

Article

A Proactive GIS Geo-Database for Castles Damaged by the 2012 Emilia Earthquake

Elena Zanazzi 

Department of Engineering and Architecture, University of Parma, 43124 Parma, Italy; elena.zanazzi@unipr.it

Abstract: The 2012 Emilia earthquake highlighted the vulnerability of fortified architecture. Based on the observed seismic behaviors, this research proposes a GIS geodatabase, designed with a proactive approach, for the prediction and prevention—at a territorial scale—of the most frequent damage mechanisms of the investigated typology. The designed geo-database allows for the identification of possible correlations between constructive features and the occurrence of damage, through statistical and geo-referenced analysis. Moreover, the designed geodatabase, by enabling the comparison of the damage level data with the seismic action of the site, through INGV (National Institute of Geophysics and Volcanology) shakemaps, allowed the definition of experimental fragility curves, for three of the most common damage mechanisms. By applying these functions to castles in the province of Parma, it was possible to define future seismic risk scenarios for the mechanisms considered, thanks to the use of the seismic hazard map. Therefore, the described methodology could be functional to identify the most urgent and high-priority interventions in order to optimize the management of economic resources. The final aim is to promote the application of the concept of minimum intervention, and more in general to preserve the architectural heritage, avoiding emergency interventions and aiming instead to apply planned conservation strategies.

Keywords: cultural heritage; fortress; fortified architecture; 2012 Emilia earthquake; damage mechanisms; masonry; GIS database; planned conservation



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1. Introduction

The 2012 earthquake, which affected the territory of the Emilia-Romagna Region (North of Italy), once again demonstrated the vulnerability of the masonry architectural heritage and in particular of the fortified architectures. This typology includes different historic military buildings (fortresses, castles, citadels, urban walls, towers). This paper specifically focuses on the Emilia castles, located in the area affected by the 2012 earthquake, as defined by [1]. These castles, constructed of masonry, are characterized by typical structures such as towers, walls, and palaces, usually arranged around a central courtyard. Due to the significant damage that these castles suffered after the 2012 earthquake, and beyond, numerous studies have analyzed the seismic behaviors and specific vulnerabilities of these complexes [2–6] or even parts of them, such as the towers [7–11] or the defensive walls [12]. However, this paper focuses on the examination of the typical vulnerabilities [13]. This analysis is based on an empirical approach that subdivides the building into macro-elements. This approach has previously been adopted in other studies for the codification of the kinematics of the church typology [14,15] and subsequently for the palaces typology [16]. One of the first studies to apply this approach to fortified architecture is [17], which observed the presence of recurring seismic damage also for the examined typology, defining a table

of 10 mechanisms. Subsequently, this table was validated and extended by [18], which analyzed more than 70 castles damaged by seismic events in Italy since 1976. Thereafter, additional studies [19], specifically focused on Emilian fortresses, further expanded and refined this table, leading to the identification of 37 recurrent mechanisms.

Based on the collected data, it is now essential to implement tools and procedures for seismic risk mitigation and thus for the planned conservation [20,21] of Cultural Heritage (CH), including the use of information systems. Therefore, this paper proposes a possible proactive methodology with the use of Geographic Information Systems (GIS). In fact, the application of GIS in the field of CH conservation has become widespread, particularly in databases that have cataloging and data management functions [22,23]. However, there is still a limited number of systems—for CH—that are specifically designed to address seismic risk management [24], and many of these are applied at the urban scale, with a focus on historic centers, such as [25–27]. While, at the building scale, the number of GIS databases is significantly reduced [28–30].

Specifically, the proactive methodology, which will be illustrated in this paper, proposes the design of a GIS geodatabase as a possible predictive tool for the prevention of typical and frequent seismic damage mechanisms of fortified architecture, in order to identify the most urgent and high-priority interventions and to plan a maintenance program. The GIS geodatabase facilitates the comparison of data related to constructive features and damage levels with the seismic action of the site, thus allowing for the definition of experimental fragility curves through the use of shakemaps provided by the Italian National Institute of Geophysics and Volcanology (INGV) [31]. These functions represent a turning point from knowledge to prediction of the seismic damage also in the CH field [32–35]. In fact, once these functions have been defined based on the real damage suffered, it will be possible, through the use of seismic hazard maps [36] that provide the maximum expected accelerations, to determine in which other areas, not yet affected by the earthquake, the investigated mechanisms are likely to be triggered. This methodology therefore identifies the potential vulnerabilities of specific macro-elements based on the predicted accelerations, before damage occurs. It aims at predicting damage with the possibility of preventing it. Through this approach, it is possible to provide targeted recommendations, on a territorial scale, regarding the necessary consolidation interventions, prioritizing them in terms of urgency, while optimizing costs and minimizing invasiveness, in line with the principle of minimal intervention for the conservation of existing heritage. Thus, this methodology could allow the replacement of the emergency restoration approach, typically adopted after natural disasters, with a large-scale strategy of planned conservation.

