approach" proposed by current Italian standards [1, 13], that individuates the three possibilities of *global retrofit* (i.e. to make the existing building able to fully satisfy the safety requirements according to current standards), *partial retrofit* (i.e. to obtain a global increment of the structural safety of the building without the complete satisfaction of standards' requirements) and *local intervention* (i.e. strengthening or consolidation of single structural elements), cannot be easily applied to the cultural heritage. This is due to the fact that such historical buildings shall be, above all, preserved towards significant modifications of their original nature, maintaining their historical aspect and providing, at the same time, a considerable margin of structural safety.

As a consequence of what presented, and often in presence of localized static problems due to morphological and intrinsic features of the building, the "global" retrofit intervention on cultural heritage is the final amount of many "local" interventions regarding single elements or different portions of the building (for example masonry walls with significant cracks to be repaired, strengthening of horizontal storey through the introduction of additional elements, replacement of wooden elements of the roof and others). Figures 11, 12 and 13 show some examples of localized interventions regarding, respectively, horizontal floors, masonry walls, and wooden structure of the internal court roof.

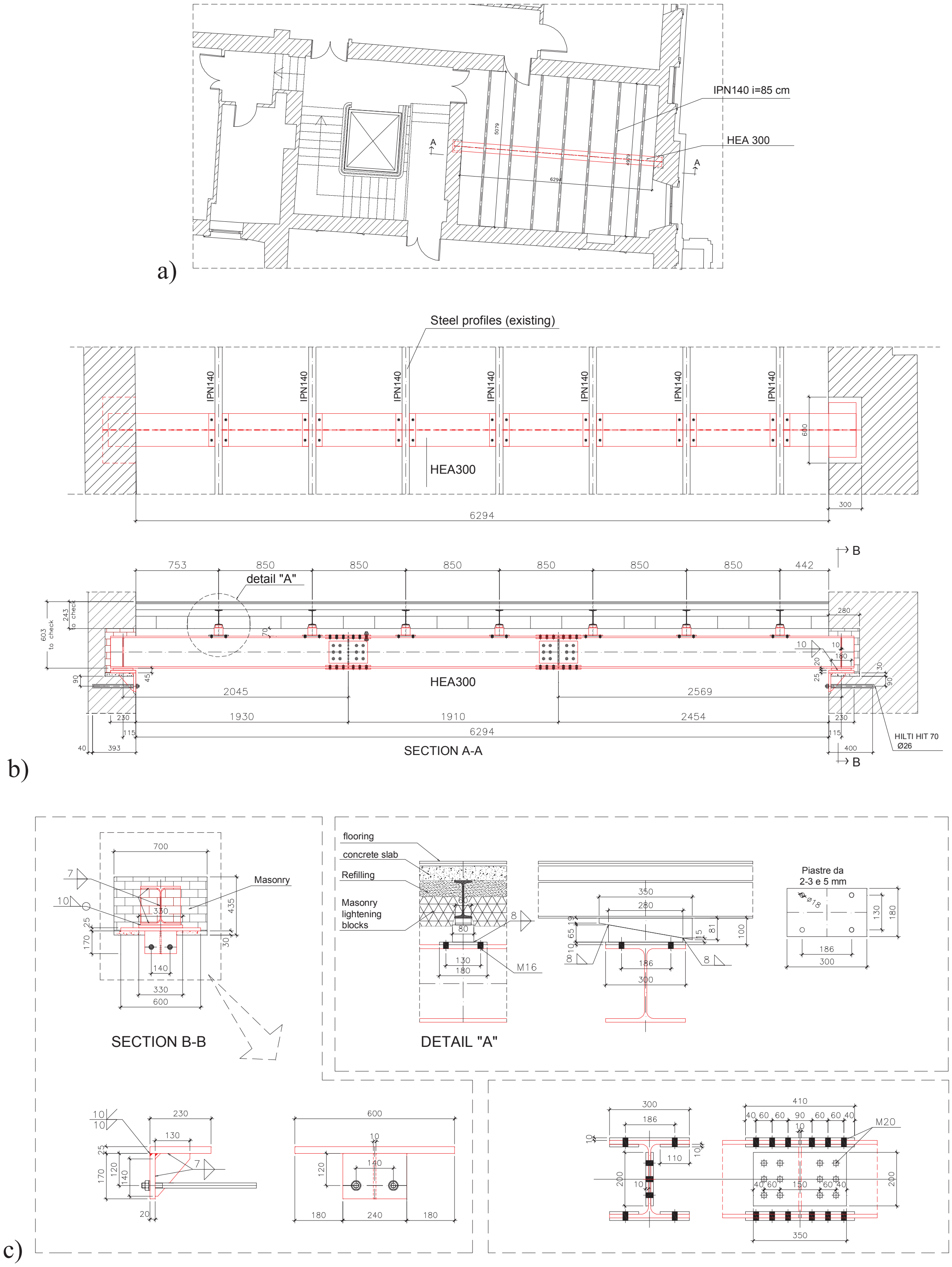

Figure 11: Local strengthening of horizontal floor: a, b) general scheme and sections, c) executive drawings.

