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GIS Methodologies for the Management of Seismic Risk and the Damage Prevention on Masonry-Built Heritage

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Abstract. The Geographic Information System (GIS) is increasingly used in the scientific field for the management and conservation of built heritage. The present paper proposes a GIS methodology for the collection and analysis of the data related to the seismic risk and for the management of damage prevention interventions on masonry architectural assets, based on the empirical approach. Indeed, starting from the observation of real damage, that occurred after the recent Italian earthquakes, it was possible to collect a large amount of data, which has been organized and queried using the GIS tool. This methodology was tested on two different architectural typologies, designing two different databases: protruding elements and fortified architectures. This proactive tool allowed both the correlation between constructive features and damage mechanisms, through statistical analyses, and the comparison of the damage levels with the seismic action of the site, through the introduction in the GIS of the shake-maps, to identify the empirical fragility curves, which represent the expected damage, depending on the seismic action. Then, these functions were applied to an area without earthquake damage, using the seismic actions provided by the hazard map. This methodology allowed the identification of the assets most at risk in case of future seismic events, on a large scale. Knowing the vulnerabilities of the heritage means being able to act preventively, with planned conservation strategies, optimizing the management of economic resources, and minimizing invasive interventions.

Keywords: Architectural Heritage, Seismic Risk, GIS Database, Fragility Curves

1 Introduction

The present paper illustrates a possible methodology for the study of the seismic risk of masonry-built heritage through the adoption of GIS systems that integrate data from post-event direct observation of actual damage. Indeed, GIS databases, in addition to providing digital, continuous, and shared data management, can be used to study the seismic risk of buildings if designed as a proactive tool.

2 The Empirical Approach

When dealing with historical built heritage, the knowledge of the asset is indispensable and propaedeutic to its conservation. Static and seismic issues do not escape this rule. In fact, the structural and seismic vulnerability assessment of heritage buildings is particularly complex, due to the high uncertainties in terms of geometries, typology, intrinsic degradation, and mechanical properties of the materials.

Seismic assessment of a specific building involves different modelling strategies to evaluate the global response and the local mechanisms. Due to the usually limited amount of time and employable human and economic resources, the applicability of detailed structural analyses, which are typical of a single building, to the broad cultural heritage stock is not feasible. Therefore, simplified approaches based on mechanical, statistical, or qualitative models can be useful for preliminary seismic assessment and for the prioritization of more detailed analyses [1].

This multi-level approach has been validated and implemented in many studies [2] [3] [4], associating the observation of damage to the building features, and identifying recurring mechanisms, which in some cases allowed the subdivision of the structure into macro-elements [5] [6] [7] [8]. Different damage mechanisms recurring in the building were associated to damage levels, ranging from undamaged state to collapse. These were finally used to define the overall damage level of the building. Finally, the damage level, either of the individual mechanism or of the building, was represented by means of fragility curves linking the probability of reaching a predetermined damage level to the seismic action, measured in different ways. This approach was first carried out with a systematic and organized analysis of two of the most widespread architectural heritage types: churches and palaces. Given the wide variety of typologies characterizing the architectural heritage, over the decades the definition of fragility curves has been expanded and enriched, allowing to better describe the observed behavior of other building typologies [2] [3] [9]. The approach still presents some open, if not unresolved issues, such as the conversion of complex information on the spread of different damage types in a 3D building into a single synthetic damage parameter (Damage Level) [10]. In addition, site effects and soil-structure interaction on seismic action are usually neglected. However, these issues do not undermine the potential of the method, which has undeniable advantages. In fact, this simplified approach allows the development of hazard mitigation and prevention strategies, that could constitute a first stage of expeditious assessment, to which detailed analyses at the individual building level should be complemented. The effectiveness of this approach is further improved by using Geographical Information Systems (GIS), which are very powerful and effective tools for collecting large-scale data.

3 The Advantages of the GIS

GIS stands for Geographic Information Systems, which is a system for managing, visualizing, and analyzing geo-localized information. Specifically, the potential of GIS is related to the possibility of storing large amounts of data, both numerical and textual, geo-referencing them and, above all, querying them through spatial or relational correlations, generating original information, based on objective statistical evaluations.

