SEISMIC PERFORMANCE-BASED ASSESSMENT AND PRESERVATION OF HISTORICAL MASONRY CONSTRUCTIONS

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Keywords: Preservation of cultural heritage, Displacement-Based Assessment, Masonry.

Abstract. Earthquakes always have caused heavy damage to cultural heritage assets. Despite the long durability of historical constructions, when subjected to proper maintenance, the occurrence of an earthquake represents a high risk for the conservation. Indeed, after any strong earthquake the necessary restoration requires strengthening and, often, partial reconstruction of elements, with a significant loose of the authenticity of the building. Therefore, it is necessary to have tools to implement a preventive policy, which takes into account the conservation requirements. For the assessment of historical masonry constructions the qualitative approach is not sufficient, both because the seismic behavior is complex and it is necessary to take also into account the safety requirements; thus, it is unavoidable to refer to a quantitative approach, even though not trivial. Aim of the paper is to propose a Performance-Based Assessment procedure for the seismic preservation of historical masonry constructions, developed within the framework adopted by well-know international standards for existing ordinary buildings. To this end, the main results of the European Research Project PERPETUATE are illustrated, which constitute a well-defined procedure that can be adopted for different types of monumental structures (palaces, churches, mosques, towers, obelisks, archeological remains, etc.). The main features are: 1) how to deal with the incomplete knowledge; 2) how to model the seismic behavior of complex masonry structures till to near collapse conditions. The use of sensitivity analysis is proposed to plan in-situ investigations and define proper confidence factors. Different modeling approaches and assessment procedures are proposed, depending on the type of structure, which are illustrated by considering two case studies. The use of the Performance-Based Assessment helps also in the selection and comparison of different preventive actions, which can be oriented to local or widespread interventions, being anyhow the result of a global assessment of the seismic behavior.
1 INTRODUCTION

Ancient monumental masonry buildings are complex structures that were not based on an engineered design, underwent many transformations during their life and, very often, present lack of connections among the structural elements. Earthquakes are the main cause of damage for ancient masonry constructions, such as churches, palaces and towers [1, 2, 3]. Earthquakes also proved that strengthening interventions adopted in the last century are invasive and sometimes are not effective or even increase the vulnerability. 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.

The preservation of cultural heritage assets must guarantee their capacity of lasting over time against decay, natural hazards and accidental events, without losing, as much as possible, their authenticity. However, there is the need of guaranteeing the structural safety for occupants, connected with the use of the building. To this end it is necessary to make reference to the principle of “minimum intervention”, under the constraint of an “acceptable safety level”, a concept that still represents an open issue for monumental buildings. Furthermore, besides the preservation of the architectural value of the building, also unmovable artistic assets should be considered in the assessment, such as: frescoes, stucco-works, pinnacles, battlements, banisters, balconies etc.

The seismic assessment of existing buildings is a complex task, basically for two different reasons: a) the difficulty of interpreting and modeling the seismic response, because they have been designed without aseismic provisions and, in the case of ancient masonry structures, by an empirical approach; b) 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 investigations.

The best known and credited international standards (Eurocode 8-Part 3 [4], FEMA 356 [5]) adopt 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, as the use of linear analysis with the behavior factor approach is not reliable enough.

The specific case of cultural heritage assets is treated in some recommendation documents [6, 7, 8], 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. All documents 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 modeling strategy. All these recommendations stress the importance of the qualitative approach, funded on the historical analysis, the accurate investigation of structural details and the interpretation of seismic behavior, on the basis of observed damage on the building (due to previous events, if any) or on similar structures.

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 behavior 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 [9] clearly states 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 [10] 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 (Eurocode 8-Part 3, FEMA 356). 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.

This PERPETUATE guidelines [11] offer the general methodological path and operative tools for the assessment of different historical architectural assets; a classification is proposed in [12], which is related to the different types of seismic behavior, considering both building morphology (architectural shape and proportions) and technology (type of masonry, horizontal diaphragms, effectiveness of wall-to-wall and floor-to-wall connections). It consists of six architectonic classes: A) box-type buildings; B) assets analyzable by independent macroelements; C) slender structures analyzable by monodimensional models; D) arched structures; E) massive structures; F) blocky structures subjected to rocking. Different modeling strategies can be adopted for describing the seismic behavior of each kind of asset. 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 columns); Q) artistic assets strictly connected to structural elements (e.g. frescoes, mosaics, stuccoes); R) artistic assets that are independent elements. Moreover, the problem of seismic local 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. This local analysis is also necessary for the verification of artistic assets of class R.