In order to illustrate the workflow used to define the proposed methodology, the paper is organized as follows. Section 2 defines the features of the examined typology and its typical vulnerabilities. Additionally, the three most frequent damage mechanisms, observed in the selected case studies, are illustrated. Section 3 deals with the design of the GIS geodatabase. Section 4 discusses the main results of the statistical analysis, which provide the basis for defining the fragility curves. Section 5 describes the proactive methodology that allowed the definition of seismic risk scenarios for the castle typology. The conclusions of the paper are presented in Section 6.

2. Castles of the Emilia Area

2.1. Definition of a Typology: From Constructive and Morphological Features to Vulnerabilities

This paper focuses on the study of 21 Emilian castles located in the area affected by the 2012 earthquake (Figure 1) and constructed between the 10th and 15th centuries, i.e., until the advent of artillery, which marked the end of the medieval defensive systems and introduced new shapes of military architecture [37,38]. The geographical and temporal

boundaries, thus defined, allowed for the identification of fortified architectures sharing common material-constructive, typological, and morphological features. Specifically, these architectures are mainly made of brick masonry and are distinguished by three main component assets: palaces, towers, and curtain walls. These elements, in the Emilian castles, are typically arranged according to a quadrangular plan with a central courtyard, with towers placed in the four corners of the complex and a gate tower. The other buildings are arranged against the curtain walls surrounding the inner courtyard. In the investigated area, the towers typically have a square plan. In addition, the component assets are characterized by typical macro-elements, such as battlements, corbels, and other protruding elements (turrets, garrets), and by the macro-elements typical of historic buildings: wooden floors, vaults, stairs, etc. The presence of the same macro-elements is essential to perform comparative analyses of seismic damage and thus to code typical mechanisms.

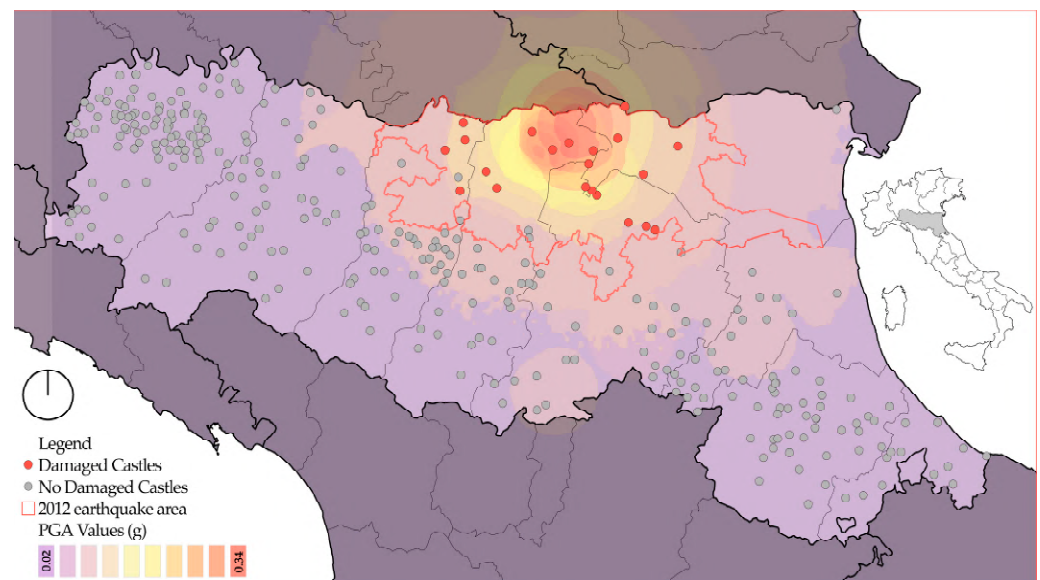


Figure 1. Map of 21 castles examined, which were damaged by the 2012 Emilia earthquake (North Italy), and the overlapping of the shakemaps (PGA) of the two main shocks of May, 20th and 29th.