According to [11] the potential of GIS could be better exploited in the cultural heritage sector, as more than 68% of the analyzed publications use GIS as simple data storage and only 18% apply a proactive approach, i.e. aimed at identifying risks that threaten heritage conservation. The percentage is further reduced if we focus only on seismic risk. In this regard [12] gives an overview of different GIS approaches for seismic vulnerability assessment and implementation of risk management procedures is provided. For example, in this field is included the GEM [13] which collects resources for transparent assessment of earthquake risk, facilitating their application for risk management around the globe, which can be implemented through open-source software and GIS systems. Among these, numerous are those that work at the urban scale, with a particular focus on historic centers, such as [14] [15] [16].

Generally, it has emerged that the effectiveness of territorial scale analyses for seismic-risk assessment is closely related to the quality of the data. In particular, [17] compares the outcomes of the same seismic risk assessment methodology applied to two different datasets of the historic center of Moncalieri, Italy. The study shows that the dataset with a leaner taxonomy tends to overestimate the probability of the occurrence of higher level of damage. The examined databases, although focused on different case studies and scales, have in common a lengthy in-situ data collection phase; at the same time, the real obstacle to implementing the use of GIS systems is the difficulty of finding accessible and reliable data [12]. However, tools for management of the large amount of data are under development: examples of GIS databases adopted in Italy, which also work at the scale of the individual building, are the Risk Map adopted by the Ministry of Cultural Heritage and CARTIS. The Risk Map [18] is a specific GIS for cultural heritage risk management, which censuses three hazard categories: environmental-air; anthropogenic; and static-structural. Thus, the Risk Map makes it possible to know not only the distribution of cultural heritage, but also to highlight which types of risk it runs. Specifically on seismic risk, seismic vulnerability forms were defined for some architectural typologies (Churches/Theaters, Villas/Palaces, Towers). These forms were then applied in a survey campaign, which allowed the census of specific constructive features, that could lead to the occurrence of seismic vulnerabilities [19]. The data thus collected implemented the platform, but only for some specific areas. CARTIS [20] is another database designed for seismic risk management, which not only defines a taxonomy of the most representative architectural typologies, but also collects information on structural characteristics (also through a specific form) and inventories the vulnerability curves found in literature. Currently, this database is applied mainly to ordinary buildings.

3.1 GIS as a Post-Event Tool: The Relation Between Building Features, Damage and Seismic Actions

In order to illustrate the application of GIS as a post-event tool, in the present paper two example of databases are presented. Both are based on data collected, during survey, from observation of earthquake damage, or from consultation of survey and consolidation project reports. The first database is designed for fortified architecture typology, taking in consideration the Italian earthquakes over the past 40 years, from Friuli earthquake in 1976 to the most recent Central Italy earthquake of 2016 [8]. The second database is focused on the study of the damage to the masonry spires of the belfries, affected by 2012 Emilia earthquake, in the North Italy [21]. The dataset that was used to populate these databases was obtained from different sources:

- the cartographic base refers to the ISTAT data set [22], from which polygonal shapefiles, relating to the boundaries of regions and provinces, can be obtained;
- the census of the assets investigated has several reference sources. On one hand, two reference databases for enlisted historical buildings, interoperable with each other, were used for the Emilia Romagna Region: the GIS CdR [18] and Web-GIS of Emilia-Romagna [23]. More specifically, for churches the diocesan databases can be

used, in which there are lists of church assets, divided by municipalities. Among these databases, particular mention should be made of the BeWeB [24], that censuses ecclesiastical properties on a national scale. In both cases mentioned, a second stage of critical selection of the case studies will be necessary, based on the constructive technology used (the study focused only on assets made of masonry), the architectural-structural typology and their state of conservation (assets in a state of ruins should not be considered);

- for seismic actions, two reference datasets were used: INGV [25] and USGS, from which shakemaps of various earthquake events can be freely downloaded in shapefile format and thus directly imported into the GIS environment. Such maps are a representation of ground shaking produced by the selected earthquake.

Thereafter, the database was implemented with the inclusion of information on building characters and seismic damage observed and its severity levels defined according to the EMS-98 scale [26]. This information was deduced from on-site surveys, photographic surveys or consultation of survey and design reports. Then, the designed GIS database can then be queried (spatial or tabular queries) and provide original outputs, through data correlations and statistical rework. In particular, the GIS system can facilitate the correlation between construction technologies and the occurrence of damage mechanisms. In turn, however, the severity of damage is closely related to the seismic actions suffered, which can be obtained from shakemaps. Therefore, thanks to the correlation between seismic accelerations and damage levels, it is possible to define empirical fragility curves for specific typological classes of buildings, through statistical analysis of data collected in situ [2] [9]. However, it is possible to define specific fragility curves for the individual macro-elements, that compose historic masonry buildings [27] [28].

