Cultural Heritage Monuments and Historical Buildings: Conservation Works and Structural Retrofitting

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1 Introduction

Historical constructions are an important part of the cultural heritage, because of their architectural value and evidence of building techniques. Their conservation over the centuries is a responsibility of our society, in order to pass on to future generations.

It is worth noting that the structural safety of historical constructions to permanent long-term actions, in many cases, has been proved over time. The diagnosis of the present conditions of the building can be made by a complete interdisciplinary knowledge based on historical notes, technological survey, non-destructive testing procedures and the interpretation of crack and decay patterns.

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Slow and inevitable aging processes might affect the current structural stability due to different possible origins: (1) material deterioration; (2) anthropic modifications, particularly in the urban environment; and (3) climate and environmental changes. Monitoring is a necessary stage in all three cases, both through advanced instrumentation techniques and qualified visual inspections, in order to detect when interventions are needed. Usually, deterioration processes can be slowdown and serious damage can be prevented by a periodic maintenance.

On the contrary, the preservation from natural hazards requires a preventive assessment aimed at the specific vulnerability and risk to different events (floods, earthquake, fire, biological, etc.), which cannot be based only on a qualitative approach and the observation of the building behaviour from the past. In particular, earthquake represents the main cause of damage to masonry structures and, due to the high return period of severe events in a prone earthquake area, a direct proof of safety is usually not available for the specific case. Moreover, after any strong earthquake the necessary restoration requires strengthening and, often, partial reconstruction, with a significant loss of the authenticity in respect to construction techniques. Therefore, it is necessary to have tools to implement a preventive policy, which takes into account the conservation requirements. Slight damage occurred due to previous earthquakes might suggest the possible collapse mechanism that the building would experience in the case of a strong event, but a reliable seismic assessment cannot be performed without quantitative models.

The seismic assessment of existing buildings is a complex task, basically for two different reasons: (1) the difficulty of interpreting and modelling the seismic response; and (2) the difficulty of acquiring as-built information on material parameters and structural details, due to their spatial variability in the buildings and the need of avoiding invasive testing.

In the last decades, earthquakes have proven that particular strengthening interventions carried out in the last century have revealed to be ineffective and, in some cases, even worsen to the seismic behaviour of the structure. Thus, proper methods of analysis and verification procedures are required for the seismic assessment and the design of interventions, with the aim of risk mitigation of cultural heritage.

Finally, it has to be stressed that, if carefully planned, the use and exploitation of cultural heritage constructions represents a sustainable approach for the conservation, because it underlies/undertakes as a continuous “health monitoring”, even in the cases in which some interventions and modifications are required. A detailed assessment through proper procedures and models allows to avoid invasive and useless interventions.

1.1 Cultural Heritage: The Origin and the Establishment of the Concept

The United Nations Educational, Scientific and Cultural Organisation (UNESCO) was constituted in London on November 16, 1945. Aimed at continuing the work begun decades before by the League of Nations, UNESCO articulated its commitment to the concept of a common cultural heritage and to the idea of strengthening and conserving this heritage through international collaboration and cooperation in its constitution [1]. In 1957 UNESCO was involved with organizing the First International Congress of Architects and Specialists of Historic Buildings, which took place in Paris and wherein a recommendation to create an "international assembly of architects and specialists of historical buildings" had met with approval. In May 1964 UNESCO's executive board adopted a resolution with an identical goal to that of the 1957 Paris congress and, in the same year, during the Second International in Venice, Italy, UNESCO put forward a resolution and draft status providing the basis for the establishment of an international non-governmental organization for monument and sites, named International Council on Monuments and Sites (ICOMOS), responsible for providing expertise in the form of consultants to UNESCO. The resolution was adopted along with twelve others, the first of which became the International Charter for the Conservation and Restoration of Monuments and Sites, known as the Venice Charter. In June 1965 the Venice Charter was ratified and the ICOMOS was officially founded in Warsaw, Poland. From its foundation, ICOMOS has stablished more than twenty-five International Scientific Committees on various themes and issues related with cultural heritage, which undertake research, develop conservation theory, guidelines and charters and foster training for better heritage conservation practice [2].

The Venice Charter is the first text wherein the concept of heritage is defined. In its introductory section it can be read that "Imbued with a message from the past, the historic monuments of generations of people remain to the present day as living witnesses of their age-old traditions. People are becoming more and more conscious of the unity of human values and regard ancient monuments as a common heritage. The common responsibility to safeguard them for future generations is recognized. It is our duty to hand them on in the full richness of their authenticity" [3]. In other words, heritage as concept can be defined as the collection of things which relates people to who they are, where they have come from, and why they are the way they are. According to [4], the documents following the Venice Charter focus on two different issues: (1) the definition of the general principles for the identification of new fields of conservation (addressed in the 1971 UNESCO Convention on the safeguarding of wetlands and in the Charter of the Council of Europe in 1972, wherein as a limited and fragile resource the soil is proposed as heritage); and (2) the attempt to integrate the principles of safeguarding with the control systems of the territory and of the economic and social development [4]. In the 1972 UNESCO Convention on the Protection of World, Cultural and Natural Heritage [5], the expression "cultural heritage" is used to refer monuments and sites of "exceptional universal value from the point of view of history art and science", a line followed later in the 1987 Charter for the Conservation of Historic Towns and Urban Areas [6], known as Washington Charter, where the need to protect historic cities is clearly stated. It is worth adding that the concepts of tangible and intangible values as the object of protection were recognized for the first time in this document. Another worthy highlighting document on this issue is the 1979 Burra Charter [7], where it is stated that the conservation of the cultural significance of a site, due to its aesthetic, historic, scientific or social value, must be safeguarded and protected. Despite its great influence, cultural heritage has not often had the recognition that it deserves. In fact, throughout history there have been many theories on the treatment and protection of cultural heritage, particularly to buildings, some of those have been considerate and respectful, whereas others have been destructive and oblivious [8].

1.2 The Safeguard of Cultural Built Heritage

Safeguarding any heritage asset, particularly heritage valued constructions, requires method, strategy and planning. The cultural built heritage includes and encloses the historical, ideological, architectural, artistic and material identity of a city and consequently any conservation, restoration or rehabilitation intervention must respect, as much as possible, the authenticity and compatibility with the original. Knowledge on past urban renewal and renovation processes are the basis of the definition of a methodology and strategy, keeping in perspective that every case has its singularities and necessary adaptations. The need for survey, through building appraisal and inspection is a decisive and guiding stage for the success of the intervention of any singular or collective regeneration process.

It is based on these concepts that the discussion presented in this chapter is developed, starting with a brief overview on the appraisal, inspection and monitoring of heritage valued construction, which is followed by the presentation of two different but complementary approaches. The first is dedicated to the conservation of restoration process of the Tower of the University of Coimbra, in Portugal, wherein non-structural and structural diagnosis and interventions were prepared and undertaken in the scope of the acknowledgement of University of Coimbra, the uptown ("Alta") and Sofia as World Heritage Sites [9]. The second is a comparison between possible seismic assessment procedures, applied to two different types of structures: an ottoman palace, the Hassan Bey's Mansion in Rhodes (Greece), and a mosque, the Great Mosque of Algiers (Algeria).

2 Survey Appraisal, Inspection and Monitoring of Heritage Valued Constructions

The survey is the starting point to assess the condition and identify defects of the constructions. Survey actions are often inadequate and unfruitful, because they are not based on a true knowledge of the building stock, from the type of materials used, construction techniques, possible systematic vulnerability features, etc. A poor survey can have a negative effect on the way the building is retrofitted and maintained, compromising its future well-being. Another aspect to take into account is the scale of appraisal and inspection pursued. This is, choosing the most adequate approach for inspection, appraisal and diagnosis is a complex task that can determine the success or the total failure of the survey purpose.

ICOMOS establishes guidelines on several levels [10]. On the survey and diagnosis level, the need of complete understanding of the structural and material characteristics of the construction is clearly stated. It recommends, as essential to collect historical information on the structure, techniques and construction methods used, subsequent alterations, present conservation state, etc. It further states that the diagnosis should be based on historical information and on qualitative and quantitative approaches and therefore, prior to any decision on intervention, it is indispensable to determine the causes of damages and degradations, and only then to evaluate the safety level of the construction based on its present knowledge. As outlined by [9], the rational approach for the survey stage must keep guided by the following general principles:

- each traditional building has different and singular aspects that make them unique, leading to slightly different survey needs, from case to case. The survey strategy to be adopted must be the most adaptable and sensitive to the building features;
- the selection of the means of inspection, appraisal and recording must be adaptable to the nature of the building, physical and in situ limitation of survey actions and available resources;
- the survey actions should be based on the general scope and most important and critical aims of the project. Any repair, maintenance, refurbishment action or intervention strategy should reflect the technical and financial effort made in the survey phase;
- the survey is a multidisciplinary task. The contribution of surveyor teams (engineers, architects, historians, archaeologists, etc.) with expertise opinion is very valuable. The greater challenge is to coordinate these specialists and their objectives;
- the surveying stage, through inspection, appraisal, diagnosis and recording tasks could attain very high level of complexity. Nevertheless, the focus on the project overview and in its general understanding must be always kept;
- the use of other sources of information, such as the documentary information is also very valuable and should be considered.