Within this context, the paper briefly describes the basics of PERPETUATE guidelines, with particular attention on two specific classes of architectonic assets, according to the above-mentioned PERPETUATE classification: class A), characterized by the so-called “box-behavior” (e.g. palaces, castles, …); class B), described by the seismic response of independent macroelements (e.g. churches, mosques, …). An example of application on two assets, the Hassan Bey’s Mansion in Rhodes and the Great Mosque in Algiers, is briefly presented in order to highlight the main distinctive features of the proposed procedure.

Finally, some comments on possible seismic strengthening strategies are provided, highlighting the usefulness of a quantitative assessment for the selection of the most effective and less invasive solutions.

2 BASICS OF PERPETUATE GUIDELINES

Seismic Performance-Based Assessment (PBA) of an existing building checks if the construction is able to fulfill some selected Performance Levels (PLs) in case of occurrence of properly defined earthquake hazard levels, in terms of annual rate of exceedance $\lambda$ (or return period $T_R=1/\lambda$).

Target PLs are properly defined in PERPETUATE guidelines for cultural heritage assets [11], which consider not only the use and safety of people but also the conservation of the architectural and artistic value of the monument. Therefore, target PLs are defined (Figure 1) with reference to three different groups of Safety and Conservation requirements ($n=U,B,A$):
- **Use and human life** (U): also for a cultural heritage asset, similarly to ordinary buildings, the possibility of an immediate occupancy after an earthquake and the protection of human life have to be considered;
- **Building conservation** (B): due to the intangible value of a cultural heritage asset, the preservation from building damage is not related, as for ordinary buildings, to the costs of repair or rebuilding but to the possibility of restoration or to the collapse prevention, in order to maintain, at least, the monument as a ruin;
- **Artistic assets conservation** (A): in many cases, severe damage to artistic assets occurs also in the case of moderate damage to structural elements; therefore, it is necessary to define specific PLs for each relevant artistic asset in the building moreover.

PLs are obviously correlated to the seismic response of the structure, which is empirically defined, in macroseismic post-earthquake assessment [13], by observational **Damage Levels** (DLs): 1) slight; 2) moderate; 3) heavy; 4) very heavy; 5) collapse.

![Figure 1: PERPETUATE performance levels, corresponding damage levels and related target return periods](image)

Figure 2 summarizes the basic steps of PBA according to the procedure of these 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). The pushover curve represents the capacity of the historical building in terms of total base shear versus displacement $u$ of a reference point; DLs are identified on the pushover curve through proper thresholds (in particular a multiscale approach is proposed for complex building, taking into account the damage in single elements, macroelements and at global scale).

The seismic demand 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 [14]. 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.

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Figure 2: Performance-based assessment of architectural and artistic assets by the PERPETUATE procedure.

The outcome of the assessment is $IM_{PL}$, which is the maximum value of the intensity measure that is compatible with the fulfillment of each target PL: it is directly computed, without any iterative procedure, by the capacity spectrum method with overdamped spectra [15]. Thus, through the hazard curve, it is possible to evaluate the annual rate of exceedance $\lambda_{PL}$ of the earthquake correspondent to this performance (or its return period $T_{R,PL}=1/\lambda_{PL}$). These values are compared with the target earthquake hazard levels $T_{R,PL} = 1/\lambda_{PL}$, defined for the assessment as a function of the asset characteristics, in terms of safety and conservation requirements (Figure 1) and properly calibrated through an importance factor $\gamma_n$, in order to take into account the architectonic and artistic value, as well as the condition of use.