3.2 GIS as a Prognosis/Proactive Tool of the Seismic Risk on Masonry Built Heritage

GIS systems, if designed with a proactive approach, allow for the identification of assets most at risk on large-scale, in case of future traumatic events. In particular, the implementation of GIS with additional datasets, compared to those listed in the previous paragraphs, can allow for the design of a prognostic database. Specifically, the example of a GIS database, focused on earthquake damage prevention of the Emilian fortifications, was presented in [21]. The achievement of this goal was obtained through the uploading of the following data:

- empirical fragility curves, developed in the previous phase.
- seismic hazard maps, expressed in terms of maximum ground acceleration (PGA), with probability of exceedance of 10% in 50 years and used in the Italian standards [7]. The map is published on the INGV website [29], from which it is possible to download table or text files, the records of which define a mesh of regular points, each of which is associated with an acceleration value. Through interpolation functions it is possible to obtain from the point data a raster file related to the distribution of accelerations over the territory. This procedure allows the expected acceleration value to be associated with each asset upload.

Thus, thanks to GIS systems, it is possible to easily associate not only the information about the listed assets located on the territory, including their collapse mechanisms, with the data related to the occurred seismic events, through shakemaps, but also to the severity of the expected ones, thanks to the seismic hazard maps [29]. Through GIS it is therefore possible to correlate the data of expected accelerations with the fragility curves of the macro-elements, identifying those most at risk, before damage occurs. Working on a territorial scale, it is not necessary to concentrate interventions on all the possible macro-elements of a single building, but it is possible to improve the seismic behavior of the most vulnerable macro-elements with localized interventions on several buildings, respecting the principles of mini-intervention and conservation of materials. Through this approach, it is then possible to draw up a priority list of consolidation interventions to be carried out on a territorial scale, both with a view to enabling better management of resources and to replace an emergency approach to restoration, often typical of emergency phases, with programmed operations for the prevention of damage, in compliance with restoration principles.

4 Two Possible Procedural Applications

The procedures described in the previous paragraphs were used for two different applications: post-event and prognostic analyses. Post-event database was developed for two case studies: masonry spires of bell-towers [21] damaged by the earthquake events that occurred in Emilia (North of Italy) in May 2012 and fortified architecture damaged by earthquakes in the last 40 years, with particular attention to merlons macro-element [30]. Prognostic database was realized for the castles in the province of Parma, in Emilia (North of Italy).

4.1 Post-Event Database: Protruding Elements and Castles of Central Italy

Spires are hollow conical or pyramidal structures, at the top of bell towers, generally made of thin layers of masonry. They are characterized by slenderness and vertical development, exceedingly even ten meters in height. Commonly they have a stone or concrete top, placed to support the metal weathervane. After the seismic events of May 2012, a mechanism observed, in a large number of cases, is the detachment and overturning of the upper part of the spire often even in the absence of other damage types (Fig. 1a). The Italian Guidelines [7] suggest an inclined fracture plane as the most probable expected damage on spires (Fig. 1a). However, the most observed mechanism was a horizontal crack, originated from slip of the top of the spire, and possibly to the bending moment that could induce overturning. The horizontal crack is located between the stone element and the masonry, probably because of a material discontinuity or a poor connection, or along the mortar joints [31]. The large number of spires surveyed in the 2012 earthquake area, (77 in total), led to the need for systematic and organized cataloging through a GIS geodatabase, designed with ArcGIS Pro, a ESRI software. Such information systems allowed geo-referencing the surveyed spires through the input of a coordinate system.