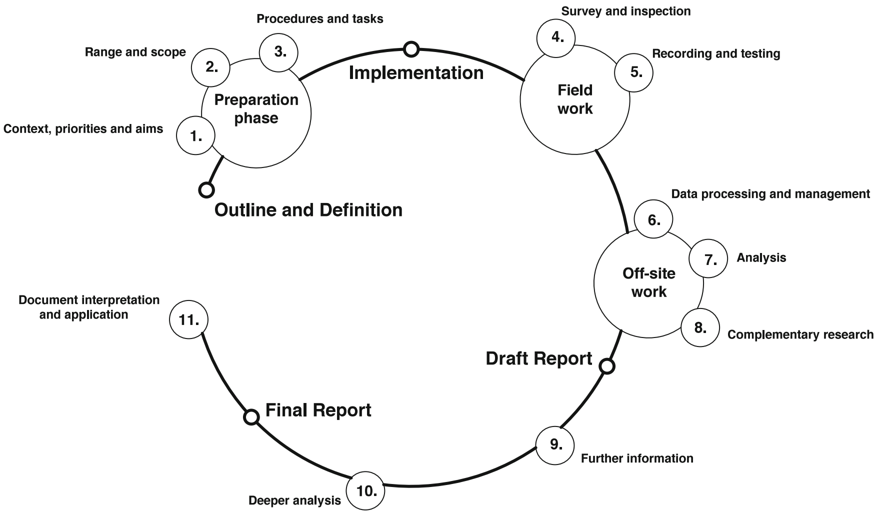

Fig. 1 Survey framework of heritage valued constructions

The surveying task is essentially a combination of complementary tasks: recording, diagnosis, inspection and testing. As depicted in Fig. 1, generally the survey process should involve three essential steps: preparation phase; field work and off-site work. In each one of these phases, several processes are carried out: organizing activities, research, analysis, recording and reporting are some of the major procedures.

3 The Tower of the University of Coimbra

With more than six centuries of history, the University of Coimbra was included in the World Heritage List of UNESCO in 2013. The area inscribed has about 36 hectares and comprises 31 groups of buildings with different ages, considered of major relevance to the history and the memory of the University [11]. Among those, the Tower of the Royal Palace, depicted in Fig. 2, is the most well known and one of the *ex-libris* of the old town, receiving more than 300 thousand annual visitors.

The 34-meter-high Tower, also known as Tower of the University of Coimbra, was planned during the reign of João V and it is considered one of the most original examples of Portuguese eighteenth century Baroque architecture. Started to build in 1728 and finished in 1733, about 22 years before the great Lisbon earthquake, during its history it suffered no more than a few and limited non-structural maintenance and restoration interventions.

Along the ten years of preparation of the dossier for UNESCO, two main challenges were identified: (1) to improve the conservation state of the buildings

Fig. 2 Tower of the University of Coimbra and Via Latina

located within the inscription area, assuring simultaneously their adequate and up-to-date response to the university everyday activities, and the preservation of their integrity and authenticity; and (2) to contribute for a needed methodological approach, as a sustainable example, more than just as an administrative acknowledgment, inspiring learning and research activities, and motivating the community for the preservation and valorisation of this heritage valued asset of national interest [12, 13].

The restoration project of the Tower followed these guidelines and was carried out by an internal multidisciplinary team of Engineers, Architects, Restoration experts, Archaeologists and a large number of other expertise contributions, with the scientific support of several professors and research groups [14]. The technical works were carried out by specialized companies (chosen through international public trends), under the supervision of University technical teams. The terms of these public trends included specific clauses on the need of compatibility between the efficient execution and ongoing of the restoration works, and the project of the pedagogical work site (presented in Sect. 3.5).

3.1 The Conservation and Restoration Project of the Tower

The general aim of the intervention is to preserve an architectural heritage element of symbolic meaning not only for the University of Coimbra but also for the city, through the strong physical presence it has in the landscape and for its socio-cultural meaning. Simultaneously, from the standpoint of a sustainable intervention over a cultural heritage asset, this project aims at reintroducing the visits to the Tower, which had to be suspended due to its poor condition. The project and the conservation work itself required a specific approach and was supported by a broad number of preliminary activities [11]:

– historical and architectural research, aiming at cross-referencing historical data of the 5-year construction of the Tower. This continuous process allowed to get a better understanding of the existing structure and to consolidate the criteria used to justify the intervention;
– the graphical base obtained both from the architectural and photogrammetric survey, as well as the mapping of the defects, provided information on features and dimensions essential for the restoration project;
– the analysis of the structural behaviour attained through a numerical model provided important data on the structural integrity of the Tower;
– the prior testing of cleaning methods defined a series of references for the execution of the project and the intervention, assuring the suitability of the solutions adopted.

As discussed in the introductory section of this chapter, the existent set along with the ethical principles inherent to the intervention in this kind of heritage led to a minimum action, mostly concerning a preventive maintenance and conservation. Moreover, the characteristics of the several materials implied coherent and sustainable methodologies and strategies of intervention, both in the preliminary works and in the several stages of intervention. The main purpose of maintaining all the original materials, establishing the physical and aesthetical balance of the architectural whole, is to assure that from the design to the execution, safeguarding the authenticity of the tower for future generations is kept [11].

3.2 State of Conservation

Despite the presence of several defects, the stones materials were in an acceptable state of conservation. The overall surface presented a heterogeneous colouring caused by different factors, namely, biological colonisation, films and dark crusts, oxidation spots of metallic elements and the orange patina resulting from the aging process of limestone. On the terrace, the abutment rail had several embedding spots that were causing fractures in the cornices. In addition, several floor slabs were identified as damaged or broken.

In the interior of the Tower, the plasters were degraded, both by the action of humidity and nitre, and the layers of whitewash were detached. The stone slabs of the stairs were fractured and cracked due to erosion and use. In the most fragile areas, there were also some situations of loss of material. Finally, in the gap of the clock weights, the surface was damaged and parts of the coating plaster was missing, leaving the ceramic bricks at sight.

3.3 Material, Mechanical and Modal Characterisation

In order to rapidly assess the mechanical conditions of the Tower, a numerical model was constructed and calibrated on the basis of a series of ambient vibration measurements, which were used to identify the structural modal shapes and natural frequencies.

3.3.1 Construction of a Finite Element Model (FEM)

Taking advantage of the already referred architectural and photogrammetric survey of the structure, the numerical model was built using 4 node tetrahedral finite elements into the software ADINA. Since both the type of foundations and the characteristics of the foundation soil were unknown, it was assumed that all displacements of the base nodes are restricted in the definition of the support conditions of the model. Moreover, the horizontal displacements of the shared walls between the tower and adjacent buildings were considered restrained in the normal direction. Regarding the mechanical properties of the materials, although the Tower is composed of two leaf masonry, an inner leaf of ceramic bricks plastered and whitewashed painted and an outer leaf of faced limestone masonry blocks, the Tower walls were assumed as homogeneous in the analysis by taking an equivalent Young's Modulus and an equivalent shear Modulus. As described in [15], such values were calibrated resorting to a dynamic identification procedure.

3.3.2 Modal Identification

The measurements of the dynamic behaviour of the Tower were performed using a frequency analyser to record the data acquired from eight accelerometers, four of them fixed and the remaining four movables, in time frames of 45 min under ambient noise vibration condition. The model analysis was subsequently performed by means of peak picking and frequency domain decomposing (FDD) techniques, implemented in the ARTeMIS Extractor software [16], from which natural frequencies as well as modal damping and shapes were estimated. The measurement plan included two stages: the first, performed only at the level of the bells and top terrace of the tower; and the second, on twenty points located at different levels of the Tower strategically selected on the basis of the comparative analysis between the measurements performed in the first stage and the results of the initial FEM [15]. The goal of the measurements consisted in identifying the first five natural frequencies and corresponding vibration mode shapes (presented in Fig. 3), with the purpose of calibrating the FEM.

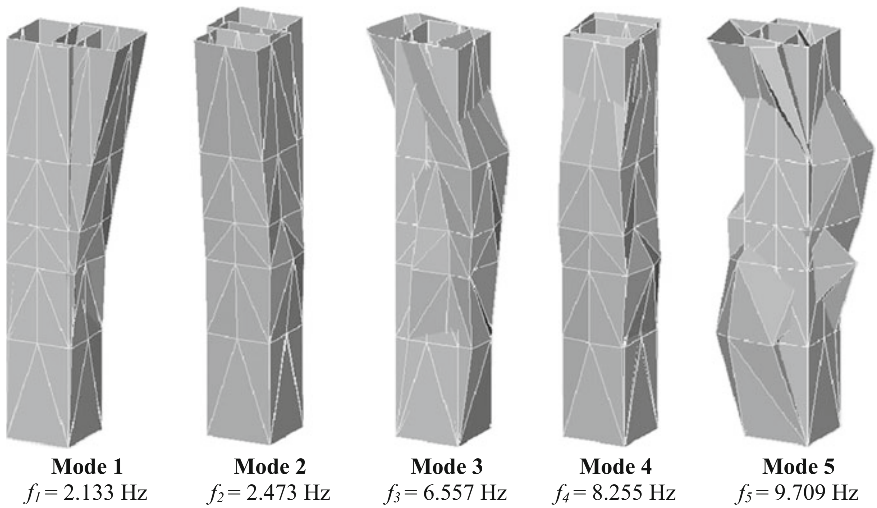

Fig. 3 First five vibration mode shapes and corresponding natural frequencies measured [15]

3.3.3 Calibration of the Numerical Model

Taking into account the uncertainties existing in the definition of some key parameters, a two-step calibration methodology, involving (1) the correction of the support conditions, through the analysis of several models with different support conditions; and (2) the values of the equivalent Young's and shear Modulus by trial-and-error, was iteratively carried out until the first five natural frequencies present a suitable coincidence. Having calibrated the model, values of 5.5 and 0.34 GPa were found for the Young's and shear Modulus respectively. It is worth noting that these values are in good agreement with other published studies, namely with [17], where a value of Young's Modulus up to 5 GPa and a shear Modulus of 0.5 GPa were assumed in the modal identification of a 48-meter-high masonry tower built in the fifteenth century. Figure 4 depicts the mesh and supports of the calibrated FEM of the Tower.