Rehabilitation decisions can be assumed thanks to the result of the assessment. Different conservation and preventive strategies can be assumed: a) no intervention, if the building in its actual state is able to fulfill the required PLs; b) interventions are necessary but can be postponed, because the safety is not far from what expected (in this case it is possible to estimate, from a probabilistic point of view, the time available before the intervention); c) retrofitting interventions, compatible as much as possible with the conservation requests (principle of “minimum intervention”), are necessary now. Whether, in order to fully fulfill the safety requirements, strengthening techniques would be too invasive, it is better to adopt only partial solutions, by postponing further interventions in a future time, when more information on seismic hazard in the region, improved numerical models for the structural analysis and new more effective and less intrusive techniques will be available. In all cases, the implementation of a Structural Health Monitoring (SHM) system is advisable, in order to detect any change in structural elements and connections and record any future event (microtremors or low intensity earthquake), with the aim of a model updating for the next safety evaluations.
2.1 Knowledge of the building, sensitivity analysis and investigations

The acquisition of the best possible knowledge for the definition of the structural model of the building is referred to: geometry of structural elements; foundations; material properties; historical data on transformation and damage; state of maintenance and damage mechanisms identification (in case of post-earthquake assessment); dynamic behavior. However, in case of historical masonry buildings it is necessary to consider that the number of investigations should be minimized for reducing the impact on conservation, as well as the costs.

In order to consider in the assessment the uncertainties due to incomplete knowledge, the common approach adopted by standards for existing structures [4, 5] is based on the definition of a discrete number of Knowledge Levels (KL), achievable as a function of gathered information, and on the application of a Confidence Factor (CF) to one parameter of the assessment, assumed a priori as the most affecting the assessment.

The PERPETUATE procedure has introduced the sensitivity analysis as essential tool for the seismic assessment of existing and monumental buildings [16], with the aim to:
- identify the parameters that most affect the structural response, allowing to optimize the investigation plan and strengthen the link between knowledge and assessment;
- include explicitly in the methodological path the evaluation of uncertainties, by considering both aleatory (treated as random variables) and epistemic (treated by the logic tree approach) ones, as well as the model error contribution;
- select properly (instead of a priori) the parameter for the application of CF and calibrate its value (instead of assuming it conventionally).

The use of sensitivity analysis is codified in a well-defined procedure, subdivided into four steps (Figure 3): 1) preliminary knowledge; 2) sensitivity analysis; 3) plan of investigations and execution of tests; 4) evaluation of the CF for the final assessment.

![Flowchart of the procedure for planning investigations through the use of sensitivity analysis.](image)

**Figure 3:** Flowchart of the procedure for planning investigations through the use of sensitivity analysis.

### 3 PBA PROCEDURE OF COMPLEX ARCHITECTONIC ASSETS

In this paper the attention is focused on the PBA of complex historical buildings. The procedure (Figure 4) is specified for two examples that can be considered representative of assets belonging to classes: A - assets with a box behavior (e.g. palaces, castles,...) and B - assets analyzable by independent macroelements (e.g. churches, mosques,...).
In the first case a global 3D model of the whole building is used, which assumes the in-plane response of masonry walls, by considering vertical piers and horizontal spandrels through the equivalent frame approach [17]. 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 [11] that takes into account the asset response at different scales: structural elements scale (local damage, E), architectonic elements scale (damage in macroelements, M) and global scale (pushover curve, G). Through the evolution of these variables it is possible to define the displacement on the overall pushover curve corresponding to a certain DL as the minimum among displacements corresponding to the attainment of those conditions.

In the case of Class B, the building is subdivided and modeled by a set of \( N_m \) independent macroelements; seismic load can be assigned by considering for each macroelement its own inertial mass or by a proper redistribution, if some limited interaction is expected. Once the \( IM_{PL,m} \) for each macroelement that composes the asset is evaluated, the assessment of the whole asset \( (IM_{PL,G}) \) is then made through a proper combination of results achieved in each macroelement. Also in this case a multiscale approach is proposed, aimed to define a fragility curve of the whole asset by combining the contribution offered by each macroelement. In particular, it is computed as:

\[
P_{PL}(IM) = \sum_{m=1}^{N_m} \rho_m H(IM - IM_{PL,m})
\]  

where: H is the Heaviside function (0 if \( IM<IM_{PL,m} \); 1 otherwise); \( \rho_m \) 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: i) the lower value of \( IM \) for which the fragility curve has \( P_{PL}(IM) \geq 0.5 \); ii) the value of \( IM \) for which the fragility curve of the performance level \((k+1)\) is greater than 0.

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Figure 4: Exemplification of the procedure for the PBA of assets of Classes A and B.
3.1 Seismic assessment of possible local mechanisms

The seismic assessment is comprehensive if also possible local mechanisms are considered, which involve only the response (usually the out-of-plane behavior) of a portion of the building that is not properly analyzed by the global numerical model; thus, they are studied by a different specific local model, by considering only a fraction of the total mass.