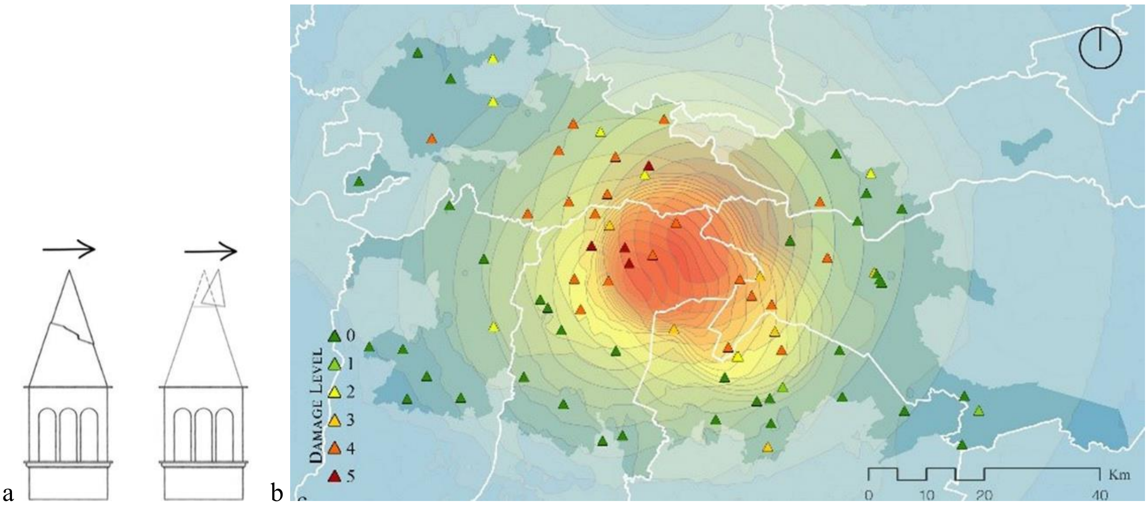
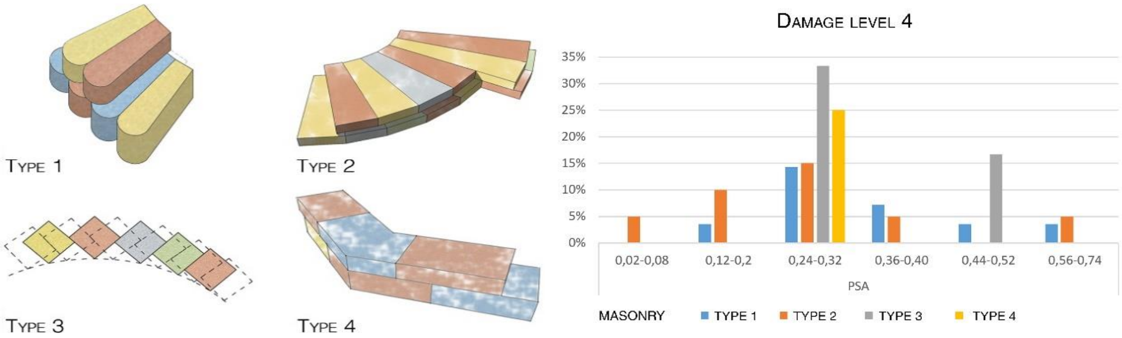


Fig. 1. (a) Damage mechanism of the spires; (b) Envelope of the shakemaps of the two main shocks of 20 and 29 May 2012 together with damage levels of the spires.

The second database has been designed for Italian fortified architecture using the open-source software QGIS. Fortified architectures represent a decidedly more complex case study because they are composed buildings with different plan-volumetric developments (curtain wall, tower, and palace), characterized by specific macro-elements (merlons, corbels, turrets, and other protruding or freestanding elements). The database included 192 assets, thanks to which it was possible to confirm and implement the table of damage mechanisms proposed by [5] [8], as well as to make objective considerations on the occurrence of these mechanisms based on statistical analysis.

The two GIS databases designed, therefore, are configured as operative tools for seismic risk analysis, which can be interrogated to understand the real vulnerabilities of the territory, obviously limited to the typology examined. Through the application of the methodology illustrated in this paper, it was possible to define the most vulnerable elements, on the basis of the queries of the data, previously collected, related to the constructive features and geometries.

Regarding the research related to the spires, it was possible to make some considerations from the statistical analyses performed with the GIS database. For example, thanks to this tool, it was possible to associate to each spire, whose damage is described according to a scale ranging from 0 to 5, the suffered pseudo-spectral accelerations PSA, deduced from the shakemaps (Fig. 1b).



(a) (b)

Fig. 2 (a) Masonry arrangement typologies of the spires; (b) Relative frequency distribution of Damage Level 4 as a function of PSA (in g) (b).