Finally, Fig. 5 shows the first five vibration mode shapes obtained with the calibrated model and their corresponding frequencies.

As revealed from the comparison between the results presented in Figs. 3, 5 and Table 1, the approximation obtained between the measured and the numerical vibration modes and frequencies reveals a good agreement.

From the results shown in Table 1, it can be concluded that there is no evidence that the structural integrity of the Tower is compromised. However, as is further discussed in [15], if inadmissibly lower values of the Young's Modulus and/or shear Modulus had been obtained or if a different level of accuracy had been registered for one or more modal frequencies, one could have been concluded that the integrity of the Tower might be affected [15].

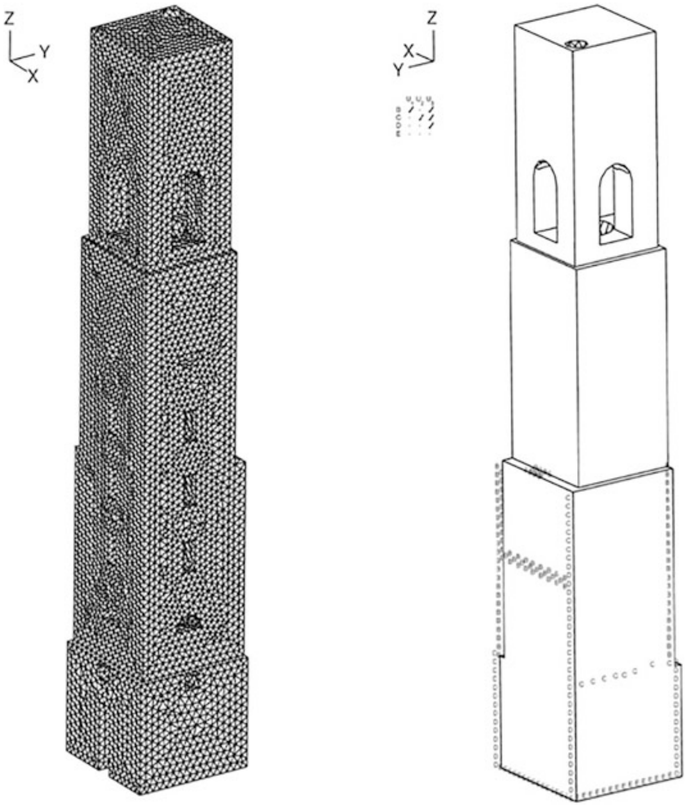

Fig. 4 Mesh and supports of the calibrated finite element model (adapted from [15])

Since the planned restoration and rehabilitation works include the correction of minor structural defects, such as cracking and small movement and displacement of stone leaf facing blocks (see Sect. 3.4.1), it was decided to carry out a re-assessment using the same methodology, correcting and adjusting the numerical model, if necessary, even though no need for deeper strengthening operations [15].

3.4 *Catalogue of the Surveyed Information and Description of the Conservation Works*

A more precise analysis of the existent defects was performed after the installation of the scaffolds. The Tower garland was one of the areas that showed more fractures and cracks that had remained unperceived until then. Therefore, the existent architectonical and photogrammetric survey was redone. Throughout the conservation works, mapping information on three important features was regularly

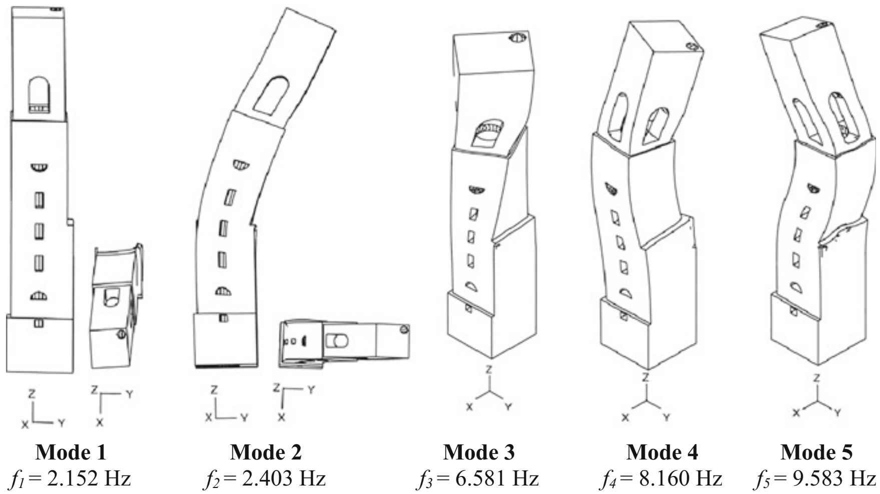

Fig. 5 Vibration mode shapes and corresponding frequencies obtained from the calibrated finite element model (adapted from [15])

Table 1 Comparison between the measured and the numerical natural frequencies [15]

Mode	Measured frequency (Hz)	Numerical frequency (Hz)	Error (%)
1	2.133	2.152	−0.89
2	2.473	2.403	2.83
3	6.557	6.581	−0.37
4	8.255	8.160	1.15
5	9.709	9.583	1.30

updated: (1) revision of the pre-existent defects survey; (2) record of all the tests performed during the appraisal works; and (3) record of all the conservation treatments of restoration performed during the restoration works. All the intervened elements during the works were also registered through general and detailed photographs before, during and after the actions of conservation and restoration.

3.4.1 Conservation and Restoration Works

The conservation and restoration works took place from March 2010 to August 2010. Besides the main action of cleaning and treatment of all surfaces, assumed as ordinary planned maintenance, other reactive maintenance actions aiming at restoring the stability conditions and the cohesion of the architectural elements, as well as of ornamentation elements that presented signs of instability and risk of imminent fall, were also taken. The suppression or mitigation of the action of agents responsible for the degradation of materials and the attainment of better conditions

Fig. 6 Conservation works performed

to resist the action of external atmospheric agents were other maintenance actions carried out [11]. It is worth highlighting that the specific nature of this intervention entailed the adoption of individual strategies and methodologies, not only during the preparation works, but also during the accomplishment of the different tasks. Figure 6 schematises the conservation works performed, which are herein grouped and described in the following paragraphs.

Disinfection and Elimination of the Microbial Colonisation

The vegetation had developed mostly in the superior part of the Tower, with more impact in the upper two-thirds. The number and the species found was variable according to the façade elevation and orientation and to the exposure to the atmospheric agents. To revert this process, a herbicide was applied by spraying directly on the vegetation growth, with particular incidence on the new leaves and shoots. The first application was performed without packaging the upper vegetation, and a second one, after a short period of time, with black plastic packaging completely closed with nylon and/or tape, avoiding this way the vegetation from direct light and increasing the efficiency of the product. The removal of the existing vegetation was carried out mechanically and manually. Finally, a biocide was applied in order to eliminate the microbial colonisation.

Treatment of the Stone Material

The cleansing actions performed sought a balanced and continuous chromatic reading, avoiding the removal or change the time patina. The methods used for cleansing were selected in function of the location and type of dirt or chromatic change, and the results achieved in the previous tests. The exterior cleansing was carried out resorting to different methods/techniques of water seepage, namely brushing with soft nylon brushes, cleaning spray complemented with interspersed soft brushing, water jet cleaning machine at low pressure and mechanical cleansing of films and old mortar. The interior cleansing was performed mainly with mechanical methods, namely spatulas and rotary abrasive devices.

Before the intervention, most of the joints were fully or partially open, allowing the proliferation of plants in their interior. Moreover, in areas of direct access, namely at the ground level of the Tower and in the bells' area, the joints were filled with incompatible and inappropriate materials, such as Portland cement. During the opening process, all corroded steel and non-functional elements were removed and, after that, the joints were cleaned with compressed air. When biological colonisation was still present inside the joint, it was removed resorting to a wet process.

The voids resulted both from the opening of joints and from the cleaning of stone surfaces were filled with traditional lime mortar. All the mapped cracked and fractured elements were consolidated, as well as the loose stone elements and fragments which were assembled resorting to a resin. Stainless steel and fiberglass bolts were used to ensure stability in cases of excessive volume or weight, also in cases where there was greater fragility as a result of the adhesive resins used. Following the mentioned actions, the areas of fractures and cracks were filled with fine-grained micro-plastering mortar.

After the execution of all conservation and restoration treatments, including the last application of biocide, a water repellent product was used aiming at reducing the capacity of water absorption of the stone surface and extending the efficiency of the final biocide treatment, allowing however water vapor permeability and increasing the durability of the treatments.

Treatment of the Metallic Elements

On the roof, it were identified: the metallic elements with no structural function, namely the fitting elements of the metallic railing; the non-structural elements, resulting from an existent old mechanism; the elements without any defined current function; and the structural elements of stone block laying and fixing. All metallic elements were identified and mapped by category and treatment action.

The methodology followed for the treatment of the metallic elements, with few exceptions, consisted on manual and mechanical removal by using pliers, drills, chisels and mallet. The non-structural metallic elements detached and with no identified function, were removed.