In general, these mechanisms have to be considered only if they are relevant for the PLs of the examined asset. If \( N_o \) local mechanisms have been selected for the given PL, the PBA of these mechanisms provides, as in the case of the global asset scale, the values \( IM_{PL,o} (o = 1..N_o) \) that are compatible with the attainment of the examined PL for each mechanism. The final outcome of the PBA is given by:

\[
IM_{PL} = \min \{ IM_{PL,G} ; IM_{PL,o} (o = 1..N_o) \}
\]

(2)

where \( IM_{PL,G} \) is the value obtained at the global scale, with the use of a global model or after the evaluation in all the macroelements (1).

Since local mechanisms usually involve portions located at a higher level of the building (different from the ground floor), it is necessary to adopt proper modified response spectra aimed to take into account the filtering effect provided by the structure. By considering analytical floor spectra [18] and after a calibration supported by nonlinear dynamic analyses, the following simplified expressions are proposed [19]:

\[
S_{dZ}(T, z) = \max \{ S_d(T) ; \sum_1^{N_r} S_{dZ,r}(T, z) \}
\]

(3)

where: \( S_d(T) \) is the displacement response spectrum of the ground motion; \( N_r \) is the number of considered building modes; \( S_{dZ,r}(T, z) \) is the contribution of mode \( r \) that is given by:

\[
S_{dZ,r}(T, z) = \begin{cases} 
S_d(T_r) \frac{\gamma_k \psi_k(z) \left( \frac{T}{T_r} \right)^2}{\sqrt{\left(1 - \frac{T}{T_r} \right)^2 + \frac{0.05}{\eta(\xi_b) \eta(\xi) \psi_k(z)} \frac{T}{T_r}}} & T < T_r \\
S_d(T_r) \eta(\xi) \eta(\xi_b) \gamma_k \psi_k(z) \left( \frac{T}{T_r} \right)^2 & T_r \leq T \leq 1.9T_r \\
3.8\eta(\xi) \eta(\xi_b) \gamma \psi(z) S_d(T_r) & T > 1.9T_r 
\end{cases}
\]

(4)

where: \( T_r \), \( \psi_k \) and \( \gamma_k \) are period, modal shape and coefficient of participation of mode \( r \), respectively; \( \eta(\xi) \) and \( \eta(\xi_b) \) are the damping correction factors due to equivalent viscous damping of the local mechanisms and the building, respectively.

Figure 5 shows an example of the local mechanism in the belfry, which is typical in the case of a bell tower (an asset of Class C) and summarizes the procedure to compute the final value of \( IM_{PL} \) that have to consider both the global response of the tower and that of the local mechanism in the belfry. In particular, in the specific case the local mechanism is verified with the seismic demand scaled to the \( IM_{PL,G} \) value; this means that it is not necessary to proceed to the computation of \( IM_{PL,L} \) (minimum IM among those related to all possible local mechanisms - \( IM_{PL,L} = \min \{ IM_{PL,o} (o = 1..N_o) \} \), because it is higher than \( IM_{PL,G} \). Thus, in this case, the attainment of the PL due to the corresponding DL at the global scale of the asset (the main body of the tower): \( IM_{PL} = IM_{PL,G} \).

It is worth noting that the approach described above for local mechanisms can be used for the assessment of PLs in artistic assets of Class R (introduced in §1).
4 EXAMPLES OF APPLICATION

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 performance-based assessment of the global response is considered, by focusing herein the attention to some specific aspects of the procedure: i) the selection of the proper modeling strategy; ii) the definition of performance levels on the capacity curve; iii) 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 found in [20, 21] where: in the case of Hassan Bey’s Mansion, the use of sensitivity analysis for planning the investigation tests and the effect of uncertainties on modeling are also illustrated; while in the case of Great Mosque, an in depth discussion is present on the integrate use of different modeling strategies and the definition of the mechanical properties.

4.1 Choice of the modeling strategy

The Hassan Bey’s Mansion is a typical Ottoman mansion located in Rhodes (Greece), built at the end of the 18th century, which has undergone many changes during the 19th century. It consists of two stories 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 m and 0.60 m at the ground floor, while it is thinner (about 0.27 m) at the upper levels (first story 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 ibn 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), was 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 meters. 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 [12] and on basis of the specific features and the expected seismic behavior of these assets, Hassan Bey’s Mansion belongs to Class A - Assets with a box-behavior, while the Great Mosque to Class B - Assets analyzable by independent macroelements. 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-behavior”. Following this classification, the modeling strategies illustrated in Figure 6 have been adopted.