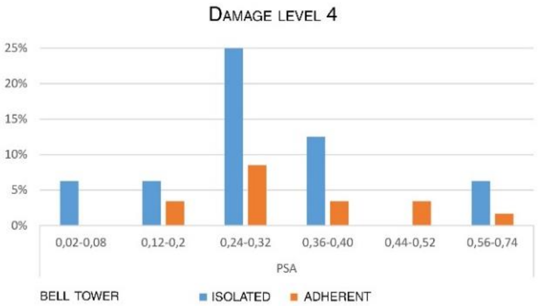
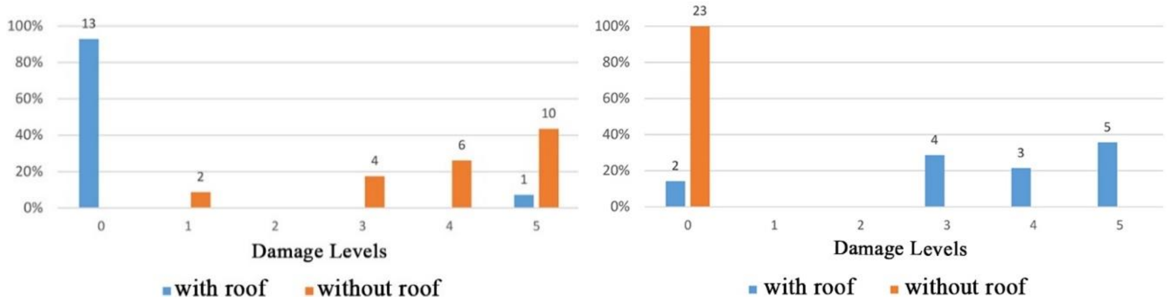


Fig. 3. The different seismic behavior of isolated and adherent belfries: the relative frequency distribution of damaged spires related to PSA (in g) and the belfry position.

This correlation highlighted a threshold at about 0.2 g, below which the expected damage is limited or absent (damage levels 0, 1, or 2). Above this value, the structural damage was always severe but without collapse, i.e., damage levels 3 and 4 (Fig. 1b). In addition, assessments were made regarding the correlation between the severity of the damage and the constructive features of the spires. In fact, it was possible to identify four different types of arrangements of the bricks (Fig. 2a): rounded wedge-shaped bricks arranged radially and with alternating courses (type 1); wedge-shaped bricks with a flat outer side (type 2); square bricks with alternating courses, arranged at 45° radially (type 3); bricks arranged in alternating stretcher courses (type 4). The statistical analyses showed that, with the same acceleration, the spires made with the square brick technique, arranged at 45° (type 3 in Fig. 2b), are more vulnerable. Instead, the spires made with stretcher bricks (type 4, in Fig. 2b) are less damaged. Moreover, it was possible to note a greater fragility of spires at the top of isolated belfries, free to oscillate (Fig. 3). This is probably caused by the fact that belfries adherent to buildings, such as churches, are subjected to a whip effect with smaller displacements but stronger accelerations in the upper part.

Likewise, regarding the castle typology, it was possible to relate the frequency of the different damage mechanisms to the values of the PGA. In fact, the data previously processed by GIS software were used to carry out a parametric analysis for limit state of collapse (LSC) and activation (LSA) for the out-of-plane overturning of merlons macro-element [30]. Analyzing specifically the damages to merlons, the data showed a greater frequency of activation for out-of-plane mechanisms for the freestanding merlons, without a constrain at the top (Fig. 4a). The merlons supporting a roof, instead, are more frequently damaged by in plane mechanisms (Fig. 4b). In [30], it was also possible to note a correlation between damage of merlons and geometry of the wall on which they are placed.