3.4.2 A Final Note About the Conservation Works Performed

Concluded the works and dismantled the scaffolds, the impact of the actions performed was notorious. The new Tower that arose from the cleansing operation and the chromatic contrast with the previous image is clear. The conservation work performed showed stone material that does not show a chromatic heterogeneity, allowing a better perception of the sculptures, many of which were imperceptible due to the existent strong biological colonisation. The maintenance of the natural aging patina of the stone was assured by tackling the defects causes of degradation and strong visual impact.

3.5 The Pedagogical Restoration Work Site Initiative "Tower-PSite"

Since the early stage of the project, it was understood that the restoration works of the Tower of the University of Coimbra could be an exceptional opportunity to test a pedagogical work site based on the permanent information and interaction with different public-targets, in order to promote, on one hand, the relevance of a responsible restoration process on the preservation of our collective memory and built heritage and, on the other hand, to promote the awareness of general public to both the technical issues and the philosophical concerns of this kind of work. Additionally, several secondary goals were also identified, namely, the increase on the scientific and technical discussion about restoration and the promotion of a public and academic recognition of the multidisciplinary of the knowledge areas involved. Other positive effects resulting from this initiative were the increase of external visibility, both national and international, through media and web, as well as the increasing credibility of the protection strategies proposed to UNESCO within the nomination to the World Heritage List [14].

Regarding the target public, four main groups were identified and subdivided into two specific categories: tourists (structured tourism; family tourism), technical and scientific public (professors and post-graduation students; professionals and researchers), general public (locals; undergraduate school community) and foreign non-visiting public (national; international). In this regards, it should be noted that Coimbra town has about 143.000 inhabitants, where students represent more than 25%, and that University of Coimbra is visited by more than 300.000 tourists a year.

To fulfil the goals mentioned above and get close to target public, four types of activities have been organized: Multi-level information outdoors; Website and follow up "newspaper"; Guided visits; and Seminars. Figure 7 establishes a holistic matching between these activities and target public.

Each one of these activities are individually detailed in the next paragraphs.

Multi-level Information Outdoors

As already referred, the Tower is visited by about 300 thousand tourists every year, who expect to observe it as the *ex-libris* of the University. For this reason, as can be seen in Fig. 8, canvas covering of the scaffolds has been adopted with real size photo of the tower on all surfaces and, at the ground floor level, the bay that protects the work site was transformed into an outdoor with multilevel information, with a studied design and a hierarchy of written and graphic information [14].

Website and Follow Up "Newspaper"

A local "newspaper" (wall or outdoor "newspaper" at the work site) and a website were created in order to provide periodical information about the progress of the restoration works. This task required a significant volume of work of several experts, namely designers, technicians, translators, etc. Unfortunately, after the two first months, this activity had to be cancelled due to a clear lack of human resources.

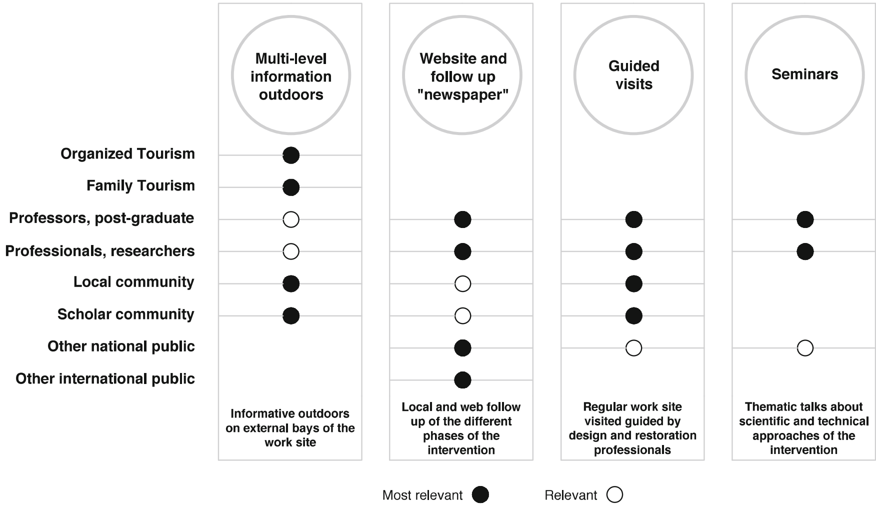

Fig. 7 Relationship between activities and target public in "Tower-PSite" project

Information Level 1 For quick view directed to organized groups of tourists, even if they don't stop (big pictures, direct and short message)	Information Level 2 For self-visiting (small or family groups) with more detail about history and about the strategy of conservation works	Information Level 3 For guided groups, with additional technical and scientific details and curiosities, using a scale of elements

Fig. 8 Hierarchical organization of the information presented on the outdoors

Guided Visits

The most visible activity was the guided visits, oriented by different technicians and researchers, such as engineers, architects, historians, archaeologists, etc., every week, up and down the 33 m high scaffold, contacting closely to specialized workers, being part of everyday site discussion and activity. Slight site adaptation had to be made in order to guaranty safety and space circulation conditions.

Seminars

For a more detailed approach, not only in technical terms but also from a scientific and philosophical point of view, four thematic seminars were organized with the collaboration of the Science Museum of the University of Coimbra, with four complementary perspectives: (1) history and identity; (2) architecture and performance; (3) restoration and integrity; and (4) safety and longevity.

4 Seismic Assessment and Preservation of Historical Structures

International standards (Eurocode 8-Part 3 [18], ASCE/SEI 41/13 [19]) adopt the evaluation of the seismic risk to existing buildings the Performance-Based Assessment (PBA), which considers several Performance Levels (PLs) that must be fulfilled in the occurrence of corresponding earthquake hazard levels (defined by the return period). The need to check the achievement of PLs that are close to structural collapse strongly recommends the use of static nonlinear models and displacement-based procedures for the assessment, because the use of linear analysis with the behaviour factor approach is not reliable enough.

The specific case of cultural heritage assets is treated in some recommendation documents [10, 20, 21], which are not only aimed to seismic vulnerability but consider all possible causes of damage and deterioration, with the aim of making a diagnosis and designing a rehabilitation intervention. They point out the complex configuration of this kind of structures, also due to the relevant transformations that have usually occurred over the time, as well as the difficulty of adopting a proper modelling strategy. All these recommendations stress the importance of the qualitative approach, founded on the historical analysis, the accurate investigation of structural details and the interpretation of seismic behaviour, on the basis of observed damage on the building (due to previous events, if any) or on similar structures.

As already mentioned in Sect. 1, it is worth noting that a preliminary assessment is usually sufficient for the diagnosis in many critical situations, such as material deterioration or soil settlements. On the contrary, the evaluation of seismic vulnerability without the support of calculations is overambitious, because the qualitative approach can only suggest which is the expected seismic behaviour and the historical analysis is not sufficient to prove the building safety. This is the reason why the Italian Guidelines for the seismic assessment of cultural heritage [22] clearly states that it is not possible to avoid a quantitative calculation of the structural safety, even if models have to be based on an accurate knowledge and the results can be adjusted by taking into account qualitative evaluations.

The PERPETUATE project [23], funded by the European Commission, has developed guidelines that are coherent with the latter cited recommendations but frame the problem of the seismic assessment of cultural heritage assets and design of interventions within the PBA approach, outlined by the international standards for current buildings. The aim is to define, even for the complex case of old masonry structures, an assessment procedure repeatable and verifiable, which leads to the quantitative evaluation of safety levels, taking also properly into account historical and qualitative information.

In case of historical buildings PLs have to be linked also to cultural relevance concepts: thus, the use and safety of people, the conservation of the building and the conservation of artistic assets (if present) have been considered in an integrated approach. Since pushover analysis is considered the standard tool for the PBA, detailed acceptance criteria are proposed for the identification of target PLs on the pushover curve, by considering the displacement u as Engineering Demand Parameter (EDP) and defining proper thresholds.

Specific PLs are introduced in PERPETUATE taking into account three different groups of requirements (n = U, B, A): *use and human life* (U); *building conservation* (B); *artistic asset conservation* (A). The seismic input is defined by the hazard curve, obtained through a Probabilistic Seismic Hazard Analysis (PSHA), which gives the selected Intensity Measure (IM) as a function of the annual probability of occurrence (or the return period). Possible IMs are: peak ground acceleration (PGA), spectral acceleration for a given period, maximum spectral displacement, Arias intensity, Housner intensity [24]. In the standard case of nonlinear static analysis, the seismic demand is represented by an Acceleration-Displacement Response Spectrum (ADRS), which must be completely defined, for the specific site of the building under investigation, as a function of the assumed IM.

Figure 9 summarizes the basic principles and steps of PBA according to PERPETUATE guidelines, where the displacement-based approach is adopted as the standard method for vulnerability assessment of cultural heritage and design of preventive interventions. In the following the attention is focused only on the use of static nonlinear analysis (pushover), while PERPETUATE procedure also considers the use of Incremental Dynamic Analysis (IDA) [25].

The outcome of the assessment is IM_{PL}, which is the maximum value of the intensity measure that is compatible with the fulfilment of each target PL: it is computed by nonlinear static procedures with overdamped spectra [26]. Thus, through the hazard curve, it is possible to evaluate the annual rate of exceedance λ_{PL} of the earthquake correspondent to this performance (or its return period $T_{R,PL} \approx 1/\lambda_{PL}$). These values are compared with the target earthquake hazard levels $\bar{T}_{R,PL} \approx 1/\bar{\lambda}_{PL}$, defined for the assessment as a function of asset characteristics, in terms of safety and conservation requirements.

