PERFORMANCE-BASED APPROACH FOR THE SEISMIC ASSESSMENT OF MASONRY HISTORICAL BUILDINGS

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ABSTRACT

The high vulnerability shown by historical masonry buildings (such as churches, towers, palaces) after past and recent earthquakes confirmed the need of proper procedures for the protection of cultural heritage in seismic prone areas. The wide variability and complexity of such classes of monuments, as well as the fact they were not based on an engineered design, make difficult to propose well-established approaches, as those adopted in codes for the case of ordinary newer buildings. In fact, as a function of various historical architectonic assets and the different seismic behaviors they may exhibit (e.g. with a prevailing in-plane or out-of-plane response), different modeling strategies and approaches may constitute the optimal choice for a reliable seismic assessment. This issue has been recently faced in PERPETUATE project (Lagomarsino et al. 2010), specifically addressed to the earthquake protection of cultural heritage. Within this context, in the paper the basic principles of the guidelines prepared in such project for the Performance-Based Assessment are illustrated, focusing the attention on their application to two specific architectonic classes, those characterized by the so-called “box-behavior” (e.g. palaces, castles, …) and those described by the seismic response of independent macroelements (e.g. churches, mosques, …).

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 is the main cause of damage for ancient masonry constructions and, in order to reduce their vulnerability with compatible and light interventions, it is necessary to have accurate models for the seismic analysis, able to simulate the nonlinear behaviour of masonry, and well-defined Performance-Based Assessment (PBA) procedures. As known, PBA is based on the fulfillment of selected rehabilitation objectives, which are defined by specific performance levels (PL) in correspondence to earthquake hazard levels (associated to selected probabilities of exceedance in a reference time or mean return periods). 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. Despite this, available standards for the seismic assessment of existing buildings (ASCE/SEI 41-06 2007, EN 1998-3 2005) do not consider explicitly historical masonry structures, for which only general suggestions or not exhaustive procedures are indicated in some documents (ICOMOS 2005, Recommendation P.C.M. 9/2/2011).

Within this context, the paper briefly summarizes the guidelines that were developed within PERPETUATE research project (Lagomarsino et al. 2010, www.perpetuate.eu), funded by FP7 of the

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European Commission and specifically addressed to the earthquake protection of monumental buildings. For the sake of brevity a state-of-art of displacement-based assessment of existing buildings is omitted, but it can be found in the references that explain with more details the PERPETUATE procedure. After a brief description of the adopted basic principles, the attention is focused on two specific classes of architectonic assets: 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, …). Then, 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.

BASICS OF PERPETUATE GUIDELINES

Figure 1 summarizes the basic principles and steps of PBA according to PERPETUATE guidelines (Lagomarsino and Cattari 2014) 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).

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 (Douglas et al. 2014). 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. The values of the target seismic demand may be properly calibrated through an
importance factor ($\gamma_p$), in order to take into account the architectonic and artistic value, as well as the condition of use, of the examined asset.

The outcome of the assessment is IMPL, which is the maximum value of the intensity measure that is compatible with the fulfillment of each target PL: it is computed by nonlinear static procedures with overdamped spectra (Freeman 1998). 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 $T_{R,PL} \approx 1/T_{PL}$, 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 project for different architectonic assets. In particular, a classification that 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), has been proposed (Lagomarsino et al. 2011). It consists of six architectonic classes: A) box-type buildings; B) wide hall buildings, made by macroelements; C) slender structures; D) arched structures; E) massive structures; F) blocky structures. Thus, the application of PBA is particularized for each class by analyzing also the use of different modeling strategies and the proper approach to describe the seismic behavior of the asset. For example, it is necessary to evaluate if the seismic behavior 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” behavior). On the contrary, the latter class of buildings consists 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.

**PBA PROCEDURE OF COMPLEX ARCHITECTONIC ASSETS**

In the paper 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 (IMPL), also implies the verification of possible local mechanisms. Despite this, for the sake of brevity these latter are not explicitly treated in this paper, while more details on this issue are illustrated in Lagomarsino (2014).

In case of Classes A and B, the PBA is faced by applying two alternative modeling approaches (Figure 2):

a) buildings characterized by box-behavior: in this case a 3D model of the whole building is possible (global scale approach);

b) buildings made by a set of $N_m$ macroelements, which exhibit an almost independent behavior: each macroelement is modeled 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.

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 (Cattari et al. 2012) that takes into account the asset response at different scales: structural elements scale (local damage), architectonic elements scale (damage in macroelements) and global scale (pushover curve). It aims
firstly to define proper Damage Levels (DLs, k=1..4) on the pushover curve, which may be correlated by proper criteria to the PLs. 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. An exemplification of such approach is discussed in the following sections.

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:

$$P_{pl}(IM) = \sum_{m=1}^{N_b} \rho_m H(IM - IM_{PL,m})$$  \hspace{1cm} (1)

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 $P_{pl}(IM)\geq0.5$; ii) the value of IM for which the fragility curve of the performance level (k+1) is greater than 0.