In many cases, the specific seismic vulnerability of this architectural typology can be attributed to its distinctive morphological and constructive features. For example, one of the most significant vulnerabilities of these fortified complexes results from their diachronic evolution, largely due to the need to adapt their different structural elements to advancements in military techniques. This led to often inadequate connections between the different parts of the complex or between masonry leaves added over time, as well as the absence of a masonry box behavior in the more recent structures, which are typically built adjacent to or incorporated into the pre-existing ones. Another element of vulnerability is linked to the inherent irregularity, both in plan and elevation, of this typology. In addition, as will be shown in the following sections, the arrangement of the component assets within the castle complex can result in eccentric constraints that make certain structures, depending on their specific placements, more prone to the occurrence of particular collapse mechanisms.

2.2. Three of the Most Recurring Damage Mechanisms

These typical vulnerabilities, in turn, contributed to the onset of specific damage mechanisms. The most frequent damages observed on the 21 castles during the 2012 earthquake (Table 1) were cataloged. In this case, all the castles shared similar morphological characteristics, but also other seismic events have provided insights and comparisons relevant to defining the typical damage of fortified architectural structures. In this regard,

particular reference is made to the seismic events of August and October 2016 in Central Italy [18], and of November 2019 in Albania. Another study [39] applied and adapted the macro-element approach to the fortifications damaged by the February 2023 earthquake in Turkey.

Table 1. The 21 fortresses damaged by the 2012 Emilia earthquake.

Name	Municipality	Province
Castle of Bentivoglio	Bentivoglio	Bologna
Galeazza Pepoli Castle	Crevalcore	Bologna
Castle of Manzoli	Minerbio	Bologna
Fortress of Minerbio	Minerbio	Bologna
Fortress	Pieve di Cento	Bologna
La Giovannina Castle	San Giovanni in Persiceto	Bologna
Fortress	Bondeno	Ferrara
Castle in S. Bianca di Bondeno	Bondeno	Ferrara
Fortress	Cento	Ferrara
Este Castle	Ferrara	Ferrara
Lambertini Castle	Poggio Renatico	Ferrara
Castle of the Pio Family	Carpi	Modena
Carobbio Castle	Finale Emilia	Modena
Este Castle	Finale Emilia	Modena
Pico Castle	Mirandola	Modena
Este Castle	San Felice	Modena
Campori Castle	Soliera	Modena
Guidotti Castle	Fabbrico	Reggio Emilia
Gonzaga Fortress	Novellara	Reggio Emilia
Castle	Reggiolo	Reggio Emilia
Este Castle	San Martino in Rio	Reggio Emilia

A detailed analysis of the 21 damaged castles revealed the particular vulnerability of specific macro-elements, such as towers and merlons. The towers are particularly exposed to seismic risk, due to the eccentric constraints and asymmetries typical of fortified complexes. These characteristics often led to hammering phenomena between towers and adjacent structures. In addition, the mechanisms that typically characterize the crack pattern of this typology include out-of-plane and in-plane shear cracks of protruding elements, such as turrets, corbels, and especially merlons. In fact, such elements, in addition to being inherently vulnerable, are typically situated at elevated heights, where accelerations are larger [40].

Given the frequency of damage, especially to towers and merlons, the research focused on three damage mechanisms that are particularly recurring for these two elements: shear cracks in the main body of the tower, with possible torsional effects; shear cracks in the upper part of the tower, standing out from the fortress or walls; out of plane overturning of merlons (Figure 2). In addition, a damage level scale was associated with each mechanism, ranging from 0 (no damage) to 5 (macro-element collapse) as defined in [41,42].