This general methodological path has been particularized in PERPETUATE guidelines for different architectural assets; a classification is proposed [27], which is related to the different types of seismic behaviour, considering both building morphology (architectural shape and proportions) and technology (masonry type, horizontal diaphragms, effectiveness of wall-to-wall and floor-to-wall connections). It consists of six architectonic classes: (A) box-type buildings; (B) assets studied by independent macroelements; (C) slender structures studied by monodimensional models; (D) arched structures; (E) massive structures; (F) blocky structures subjected to rocking. Different modelling strategies can be adopted for describing the seismic behaviour of each kind of asset. Moreover, the problem of seismic local

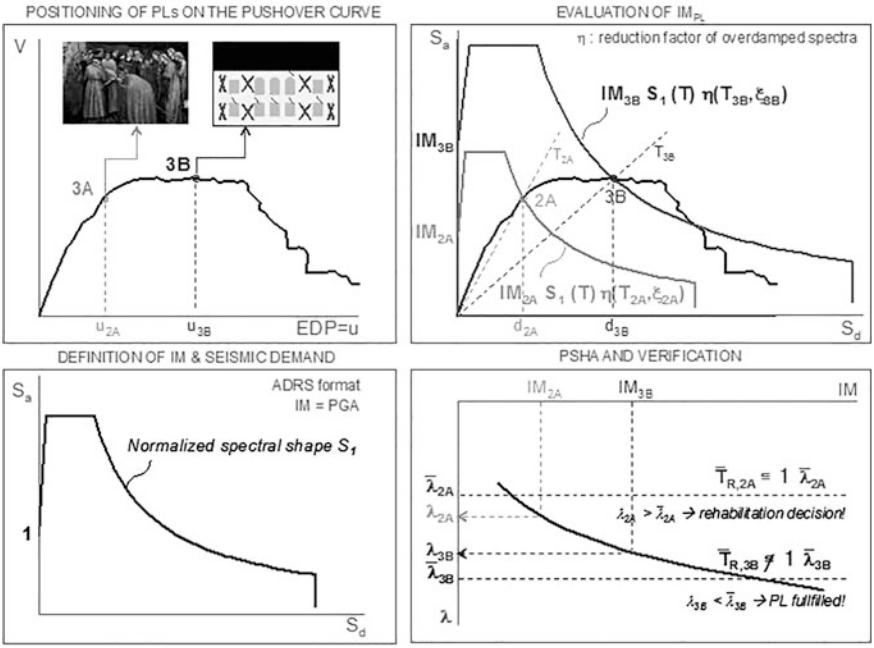

Fig. 9 PBA of architectonic and artistic assets according to PERPETUATE guidelines [23]

mechanisms is treated, which has to be taken into account in all the above-mentioned architectural assets classes, in order to assess the vulnerability of single elements that are not described by the structural models used for the assessment at global scale. The seismic assessment considers also the presence of artistic assets that has to be preserved; three different classes have been introduced: (P) artistic structural elements (e.g. carved stone column); (Q) artistic assets strictly connected to structural elements (e.g. frescoes, mosaics, stuccoes); (R) artistic assets that are independent elements (e.g. pinnacles, spires, merlons).

The application of PBA is particularized for each class by analysing also the use of different modelling strategies and the proper approach to describe the seismic behaviour of the asset. For example, it is necessary to evaluate if the seismic behaviour of the building can be represented by a single model or by a set of different models. The former is the case of assets made by a single element (such as those belonging to classes C, D and F) or by many macroelements (masonry walls, horizontal diaphragms etc.) that can be represented by a global model (such as those of class A, which presents the so-called “box-type” behaviour). On the contrary, the need to consider different models is characteristic of complex assets, made by macroelements that behave quite independently; in this case the assessment requires to develop more than one model, even of different types (it is typical for assets of class B), and the result of the analyses in each macroelement must be then properly blended, in order to define the seismic assessment of the whole asset.

4.1 PBA Procedure of Complex Architectonic Assets

In this chapter the attention is focused on the PBA of complex architectonic assets belonging to classes A—*assets subjected to prevailing in-plane damage* (e.g. palaces, castles, …) and B—*assets subjected to prevailing out-of-plane damage* (e.g. churches, mosques, …); the global assessment, in terms of compatible Intensity Measure ($IM_{PL,G}$), also implies the verification of possible local mechanisms. Despite this, for the sake of brevity these latter are not explicitly treated, while more details on this issue are illustrated in [28].

In case of Classes A and B, the PBA is faced by applying two alternative modelling approaches (Fig. 10):

- buildings characterized by box-behaviour: in this case a 3D model of the whole building is possible (global scale approach);
- buildings made by a set of N_m macroelements, which exhibit an almost independent behaviour: each macroelement is modelled independently (macroelement scale approach) and the seismic load needs to be assigned by a proper redistribution; the assessment of whole asset is then made through a proper combination of results achieved in each macroelement.

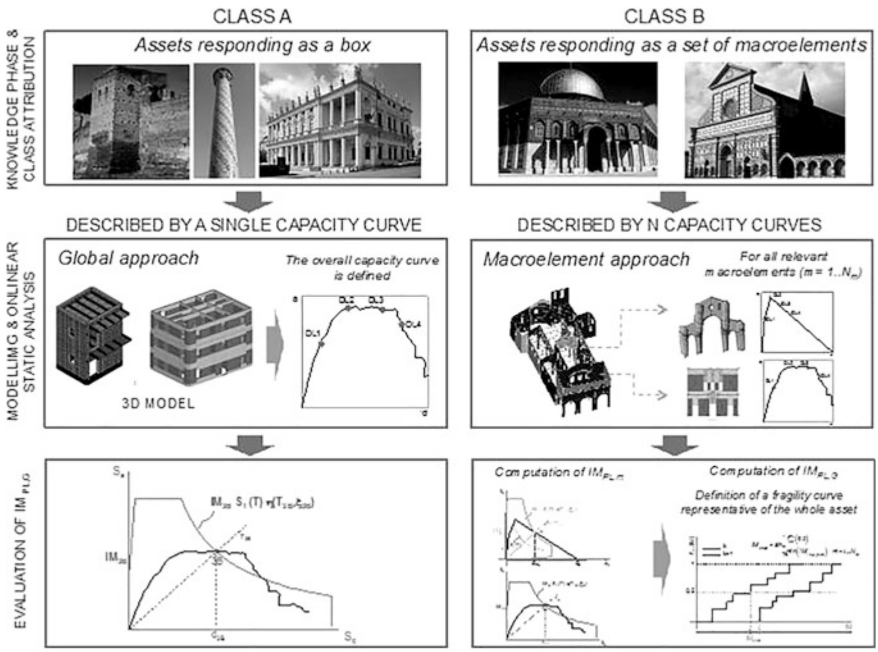

Fig. 10 Basics of PBA for assets of *Classes A* and *B*

The global scale approach is typical of buildings of class A but can be sometimes adopted also for architectonic assets of class B, when macroelements are well connected and there is a horizontal diaphragms which is able to redistribute inertial actions among them. The macroelement scale approach is necessary for most of structures of class B, but also for very few buildings of class A, when horizontal diaphragms are very flexible and/or internal walls are sparse.

One of the critical issues in the PBA is the availability of reliable criteria to define the PLs on the pushover curve. To this aim, a multiscale approach has been proposed that takes into account the asset response at different scales: structural elements scale (local damage), elements scale (damage in macroelements) and global scale (pushover curve). It aims firstly to define proper Damage Levels (DL_k, k = 1.4) on the pushover curve, which may be correlated by proper criteria to the PLs [23]. In case of Class A, its application implies to perform checks at these different scales by considering the evolution of various variables; at the end, the displacement on the overall pushover curve corresponding to a certain DL is defined as the minimum among the displacements corresponding to the attainment of those conditions.

In the case of Class B, once evaluated the $IM_{PL,m}$ for each macroelement that composes the asset, it is necessary to define the intensity measure representative of the whole response ($IM_{PL,G}$). Also in this case a multiscale approach is proposed, aimed to define a fragility curve of the whole assets by combining the contribution offered by each macroelement. In particular, it is computed as:

$$P_{PL}(IM) = \sum_{m=1}^{N_m} \rho_m H\left(IM - IM_{PL,m}\right) \tag{1}$$

where: H is the Heaviside function (0 if $IM < IM_{PL,m}$; 1 otherwise); ρ_m is the weight that has to be assigned to each macroelement. Finally, the value of $IM_{PL,G}$ is obtained as the minimum of the following two conditions: (1) the lower value of IM for which the fragility curve has $P_{PL}(IM) \geq 0.5$; (2) the value of IM for which the fragility curve of the performance level (k + 1) is greater than 0.

4.2 Examples of Application: The Hassan Bey's Mansion in Rhodes and the Great Mosque of Algiers

The procedure illustrated in previous sections is applied to two assets, the Hassan Bey's Mansion in Rhodes and the Great Mosque in Algiers, which belong to Classes A and B, respectively. Only the PBA of the global response is considered, by focusing herein the attention to some specific aspects of the procedure: (1) the selection of the proper modelling strategy; (2) the definition of performance levels on the capacity curve; (3) the analogies and differences in applying the proposed multiscale approach to such different classes. Moreover, the effect of increasing the stiffness of diaphragms as a possible strengthening intervention is discussed for both assets. More detailed information and results on these two buildings may be founded in [29] and [30] where: in the case of Hassan Bey's Mansion, the use of sensitivity analysis for planning the investigation tests and the effect of uncertainties are also illustrated; while in the case of Great Mosque, an in depth discussion is present on the integrate use of different modelling strategies and the definition of the mechanical properties.