![Figure 6: Modeling strategy adopted in case of Hassan Bey’s Mansion (Class A) and Great Mosque (Class B).](image)

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 [17]. The choice of such approach is justified by the quite regular opening pattern; moreover, the use of software able to simulate the presence of flexible floors (modeled 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 [20] the effect of this uncertainty has been analytically treated by the logic tree approach.

On the contrary, in the case of Great Mosque, the most suitable modeling strategy is different for each type of macroelement that constitutes the building in two orthogonal directions, that is: i) the system of internal arcades; ii) the four external walls; iii) the portico (forward the NW façade). In particular, while the external walls and the portico have been modeled through the equivalent frame approach, for the arcade system a Macro Block Model (MBM) by using the MB-PERPETUATE software [22] has been adopted (Figure 6). Indeed, in the
examined case, the a-priori identification of the kinematism to be analyzed by the limit analysis has been also supported by the combined use of a detailed finite element model (Figure 7). In particular, the latter has been performed by using ANSYS software and by assuming the constitutive laws proposed in [23] to describe the nonlinear response of masonry material. Further details on the models and mechanical properties adopted are illustrated in [21].

Figure 7: Kinematism analyzed for the Y5 arcade through the MBM model (left) and inelastic strain perpendicular to bed joints, obtained by means of the CCLM model (right).

### 4.2 Nonlinear analyses and definition of performance levels

Once the most suitable modeling strategies are selected, 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 (PLs) on the pushover curves. Firstly, it is necessary to specify the PLs selected for the examined buildings, according to the proposal illustrated in Figure 1. For the Great Mosque the considered PLs are: 2U - Immediate occupancy, 3U - Life Safety and 3B - Significant but restorable damage; 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, as illustrated in detail in [21]: it consists in a mihrâb constituted by an arched niche decorated by two spiral columns on both sides, some stuccos and small decorated tiles attached to South-East (SE) wall (Figure 8).

In particular, the position of PLs has been assumed to be coincident with the corresponding damage levels (DL). These latter have been computed by the multiscale approach proposed in [11], in case of SEM models, and on basis of the criteria proposed in [19], in case of MBM ones.

For the Great Mosque, PLs have been defined for each macroelement. In particular, Figure 10b 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 0.25 $d_0$, 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 s and 0.6 s in case of Y5 and X11 arcades, respectively) has been calibrated on basis of results coming from the detailed finite element model. Figure 8 depicts the application of the multiscale approach for the (SE) perimeter wall, in which the variables monitored are: the cumulative rate of piers ($\Sigma_P$) and span-drels ($\Sigma_S$) 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.
Figure 8: 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 mihrāb is connected to).

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 Figure 9 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, Figure 10a shows the final position of DLs on the overall pushover curves for X and Y directions, as deriving from the minimum among the 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 Figure 9).

Figure 9: Checks of interstorey drift at macroelement (wall) scale 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 (vertical lines correspond to DLs coming from the multiscale approach, horizontal lines indicate the assumed thresholds); c) damage pattern of Wall 4 (see Figure 15 for the legend).
4.3 Performance based assessment and computation of the maximum Intensity Measure 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 $IM_{PL,G}$ according to the procedure illustrated in [11]. 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 $IM_{PL,G}$ is based on the adoption of overdamped spectra (as proposed in [15] and adopted also in [5]), while the conversion of the pushover curve (representative of the MDOF system) in the capacity curve (equivalent SDOF) is made:

i) through the participation coefficient ($\Gamma$) and the participation mass ($m^*$), according to the proposal originally illustrated in [24], in the case of nonlinear static analyses (SEM model);

ii) as explained in [19], in the case of nonlinear kinematic analyses (MBM model).

In the case of the Great Mosque, the computation of $IM_{PL,G}$ at global scale passes from that of each single macroelement ($IM_{PL,m}$). In particular, Figure 11 shows the construction of the global fragility curves according to (1).