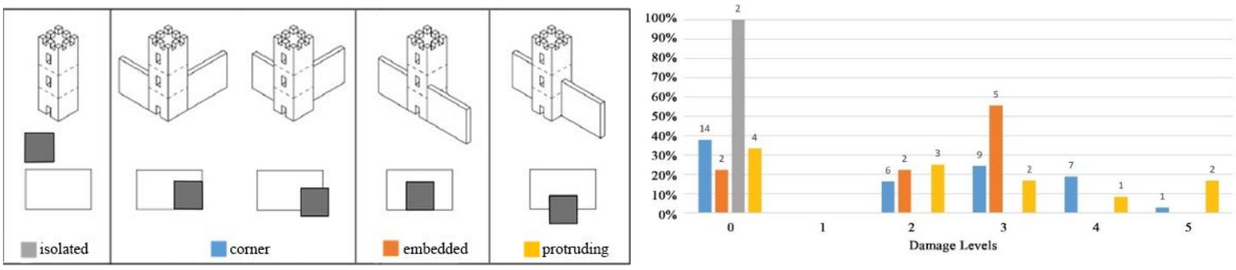


(a) (b)

Fig. 4 Relative frequency distribution of damage levels of merlons with and without roof: (a) out-of-plane overturning mechanism; (b) in plane shear mechanism.

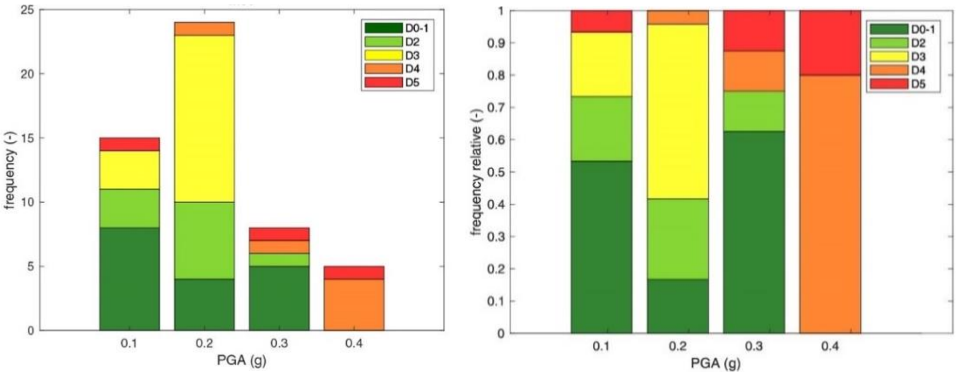
4.2 Prognostic Database: Fortified Architecture in Emilia (North Italy)

The studies on fortified architecture were subsequently extended through the application of the predictive methodology previously explained. In a first phase, a GIS database was designed based on data and observations of post-earthquake damage on 21 castles in Emilia after the 2012 earthquake. Through statistical and geo-referenced analysis, this database allowed the identification of some typical vulnerabilities. For example, it was highlighted a correlation between a damage mechanism and the tower position within the building (Fig. 5a). It emerged that protruding towers are the most damaged, followed by angular towers (Fig. 5b), probably due to the strongly asymmetrical constraints at the base that leads to the onset of flexural-torsional stresses and to a sharp change of stiffness at the point where the tower becomes freestanding. Isolated towers, on the contrary, are the least damaged. However, the severity of the damage mechanism is also necessarily related to the suffered seismic accelerations provided by INGV shakemaps, as shown in Fig. 6. Based on these data it was then possible to define empirical fragility curves for the considered mechanisms [32], thus correlating the probability of a certain damage level to the acceleration values, in terms of PGA.



(a) (b)

Fig. 5 (a) The different position of the towers; (b) Frequency of damage levels in the 21 castles analyzed in Emilia.



(a) (b)

Fig. 6 Distribution of damage as a function of PGA in the towers of 21 castles hit by Emilia 2012 seismic sequence: (a) frequency; (b) relative frequency.