4.2.1 Choice of the Modelling Strategy

The Hassan Bey's Mansion is a typical Ottoman mansion located in Rhodes (Greece), built at the end of the eighteenth century, which has undergone many changes during the nineteenth century. It consists of two storeys and an attic at the South-East corner, with overall dimensions 17.75 m by 15.50 m. The plan is quite regular; the wall thickness varies between 0.35 and 0.60 m at the ground floor, while it is thinner (about 0.27 m) at the upper levels (first storey and attic). The building is a masonry structure formed by sandstones and lime mortar: a rubble masonry characterizes the ground floor, while a cut stone masonry the other levels (ashlar masonry). Diaphragms are made by timber floors (with a single boarding), while the building is covered by wooden ceiling (and the attic by wooden roof and French tiles). Actually the building is not in use and characterized by a very bad maintenance state: thus, the PBA carried out refers to the original state of the building, where "original" means before the ongoing deterioration, in order to provide information on the original safety level of the structure.

The Great Mosque, also known as El Jedid Mosque, is located in Algeria's capital city. It was built in 1097 under the direction of Sultan Ali Yusuf (1106–1142), and it is the oldest mosque in Algiers as well as one of the few remaining of Almoravid architecture. Its architectural features and layout, with naves perpendicular to the *qibla* wall, and its rectangular courtyard, bordered on both its narrower sides by a *riwaq* (gallery), were destined to become a model of much religious architecture, particularly in al-Aqsa Maghreb mosques in Algeria. The building is almost square in plan, measuring approximately 40 by 50 m. The interior is a series of hallways, passages and rooms, with the common theme of pillars and archways throughout the building based on a 9 by 11 grid.

According to the architectonic asset classification proposed in PERPETUATE [27] and on basis of the specific features and the expected seismic behaviour of these assets, Hassan Bey's Mansion belongs to Class A—*Assets subjected to prevailing in-plane damage* while the Great Mosque to Class B—*Assets subjected to prevailing out of plane damage*. For this latter such assumption is supported by the fact that the building is characterized by a large hall partitioned by a set of orthogonal system of arcades, without any intermediate horizontal diaphragms, except the wooden roof that is not enough stiff to guarantee a "box-behaviour". Following this classification, the modelling strategies illustrated in Fig. 11 have been adopted.

In particular, in the case of Hassan Bey's Mansion a global 3D model has been assumed by adopting a Structural Element Model (SEM) based on the equivalent frame approach by using the software Tremuri [31]. The choice of such approach is justified by the quite regular opening pattern; moreover, the use of a software able to simulate the presence of flexible floors (modelled as orthotropic membrane finite elements) is essential for the simulation of the original state of the building. Moreover, a distinctive feature of the building is the presence of many infilled openings consequent to the various transformations that occurred during the centuries. In the following, results presented refer to a model in which they have been considered as windows (thus assuming the infill material as not able to interact effectively with the original masonry panels of the building), while in [29] this uncertainty has been analytically treated by the logic tree approach.

On the contrary, in the case of Great Mosque, the most suitable modelling strategy is different for each type of macroelement that constitutes the building in two orthogonal directions, that is: (1) the system of internal arcades; (2) the four external walls; (3) the portico (forward the NW façade). In particular, while the external walls and the portico have been modelled through the equivalent frame approach, for the arcade system a Macro Block Model (MBM) by using the MB-PERPETUATE software [32] has been adopted (Fig. 11). Indeed, in the examined case, the a priori identification of the kinematism to be analysed by the limit analysis has been supported by the combined use also of a detailed finite element model (Fig. 12). In particular, the latter has been performed by using ANSYS software and by assuming the constitutive laws proposed in [33, 34] to describe the nonlinear response of masonry material. Further details on the models and mechanical properties adopted are illustrated in [30].

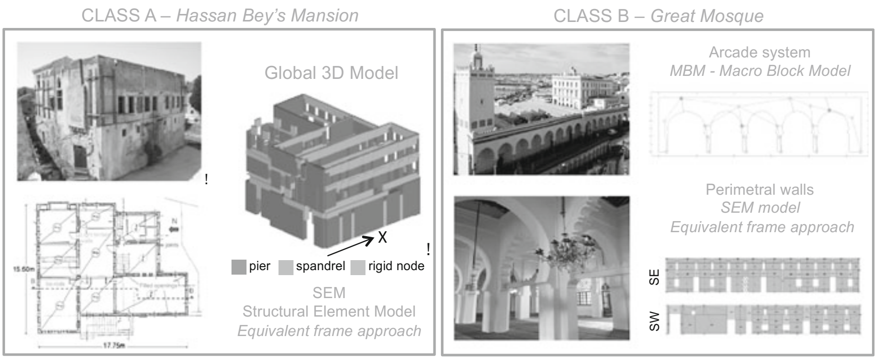

Fig. 11 Modelling strategy adopted in case of Hassan Bey's Mansion (belonging to *Class A*) and Great Mosque (belonging to *Class B*)

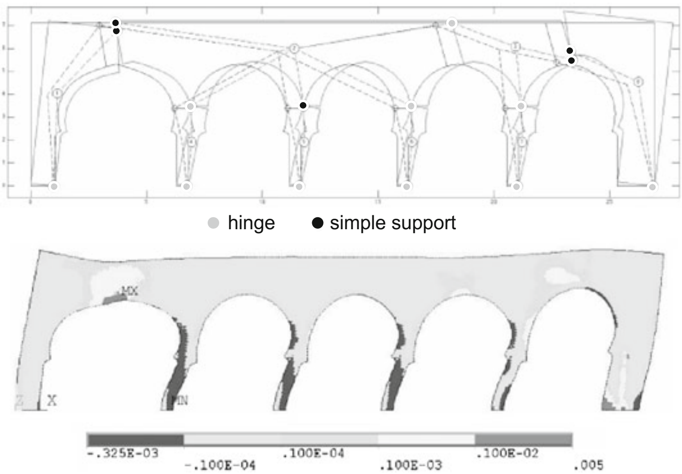

Fig. 12 Kinematism analysed for the Y5 arcade through the MBM model and inelastic strain perpendicular to bed joints, obtained by means of the CCLM model, from [30]

4.2.2 Nonlinear Analyses and Definition of Performance Levels

Once selected the most suitable modelling strategies, the PBA proceeds with the execution of nonlinear static and kinematic analyses in case of SEM and MBM models, respectively. As aforementioned, one of the most critical issues in PBA is the adoption of proper criteria to define the performance levels on the pushover curves. Firstly, it is necessary to specify the PLs selected for the examined buildings. For the Great Mosque the considered PLs are: 2U—*Immediate occupancy*, 3U—*Life Safety* and 3B—*Significant but restorable damage*; on the contrary, only the PL 3B is assumed for the Hassan Bey's Mansion. Indeed, in the case of Great Mosque also the verification with respect to the preservation of an artistic asset has been considered: it consists in a *mihrâb* constituted by an arched niche decorated by two spiral column on the both sides, some stuccos and small decorated tiles attached to South-East (SE) wall.

In particular, the position of PLs has been assumed to be coincident with the corresponding damage levels (DL). These latter have been computed on basis on the multiscale approach proposed in [23] in case of SEM models and on basis of the criteria proposed in [28] in case of MBM ones.

For the Great Mosque, PLs have been defined for each macroelement. In particular, Fig. 15b) illustrates their position in case of two arcades representative of the recurring systems in X and Y directions: performance level 2U corresponds to the intersection between the elastic branch and that from the incremental kinematic analysis; while, PLs 3U/3B (assumed to be coincident) correspond to a displacement capacity equal to $0.25d_0$, where d_0 is the displacement in which the capacity curve is zero. It is worth noting that the initial branch of the pushover curve (that correspond to a period equal to 0.55 and 0.6 s in case of Y5 and X11 arcades,

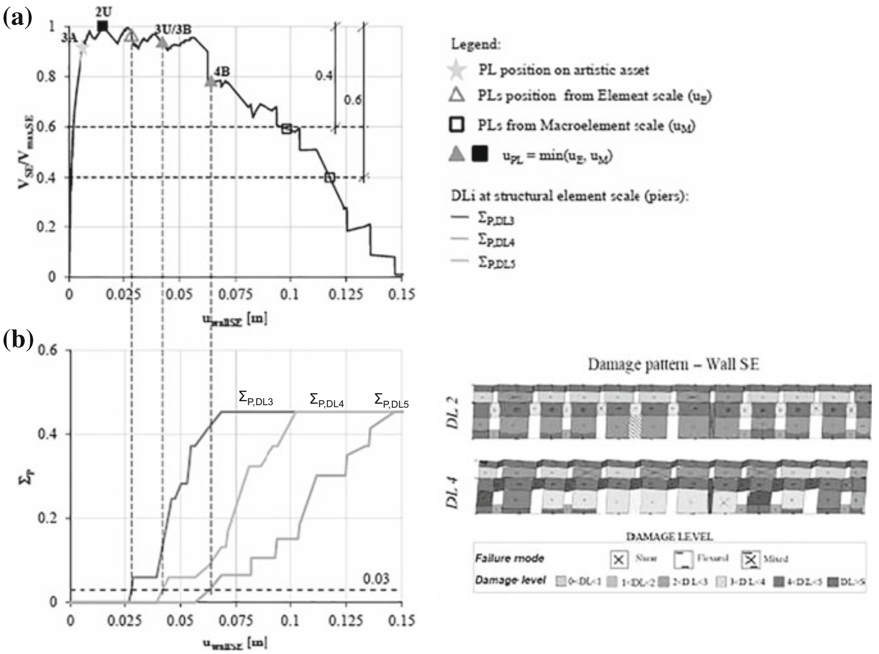

Fig. 13 Definition of PLs on the pushover curve of SE wall of Great Mosque according to the multiscale approach (by the strips is indicated the pier which the *mihrâb* is connected to) (adapted from [30])

respectively) has been calibrated on basis of results coming from the detailed finite element model. Figure 13 depicts the application of the multiscale approach for the SE perimetral wall, in which the variables monitored are: the cumulative rate of piers (Σ_P) and spandrels (Σ_S) that reached a certain damage level at local scale (where the summation is extended to the elements present in each macroelement); fixed rates of the base shear of the macroelement examined. In this case, checks at structural element scale tend to prevail.