Table 1 summarizes the resulting values of $IM_{PL,G}$ for two examined assets, where the reference target values of the seismic demand are also reported (in terms of PGA). These latter have been computed on basis of the probabilistic seismic hazard analysis illustrated in [25], for the Hassan Bey’s Mansion in Rhodes, and in [26], for the Great Mosque of Algiers. The return periods assumed as reference $T_{PL}$ 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 1, both assets show some deficiencies in fulfilling the required PLs: very strong and in both directions, in the case of Hassan Bey’s Mansion, and in particular in Y direction, in the case of the Great Mosque.

<table>
<thead>
<tr>
<th>Case study</th>
<th>PGA [m/s²] ($T_{PL}$ [years])</th>
<th>IM kn,G [m/s²] ($T_{kn}$ [years])</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2U</td>
<td>3U</td>
</tr>
<tr>
<td>Hassan Bey’s Mansion</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Great Mosque</td>
<td>1.96 (120)</td>
<td>3.8 (570)</td>
</tr>
</tbody>
</table>

Table 1: IMkn,G values and target seismic demand for two examined case studies.
Figure 11: Great Mosque case study: fragility curves representative of the seismic behavior of the whole asset in X (left) and Y (right) directions and computation of \( IM_{PL,G} \).

4.4 Preventive strategies by strengthening interventions

The PBA in the present 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 the insertion of a double timber boarding), thus compatible in terms of conservation and also effective for the seismic response, because this solution is not associated with a significant increase of masses.

While in the case of Hassan Bey’s Mansion such intervention only affects the capability of horizontal diaphragms to redistribute the seismic actions among walls, in the case of the Great Mosque it modifies more significantly the behavior, 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. Thus, according to this latter issue, also the modeling 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: (i) the geometry of the equivalent frame idealization; (ii) 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, as described in more detail in [21, 27]. Figure 12 illustrates the complete 3D SEM model and a sketch aimed to clarify the rules adopted in the equivalent frame idealization of arcade systems.

Figure 13 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 \( IM_{PL,G} \), the intervention revealed to be quite effective leading to the fulfillment 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.
Figure 12: 3D SEM model of the Great Mosque and equivalent frame idealization of the arcade system.

Figure 13: Pushover curves obtained on the 3D model of Great Mosque and position of performance levels.

Figure 14 shows the effect of diaphragm stiffening in terms of pushover curves and position of PLs in the case of Hassan Bey’s Mansion. As it is evident, the Y direction is greatly affected in terms of both base shear and global ductility by the improved actions redistribution among walls. This is highlighted also by the damage pattern (Figure 15), from which it is evident that the damage is widespread among the different walls and not concentrated only in some of them.

Figure 14: Effect of floor stiffening in the Hassan Bey’s Mansion on the pushover curve and the position of DLs.
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 (Figure 14). In fact, more rigid floors tend to produce a more homogeneous behavior 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 also Figure 9). Indeed, the multiscale approach adopted revealed to be quite effective in capturing the effects on modification of such types of local behaviors.

Despite this, in terms of final outcome of the PBA (values of $IM_{PL,G}$), in 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.

![Damage Pattern](image)

Figure 15: Effect of floor stiffening in the Hassan Bey’s Mansion on the damage pattern and the overall response.

5 GUIDELINES FOR THE SEISMIC ASSESSMENT AND DECISION-MAKING ON INTERVENTIONS

The theoretical, numerical and experimental research developed within the PERPETUATE project has produced exploitable tools and comprehensive procedures for the PBA of cultural heritage assets. The main idea is to consider for historical masonry structures both safety and conservation requirements, by an optimal integration between qualitative and quantitative information. The procedure assumes as essential the use of numerical modeling and nonlinear analysis but makes less mandatory the verification of fixed safety levels; the quantitative assessment of the seismic intensity measure which produces the attainment of the required PLs is anyway necessary, in order to make the procedure repeatable and verifiable.
An important feature of the procedure is the use of sensitivity analysis, which allows limiting the number (and consequently the invasiveness) of in-situ investigations and testing and, at the same time, optimizing their usefulness for the assessment. An original method is proposed for the definition of the Confidence Factor, to be adopted in order to take into account the incomplete knowledge; also the estimate of the model error can be implemented in the assessment, which allows to considers quantitatively those cases in which the qualitative approach proves the actual safety is higher than that provided by the numerical model (this is useful for limiting invasiveness of strengthening interventions, for the sake of conservation).