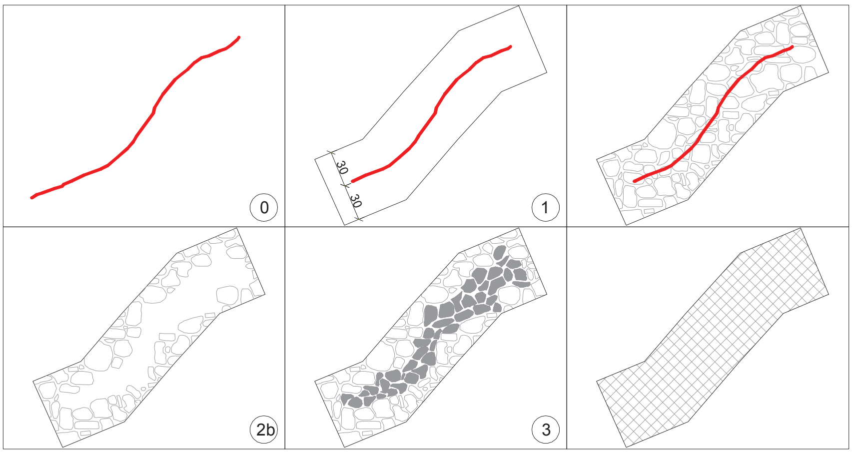

Figure 12: Example of local retrofit intervention of significant cracks on masonry walls.

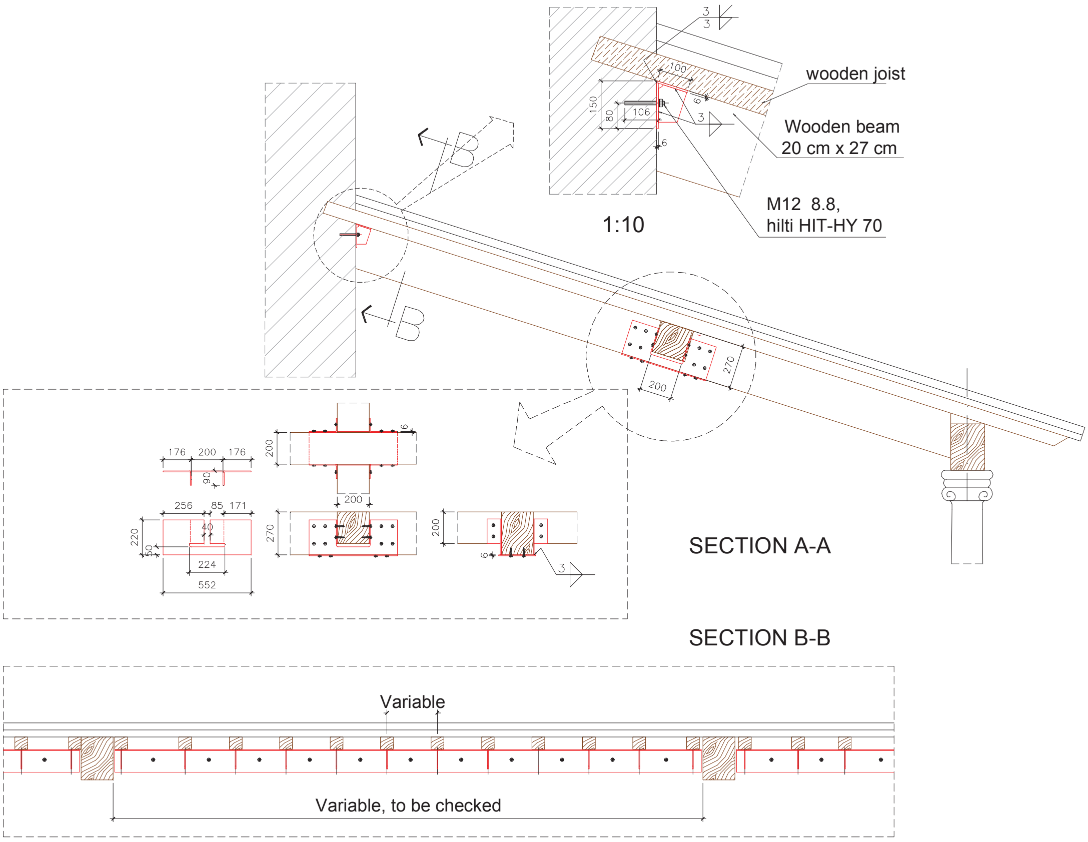

Figure 13: Example of retrofit of wooden elements of the internal court.

6 CONCLUSIONS

According to what presented in the previous paragraphs, the analysis of complex historical buildings such as Palazzo La Sapienza in Pisa shall be executed considering the construction not a single unit but a "structural aggregate", made up of different parts interconnected to each other in various ways and often realized at different times and using different techniques. Such complexities and structural heterogeneity usually result in widely disparate responses of different parts of the building to external actions, with widespread cracking phenomena and possible structural problems and failures similar to the ones occurred over the centuries and sometimes repaired with singular/local interventions. Moreover, the strong variation in the stiffness of the building's different existing foundation structures (Figure 10) led to differential settlements, with consequent load concentrations, making even worse the already existing instability.

The aforementioned complexity and structural heterogeneity translate into differences in the structural response and performance, consequently requiring detailed analyses of every single portion of the building and of its conditions of use, management and functional aspects. The structural analysis of La Sapienza building was therefore performed, considering the global behaviour of the structure (bearing in mind the simplifications necessarily to perform the numerical modelling for safety checks), and, at the same time, the behaviour of particularly significant sub-portions of building, subjected to the possible activation of local collapse mechanisms (for example out-of-plane tilting and overturning of façades or corners, horizontal thrusts due to vaults and roofing structures, presence of intermediary mezzanines with mechanisms of simple bending, etc.). A critical evaluation of the building's safety, together with a clear, deep understanding and knowledge of the structure itself, constitute the basis to define the objective of any structural interventions, carefully designed to achieve appropriate safety levels, durability of relevant portions of the building and, at the same time, produce the least impact possible on this important living example of Italy's historical heritage.

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