The application of the multiscale approach in the case of Hassan Bey's Mansion has been extended by monitoring the reaching of fixed values of the interstorey drift in each wall (see Fig. 14 for those oriented in X direction) and fixed rates of the overall base shear; moreover, at element scale, the summation has been extended to all the elements present in the building. Finally, Fig. 15a) shows the final position of DLs (assumed as reference to define the corresponding PLs) on the overall pushover curves for X and Y directions, deriving from the minimum among checks performed at three different scales. Checks performed at macroelement scale tend to prevail in this case: this is mainly due to the fact that in the original state, the seismic response of Hassan Bey's mansion is strongly affected by the presence of flexible diaphragms that do not allow the distribution of actions among the walls (as evident from Fig. 14).

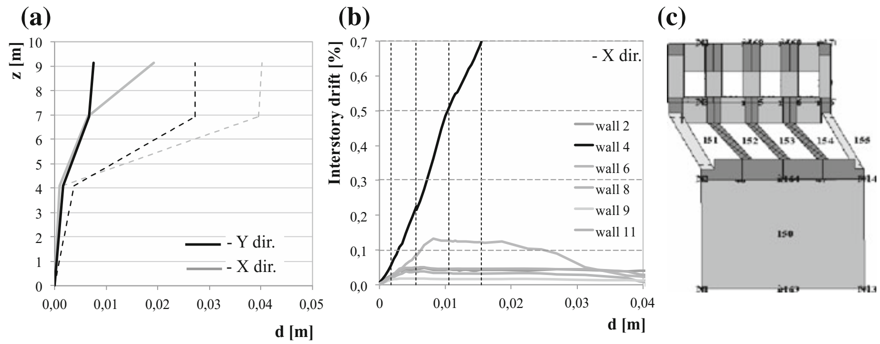

Fig. 14 Role of checks at macroelement scale (in terms of interstorey drift) in case of Hassan Bey's Mansion: **a** profile of the deformed shape in height at DL3 (*continuous line*: mean value; *dotted line*: maximum value occurred), **b** evolution of interstorey drift at first level in case of -X dir. (*vertical lines* correspond to the DLs coming from the multiscale approach, *horizontal lines* indicate the thresholds assumed as reference at macroelement scale), **c** damage pattern of Wall 4 (see Fig. 10 for the legend) (adapted from [29])

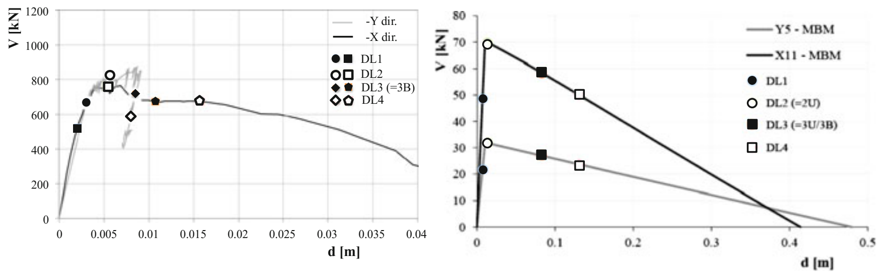

Fig. 15 Definition of PLs on the pushover curves of: **a** Hassan Bey's Mansion (*circles* indicated the DLs in Y direction, while *square* for the X direction), **b** two arcade systems of Great Mosque

4.2.3 Performance Based Assessment and Computation of the Maximum IM Compatible with the Fulfillment of Performance Levels

Once the pushover curves have been obtained and the PLs fixed on them, the PBA consists of computing the value of $IM_{kn,G}$. In both cases, the Peak Ground Acceleration (PGA) has been assumed as reference IM, being the two assets quite rigid. In particular, the computation of $IM_{kn,G}$ is based on the use of overdamped spectra [26], while the conversion of the pushover curve (representative of the MDOF system) in the capacity curve (equivalent SDOF) is made: (1) through the participation coefficient (Γ) and the participation mass (m^*), according to the proposal originally illustrated in [35], in the case of nonlinear static analyses (SEM model); (2) as explained in [28], in the case of nonlinear kinematic analyses (MBM model).

In the case of the Great Mosque, the computation of $IM_{kn,G}$ at global scale passes from that of each single macroelement ($IM_{kn,m}$). In particular, Fig. 16 shows the construction of the global fragility curves according to (1).

Table 2 summarizes the resulting values of $IM_{kn,G}$ for two examined assets, where the reference target values of the seismic demand are also reported (in terms of PGA), which have been computed on basis of the probabilistic seismic hazard analysis illustrated in [36]. The return periods assumed as reference $\bar{T}_{kn}$ reflect the importance coefficients assumed for the two assets, equal to 1 in the case of requirement related to the building conservation (B) but equal to 1.2 in the case of that related to the use and human life (U) in the case of the Great Mosque (due to its condition of use, frequent and subjected to possible crowding). As evident from Table 2, both assets show some deficiencies in fulfilling the required PLs: very strong in the case of Hassan Bey's Mansion in both directions and in particular in Y direction in the case of the Great Mosque.

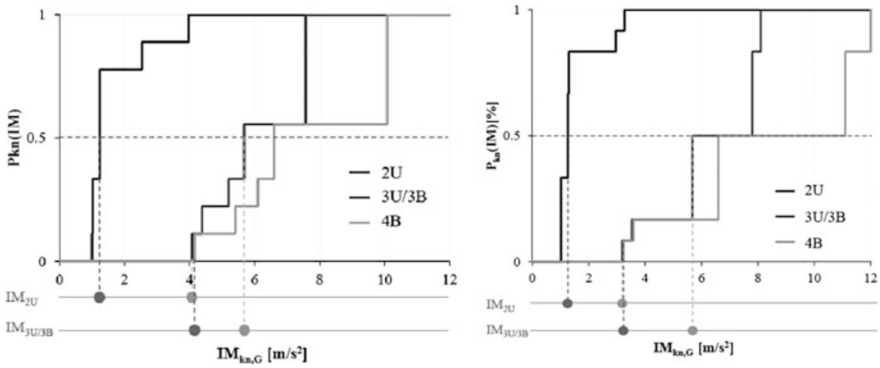

Fig. 16 Great Mosque case study: fragility curves representative of the seismic behaviour of the whole asset in *X* (*left*) and *Y* (*right*) directions and computation of $IM_{kn,G}$ [30]

Table 2 $IM_{kn,G}$ values and target seismic demand for two examined case studies

Case study	$\overline{PGA}$ (m/s^2) ($\bar{T}_{kn}$[*years*])			$IM_{kn,G}$ (m/s^2) (T_{kn}[years])			
	2*U*	3*U*	3*B*	2U		3U/3B	
				X	*Y*	*X*	*Y*
Hassan Bey's Mansion	–	–	1.78 (475)	–	–	0.55 (95)	0.71 (119)
Great Mosque	1.96 (120)	3.8 (570)	3.55 (475)	1.10 (55)	1.23 (63)	4.16 (692)	3.23 (383)

4.3 Preventive Strategies by Strengthening Interventions

The PBA in the original state of the two examined assets highlighted the need of strengthening interventions. In the following the effect of a possible intervention consisting in the stiffening of diaphragms is illustrated. In both cases it could be achieved by adopting some solutions still based on the conservation of timber floors (e.g. based on a double boarding), thus more compatible in terms of preservation and also more effective for the seismic response, because these solutions are not associated to a significant increase of masses.

While in the case of Hassan Bey's Mansion such intervention only affects the capability of floors to redistribute the actions among walls, in the case of the Great Mosque it modifies more significantly the behaviour, that now involves the independent response of each wall/arcade while in the strengthened configuration consists of a "box-type" structure, passing from Class B to Class A. The change in the class implies the modelling strategy has to be updated, requiring the adoption of a global 3D model. Among the different possible choices, the SEM approach has been considered due to its quite limited computational effort. However, in order to provide a reliable response not only for ordinary walls but also for the arcade system, in this latter case it has been necessary to calibrate: (1) the geometry of the equivalent frame idealization; (2) the mechanical parameters of masonry to be adopted in order to correctly simulate the damage response. To this aim, results achieved through the MBM and finite element models constituted as essential supporting tool. Figure 17 illustrates by way of example the complete 3D SEM model and a sketch aimed to clarify the rules adopted in the equivalent frame idealization of arcade systems.