The application to different case studies has formed the basis for proposing the following guidelines for the seismic assessment and the decision-making on the need of preventive strengthening interventions. The following steps should be followed:

1. QUALITATIVE DIAGNOSIS
   a. Visual inspection of the building.
   b. Recognition of crack patterns, static movements, past earthquakes damage.
   c. Historical analysis (sequence of construction, transformations, interventions).
   d. Identification of the structural system.

   ➔ Foresight of the seismic behavior and the specific vulnerability, taking advantage of the comparative seismic damage observation on similar structures or, if present, of minor seismic damage (it is worth noting that in the case of past strong earthquakes, usually buildings are significantly modified, so it is hard to infer the seismic behavior)

2. PRELIMINARY KNOWLEDGE AND SENSITIVITY ANALYSIS
   a. Geometric survey.
   b. Constructive/structural survey, by visual inspections or non-destructive investigations.
   c. Few non-destructive or slightly-destructive diagnostic tests on material properties.
   d. Structural modeling, by one or more approaches (in case of epistemic uncertainties), and definition of plausible ranges for the parameters (aleatory uncertainties).
   e. Sensitivity analysis, to the above-mentioned parameters and modeling strategies.

   ➔ Detection of the most significant parameters to be investigated, in order to improve the reliability of the assessment

3. PLAN INVESTIGATIONS AND DEFINITION OF CONFIDENCE FACTORS
   a. Choice of the non-destructive or slightly-destructive investigations and diagnostic tests to be performed, in order to improve the knowledge of the most significant parameters, taking also into account the invasiveness and the reliability of each technique.
   b. Execution of the program of investigations and updating of mean geometric and material parameters in the structural model.

   ➔ Evaluation of the Confidence Factor to be used in the assessment

4. PERFORMANCE-BASED ASSESSMENT IN THE CURRENT STATE
   a. Selection of PLs to be considered for the building, in terms of use and safety of human life, building conservation and artistic assets conservation.
   b. Probabilistic Seismic Hazard Assessment in the region, with evaluation of seismic input for different return periods.
   c. Global seismic analysis:
      1. Evaluation of the capacity (pushover analysis).
2. Identification of PLs on the pushover curve, by the multiscale approach (in the case of artistic assets that are strictly connected to structural elements, the correspondent PLs are related to specific points of the pushover curve).

3. Evaluation of the seismic intensity measure values which produce the attainment of each PL \( (IM_{PL,G}) \).

d. Local seismic analyses:
   1. Selection of local mechanisms that are worth to be considered and are not properly modeled by the global analysis (e.g. out-of-plane of portions of the façade, when the numerical model considers only the in-plane behavior).
   2. Identification of artistic elements that are independent (e.g. a carved stone pinnacle).
   3. For each one: evaluation of the seismic demand (floor spectra), of the capacity (with PLs) and of the corresponding intensity measure \( (IM_{PL,L}) \).

e. Evaluation of the seismic intensity measure values that produce the attainment of each PL \( (IM_{PL}) \), by considering the results obtained both at global and local scale.

\[ \text{Evaluation of the annual probability of occurrence of each PL \( (\lambda_{PL}) \) and comparison with the corresponding target values} \]

5. DECISION-MAKING ON PREVENTIVE INTERVENTIONS

a. The outcome of the PBA is positive \( (\lambda_{PL} \leq \bar{\lambda}_{PL} \text{ or } T_{R,PL} \geq \bar{T}_{R,PL}) \): this means the historical building is able to fulfill all the desired performances, in terms of safety and conservation, and thus no intervention is needed (the installation of a SHM system, or at least the plan of regular inspections, is advisable in order to check whether the present structural conditions remain the same in the future).

b. The seismic safety is not sufficient, even if close to what required, but it is not possible to intervene with a retrofitting at the moment (due to budget limitation or because the available techniques of interventions would be too much invasive for the conservation of the cultural value): a limitation of use can be decided (therefore, the importance factor \( \gamma_U \) changes the target earthquake hazard levels for the fulfillment of Use and human life PLs), as well as some provisional interventions (that have usually the merit to be reversible). A probabilistic justification for postponing the intervention without limiting the use of the building is given by the definition of the nominal life \( V_N \) of the asset, which is defined as the number of years in which the building can be used and the architectural and artistic assets can be considered preserved from earthquake risk, assumed that it is subject to regular maintenance [9]. Since hazard levels are usually defined by probabilities of exceedance in 50 years, the nominal life is given by:

\[
V_{N,PL} = 50 \frac{T_{R,PL}}{\bar{T}_{R,PL}}
\]