**Figure 2. Basics of PBA for Classes A and B (adapted from Lagomarsino and Cattari 2014)**

**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 Cattari et al. (2014a) and Rossi et al.
(2014a, 2014b) 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.

**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 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 m 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), 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 (Lagomarsino et al. 2011) and on basis of the specific features and the expected seismic behavior 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-behavior”. Following this classification, the modeling strategies illustrated in Figure 3 have been adopted.

![Figure 3. Modeling strategy adopted in case of Hassan Bey’s Mansion (belonging to Class A) and Great Mosque (belonging to Class B)](image_url)
(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 Cattari et al. (2014a) 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 modelling 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 modelled through the equivalent frame approach, for the arcade system a Macro Block Model (MBM) by using the MB-PERPETUATE software (Lagomarsino and Ottonelli 2012) has been adopted (Figure 3). 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 (Figure 4). In particular, the latter has been performed by using ANSYS software and by assuming the constitutive laws proposed in Gambarttala and Lagomarsino (1997) and Calderini and Lagomarsino (2008) to describe the nonlinear response of masonry material. Further details on the models and mechanical properties adopted are illustrated in Rossi et al. (2014a, 2014b).

**Figure 4.** Kinematism analysed for the Y5 arcade through the MBM model (left) and inelastic strain perpendicular to bed joints, obtained by means of the CCLM model (right)

**Nonlinear analyses and definition of performance levels**

Once selected the most suitable modeling 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 (PLs) on the pushover curves. Firstly, it is necessary to specify the PLs selected for the examined buildings, according to the proposal illustrated in Cattari et al. (2012). 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, as illustrated in detail in Rossi et al. (2014a): 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 Lagomarsino and Cattari (2014) in case of SEM models and on basis of the criteria proposed in Lagomarsino (2014) in case of MBM ones.

For the Great Mosque, PLs have been defined for each macroelement. In particular, Figure 7b 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 5 depicts the application of the multiscale approach for the (SE) perimetral wall, in which the variables monitored are: the cumulative rate of piers ($\Sigma P$) and spandrels ($\Sigma S$) 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 5. 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) (Rossi et al. 2014)

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 6 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 7a 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 6).

Figure 6. 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 Figure 10 for the legend)
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 $IM_{kn,G}$ according to the procedure illustrated in Lagomarsino and Cattari (2014). 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 adoption of overdamped spectra (as proposed in Freeman 1998 and adopted also in ASCE 41-06 2007), 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 Fajfar (2000), in the case of nonlinear static analyses (SEM model); ii) as explained in Lagomarsino (2014), 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, Figure 8 shows the construction of the global fragility curves according to (1).

Table 1 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). These latter have been computed on basis of the probabilistic seismic hazard analysis illustrated in Fouzi and Nasser (2013) and Gherboudj et al. (2011), respectively. The return periods assumed as reference $T_{kn}$ 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 1, 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.

<table>
<thead>
<tr>
<th>Case study</th>
<th>PGA [m/s²] ($T_{kn}$ [years])</th>
<th>$IM_{kn,G}$ [m/s²] ($T_{kn}$ [years])</th>
<th>2U</th>
<th>3U</th>
<th>3B</th>
<th>X</th>
<th>Y</th>
<th>X/3U</th>
<th>X/3B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hassan Bey’s Mansion</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.78 (475)</td>
<td>-</td>
<td>-</td>
<td>0.55 (95)</td>
<td>0.71 (119)</td>
</tr>
<tr>
<td>Great Mosque</td>
<td>1.96 (120)</td>
<td>3.8 (570)</td>
<td>3.55 (475)</td>
<td>1.10 (55)</td>
<td>1.23 (63)</td>
<td>4.16 (692)</td>
<td>3.23 (383)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. $IM_{kn,G}$ values and target seismic demand for two examined case studies
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 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 Rossi et al. (2014a, 2014b). Figure 8 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 9 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 IMkn,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.

Figure 10 illustrates 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 (Figure 11), from where it is apparent that the damage is distributed among the different walls and not concentrated only in some of them.
Figure 8. 3D SEM model of the Great Mosque and rules adopted for the equivalent frame idealization of the arcade system.

Figure 9. Pushover curves obtained on the 3D model of Great Mosque and position of performance levels.

Figure 10. Effect of floor stiffening in case of the Hassan Bey’s Mansion on the positioning of damage levels on the pushover curve

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 10). 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 also Figure 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$_{kh,C}$), 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.

CONCLUSIONS

PERPETUATE procedure for the PBA of cultural heritage assets has been applied to two different ancient masonry structures, a building and a mosque. The different configurations and behaviour of these two structures have required the adoption of different modelling strategies; the combined use of them allows the validation of results and the appraisal of model uncertainties. 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. This latter 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). Another very important issue, which is not treated in the paper but can be found in Cattari et al. (2014b), is the use of sensitivity analysis, as a tool for planning investigations and treating uncertainties, by the use of confidence factors.

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