The shear and torsion mechanism of the tower body is activated by in-plane deformations of the masonry. In addition, torsional effects can occur due to the presence of eccentric constraints at the location of curtain walls or other adjacent structures of the fortified complex. An effective connection between the two structures, the installation of hoops or tie-rods helps prevent the occurrence of this mechanism. On the other hand, the inherent irregularity of the fortresses, both in plan and in elevation, the different height and slenderness of the walls compared to the towers determine a different dynamic response that contributes to the activation of the mechanism. Similar kinematic behavior has already

been identified in the table of the churches (A-DC form) [43], specifically in mechanism number 27, related to the bell tower.

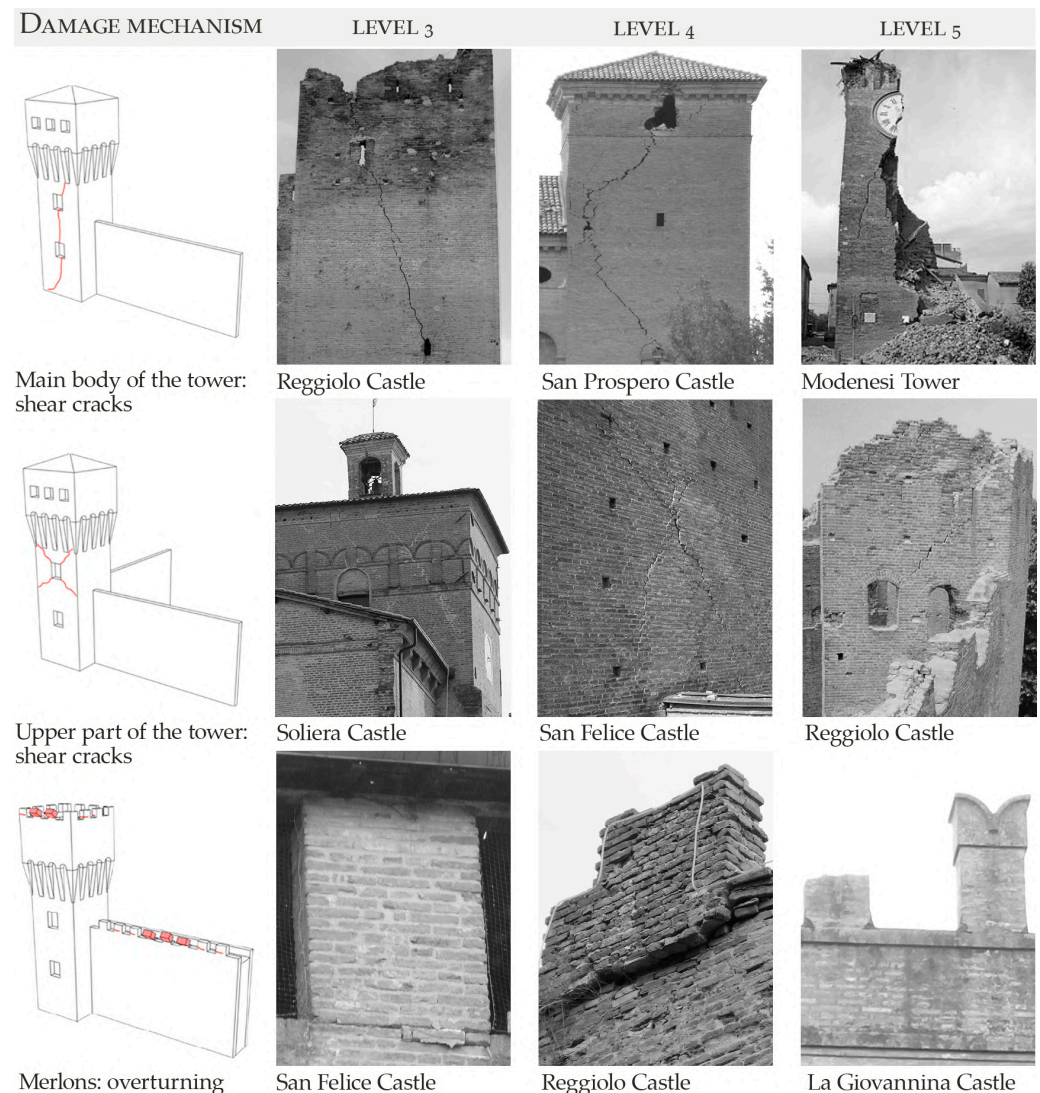


Figure 2. Three damage mechanisms on which the research is focused and some significant pictures of the three most serious levels of damage.