Figure 18 shows the resulting pushover curves for the Great Mosque in X and Y directions and the final position of the PLs that have to be checked (defined on basis of the application of the multiscale approach aforementioned). In terms of PBA and computation of $IM_{kn,G}$, the intervention revealed to be quite effective leading to the fulfilment of all PLs, corresponding to a value of 2.65 and 3.96 m/s^2 in *Y* direction (the most critical one) for 2U and 3U/3B, respectively.

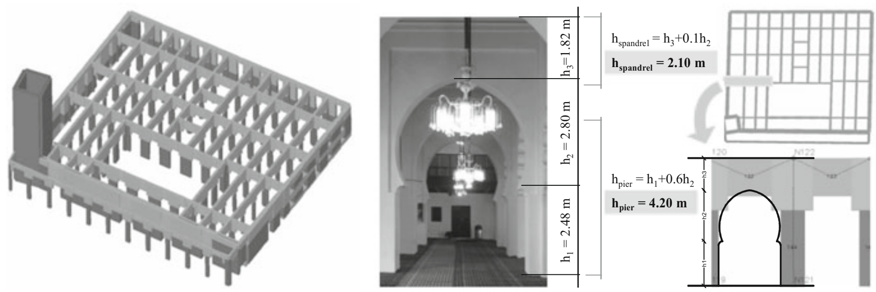

Fig. 17 3D SEM model of the Great Mosque and rules adopted for the equivalent frame idealization of the arcade system [30]

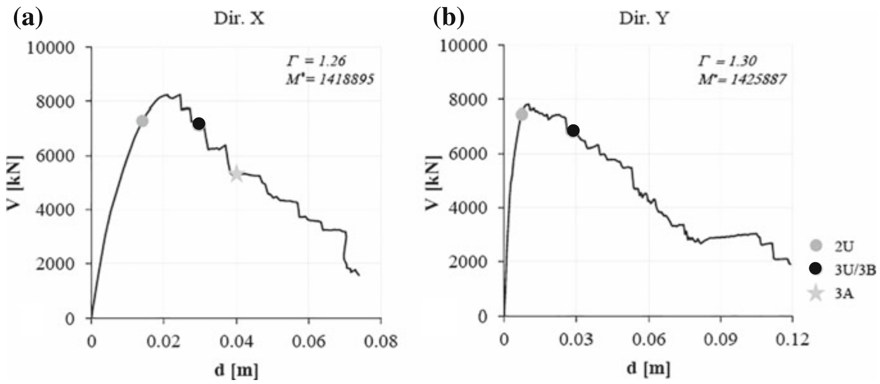

Fig. 18 Pushover curves obtained on the 3D model of Great Mosque and position of performance levels (adapted from [30])

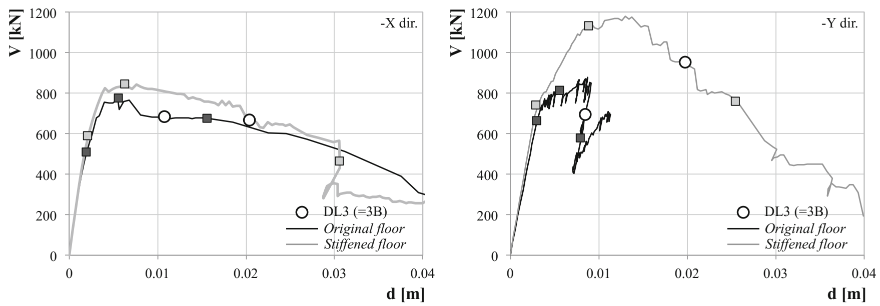

Fig. 19 Effect of floor stiffening in case of the Hassan Bey's Mansion on the positioning of damage levels on the pushover curve (adapted from [29])

Figure 19 shows the effect of diaphragm stiffening in terms of pushover curves and position of PLs in the case of Hassan Bey's Mansion. As evident, the *Y* direction is greatly affected in terms of both base shear and global ductility by the effect of the improved actions redistribution among walls. This is highlighted also by the damage pattern (Fig. 11), from where it is apparent that the damage is distributed among the different walls and not concentrated only in some of them.

Although in the case of *Y* direction the beneficial effect of such intervention is more evident than in *X*, it is interesting to note that in this latter case it affects the DLs position on the pushover curve (Fig. 19). In fact, more rigid floors tend to produce a more homogeneous behaviour limiting the occurrence of very high interstorey drift values in some single walls, this latter condition being very critical for the premature attainment of DL3 and DL4 in the case of flexible floors (see Fig. 20 and also Fig. 6). Indeed, the multiscale approach adopted revealed to be quite effective in capturing the effects on modification of such types of local behaviours. Despite this, in terms of final outcome of the PBA (values of $IM_{kn,G}$), in

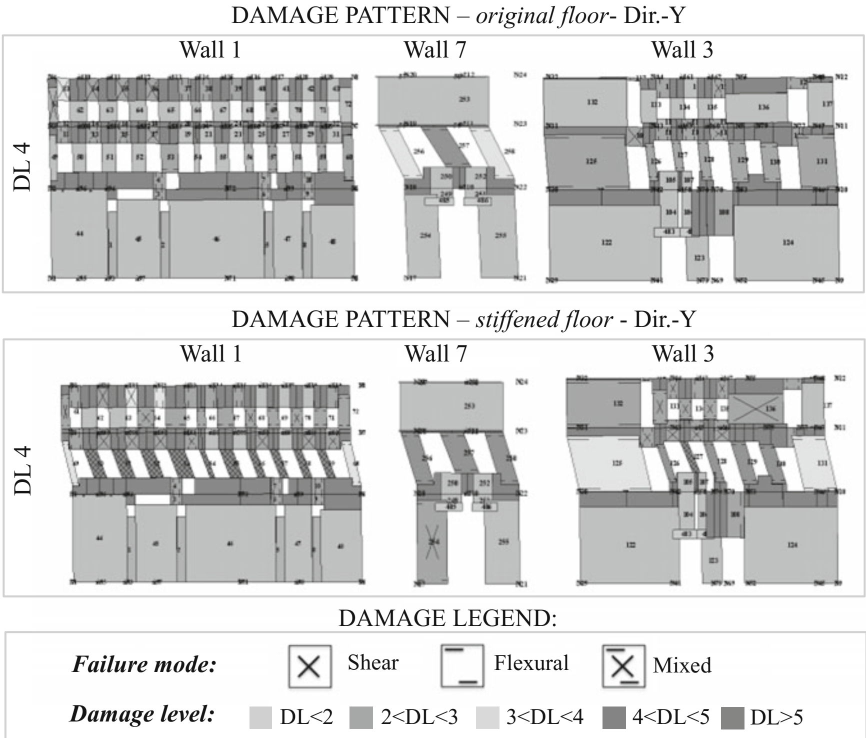

Fig. 20 Effect of floor stiffening in case of the Hassan Bey's Mansion on the damage pattern and the overall response (adapted from [29])

the case of Hassan Bey's Mansion such intervention proved to be not decisive. Indeed, the building is characterized by some strong structural deficiencies (like as the presence of very thin walls, numerous openings or of flue that strongly reduce the seismic capacity of walls), which require a more invasive strengthening.

5 Conclusions

The preservation of cultural heritage assets should consider both the monitoring of slow processes (material deterioration, anthropic transformations and climate change effects) and the risk associated with natural hazard (rare catastrophic events such earthquakes, floods, fire and cascading events).

With reference to the first aspect, the case study of the Tower of the University of Coimbra has proved the importance of the following steps:

– Diagnosis and appraisal—The importance and influence of the survey and appraisal must not be underestimated. It is the natural point of interest at which

all interested and involved parties will focus and discuss, identifying the needs of the building, understanding the buildings and finally putting forward solutions, demands, decisions and good practices;
- Structural assessment tools—A finite element model of the Tower of the University of Coimbra was developed and calibrated on the basis of vibration measurements and modal analysis using modal extraction techniques in the frequency domain. As is fully discussed in [15], despite the lack of information in relation to parameters with direct influence on the structural behaviour of the Tower, such as the supporting conditions and the mechanical characteristics of the materials, the analysis of the results obtained allows to conclude that the numerical model satisfactorily reproduces the dynamic response of the Tower;
- Pedagogical and scientific use—The excellent receptivity of all publics, the final positive evaluation and the reduced costs of the initiative lead to the conclusion that the process should be studied and organised in order to expand its implementation, not only in the University of Coimbra, but also in all the places were built heritage is a relevant resource and should be closer to populations and carefully protected and promoted.

Regarding the second aspect, related to the vulnerability to natural hazards, the relevant problem of seismic assessment has been deepened by the description of the PBA procedure for cultural heritage assets developed within the PERPETUATE project [23] pointing out as follows:

- Numerical analysis—The procedure has been applied to two different ancient masonry structures, a building and a mosque. These two structures highlighted how the choice of the most reliable modelling strategy needs to properly consider the specific configuration and the behaviour expected for the asset under examination. In some cases the combined use of different modelling strategies reveals very effective to manage the model uncertainties;
- PERPETUATE procedure—The parallel description of the different steps of PERPETUATE procedure on two case studies highlights its capability to treat the problem of seismic assessment within a general common framework. A distinctive feature of ancient masonry structures is the absence of rigid horizontal diaphragms; to this end, the proposed models appears to be able to describe the actual behaviour of these structures and the multiscale approach, differently formulated for "box-type" and macroelement structures, turns out to be able to define the displacement thresholds correspondent to each Performance Level.
- Strengthening interventions—Such displacement thresholds revealed to be quite effective also in capturing modifications in the behaviour induced by strengthening interventions not so evident in terms of the overall pushover curve (like as the case of the Hassan Bey's Mansion).

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