Thus, it may be assumed that the seismic performance of the architectural asset is adequate if \( V_{N,PL} > 50 \) years. The nominal life \( V_{N,PL} \) is a useful parameter to quantify the time within which preventive actions have to be implemented. This approach is correct if Building conservation (B) and Artistic assets conservation (A) targets of performance are considered, because the accepted safety level refer to a probability of occurrence in a long time window. On the contrary, as far as Use and human life (U) performance levels are concerned, in particular 3U (Life Safety), it is evident the accepted probability of occurrence refers to a short time window (e.g. annual rate of exceedance), because it is related to the presence of people in the buildings. Moreover, it is worth noting that the use of \( V_{N,PL} \) is correct from a conceptual point of view only if a time-dependent hazard is available. In the most common case of a Poisson hazard
model, the definition of $V_{N,PL}$ represents only a rational approach to face the problem of finding a balance between safety and conservation requirements.

c. The historical building is very vulnerable ($\lambda_{PL} \gg \bar{\lambda}_{PL}$ or $T_{R,PL} \ll T_{R,PL}$): seismic retrofitting interventions have to be designed, according to the following sequential steps: i) prevention from local mechanisms (if they are more vulnerable than the global seismic behavior of the building); ii) local interventions on independent artistic assets that are not verified; iii) identification of a global strengthening strategy, according to an approach coherent to the conservation of the cultural heritage, by taking advantage both of qualitative interpretation and numerical results. The PBA procedure is then applied to the retrofitted configuration, in order to evaluate the improved values of $IM_{PL}$ and compare them with the target values. If the improvement is significant, even if not sufficient to fulfill all the requirements, it is possible to adopt the same approach of the previous point (5b). Also in this case the installation of a SHM system is advisable in order to check whether the structural conditions achieved after the interventions remain the same in the future.

→ Choice of the seismic preventive actions, based on the outcome of the assessment and the compatibility with the cultural value of the monument (if necessary, with an immediate partial intervention, the activation of monitoring and planning of future new assessment and interventions)

The use of static nonlinear analysis (pushover), for the evaluation of the capacity, is very effective for historical masonry buildings, because it allows to identify the causes of vulnerability and the possible alternative strategies of intervention. In particular, the adoption of the displacement-based approach for the seismic assessment helps to figure out that in order to reach the required performance it is possible to:

• increase the displacement capacity;
• increase the strength;
• increase both strength and displacement capacity.

Sometimes first option is not feasible, because if the strength is too low it would be necessary to rely on a very flexible behavior; however, ductility can not be increased beyond a certain limit and geometric nonlinearity becomes important. Moreover, the building would be too much vulnerable to low intensity earthquakes, with reference to the damage limitation state.

Techniques that increase strength are usually associated with significant increase of stiffness and consequent reduction of ductility, which is not necessarily positive in terms of seismic performance. Moreover, in most cases, these techniques are very invasive for the conservation of the cultural value of the building.

Usually last option is the best and may be obtained through the following interventions: 1) displacement capacity - by improving the connections between structural elements (wall-to-wall, floor-to-wall, roof-to-wall, etc.), without increasing too much the stiffness of horizontal diaphragms; 2) strength capacity - by a light enhancement of the masonry strength, when the quality is below the one related to the application of the traditional rules of art in the area or it has been deteriorated by the time or other environmental/anthropogenic actions. It is worth noting that a global insufficient strength/displacement capacity could be due to an irregular behavior of the building (torsional effects, presence of a single weak macroelement, etc.); the multiscale approach is very effective to single out these problems, which otherwise would be lost with the definition of a s.d.o.f. equivalent system. In these cases, local interventions (i.e. selective strengthening of weak elements or introduction of new elements for limiting eccentricity) could be very useful.
ACKNOWLEDGMENTS

The research project PERPETUATE (www.perpetuate.eu) has received funding from the Seventh Framework Programme (FP7/2007-2013) of the European Commission, under grant agreement n° 244229. I also acknowledge Italian Research Network ReLUIS (www.reluis.it), supported by the Italian Civil Protection Agency, which has funded the research of my group in the field of seismic assessment of masonry structures.

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