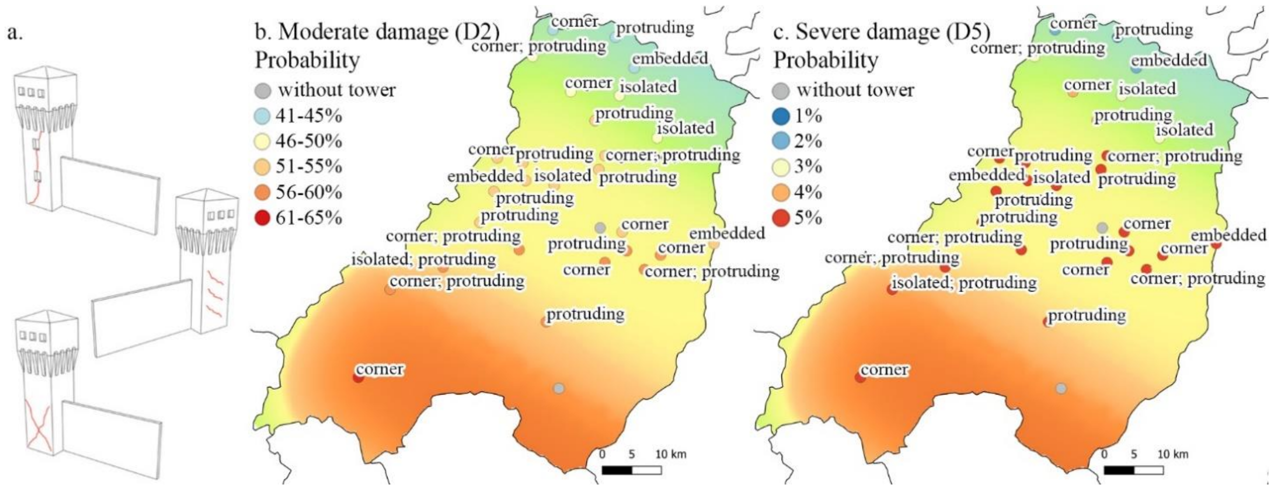


Fig. 7 Prognostic analysis of seismic damage of the castles in Parma province: (a) Mechanism of damage in the tower; (b) Probability of activation of moderate damage D2 in the tower; (c) Probability of activation severe damage D5 in the tower.

A second phase involved the implementation of the database, according to a prognostic/proactive approach, for an area not affected by the 2012 seismic events. Specifically, the area of the province of Parma was chosen, which was not affected by the Emilia 2012 earthquake but, being in Emilia, has characteristics of castles quite similar to those damaged (Fig. 7). The aim was to identify which castles should be given priority for intervention, based on the estimated level of risk. In principle, the castles subjected to the greatest risks are located in the Appennine Mountain area, south of the Parma province, where the expected accelerations are larger. But the procedure allowed to identify the single mechanisms which are more likely to occur, and the level of damage expected. For instance, the probability that medium shear and torsional damage (D2) will occur in the main body of the tower are over 40% for all the assets considered in this area (Fig. 7b), while the probability of severe damage (D4-D5) is about 5% (Fig. 7c). In addition, considering the tower positions, it would be recommended to give priority to those castles with protruding towers, among assets with the same expected acceleration, as they demonstrated to be more vulnerable.

5 Conclusions

This paper presents three examples of the application of GIS to the analysis of seismic damage to masonry heritage assets. Case studies of spires and castles demonstrated the ability of the proposed method to quantitatively relate structural characteristics (brick patterns, geometries, location, constraints) to the level of damage suffered as a result of the earthquake. Furthermore, when it was possible to collect a sufficient amount of data for an individual mechanism, it was possible to define its corresponding fragility curves. Applying this information to an area different from the one affected by the earthquake, but with similar characteristics, made it possible to define the most probable damage scenario, identifying not only the most vulnerable buildings but also the corresponding mechanisms. For the same economic and human resources, such a territorial approach makes it possible to identify the main vulnerabilities of more buildings, instead of focusing on a few of them. The resulting interventions can then be spread over the territory and aimed at first reducing the most important vulnerabilities.

Thus, this methodology potentially has the double advantage of optimizing the management of economic resources and enabling the protection of architectural heritage by avoiding operating in emergency and aiming, instead, at the application of planned conservation strategies.

This type of approach thus fits into the broader strand known as *planned conservation* [33]. A global strategy that focuses on the integrated management of interventions at different scales and over the long term. In fact, unlike the traditional concept of restoration, it shifts the focus from the individual intervention to a process logic, in which future interventions are planned based on the history of past ones, also and especially from a preventive perspective. To succeed in this intent, decisive is the adoption of new technologies that can integrate and facilitate the knowledge path and manage in an organized way the information produced (GIS systems are a paradigmatic example). The knowledge process is also supported by diagnostic and prognostic activities. The first ones able to trace the causes of degradation through the analysis of the effects that generated them. The others to predict possible degenerative developments to prevent or mitigate them. Ultimately, this type of "proactive" planning could have important advantages not only in the preservation of the historic building, of course, but also in public financial investment in the cultural heritage sector, optimizing often limited economic resources and directing them in a more effective and timely manner.

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