The shear mechanism in the freestanding part of the tower is activated by in-plane deformations. The crack pattern typically consists of inclined cracks, which may be either single or X-shaped, depending on the type of structural constraints. This mechanism occurs when the tower is properly connected to the curtain wall or to other buildings of the complex. Thus, the significant difference in stiffness between the bottom and the upper part of the tower can produce stress concentrations and trigger damage on the freestanding part. The presence of tie rods and hoops in the upper part of the tower contributes to the good behavior of this macro-element. On the other hand, the presence of large openings (even if bricked up) and the high slenderness favors the activation of the mechanism.

The out-of-plane overturning of the merlons is activated by the development of a horizontal crack, which is typically located at the base of the element. The presence of steel dowels between the merlons and the underlying masonry contributes to the effective performance of this element. On the other hand, the high slenderness, the placement at elevated heights, and the lack of an effective constraint at the top of the merlons could facilitate the activation of the mechanism. As will be illustrated by the statistical analy-

sis, shear phenomena are not common for free-standing merlons, while the out-of-plane overturning damage is more frequent and often observed at moderate to severe levels (3, 4, or 5). Regarding the slenderness of the battlement, it should be noted that it evolved alongside advancements in military techniques. In particular, the merlons, which were built before the transition period, are thinner and therefore more fragile than the squat merlons built after the advent of artillery. Similarly, the merlons, built with slender proportions for aesthetic and decorative purposes, during the Gothic Revival period, are also vulnerable.

3. Materials and Methods for the Design of a Proactive GIS Geodatabase

Given the frequency of the described damage mechanisms, which can severely compromise the conservation of the analyzed castles, it is essential to develop suitable tools for future seismic risk management. Specifically, the proactive methodology, presented in this paper, makes use of GIS systems. In particular, a GIS geo-database was designed, using ESRI's ArcGIS Pro software (Figure 3), in order to identify the vulnerabilities and prevent seismic damage to the fortified architecture. Indeed, the GIS environment facilitates the association of the information of the recurrent examined mechanisms with the acceleration values recorded for one, or more, seismic events. These values can be obtained from shakemaps, available as shapefiles [31]. Moreover, the proactive methodology aims to define which mechanisms are likely to be activated in the future as a function of expected accelerations. For this reason, the proposed methodology employs fragility curves. In fact, these curves express the likelihood of a structure—or a macro-element—reaching or exceeding a specific damage level as a function of seismic actions. In this study, experimental fragility curves were developed using MATLAB (version number R2021b) for three frequently observed collapse mechanisms, through the correlation between seismic accelerations, recorded by shakemaps, and damage levels. When combined with Peak Ground Acceleration (PGA) values derived from seismic hazard maps [44], these functions define threshold values that can be used, within a GIS environment, to outline potential future seismic risk scenarios in areas not yet impacted by an earthquake. Therefore, through this approach, it will be possible to provide accurate guidelines, on a territorial scale, for the definition of a priority order for the consolidation interventions, optimizing costs, and minimizing invasiveness, in accordance with the principle of minimum intervention and conservation of CH.

The designed database limited its investigation to the 21 castles in Emilia damaged by the seismic events of May–June 2012. The design and management of the database were structured in the following work phases.

3.1. Data Collection

- From existing databases: open-source databases proved to be an important resource for this research. In particular, the following shapefiles were acquired: cartographic bases (maps of regional, provincial, and municipal boundaries represented by polygons), downloaded from the ISTAT website [45]; shakemaps, with polygon geometry type, from the INGV website [31], for events with a magnitude equal to or greater than 5 (Table 2), in terms of PGA. In addition, the Regional Secretariat provided the shapefile of the data about CH of the Region of Emilia-Romagna, used in the WebGIS [22] and represented by points. Then, the records of its attribute table were appropriately selected and simplified with only the fields related to castles typology to define the feature class Damaged_Castles.
- From archival research: A large amount of data was acquired through examination and study of architectural technical drawings, reports, and photographic material of all the 21 castles damaged by the seismic events of May–June 2012. These data were

then included in the attribute tables of the three component assets (Palace, Tower, and Curtain walls). Specifically, data were collected on 31 palaces, 60 towers, and 15 curtain walls, associated with the 21 fortified complexes analyzed in the study.

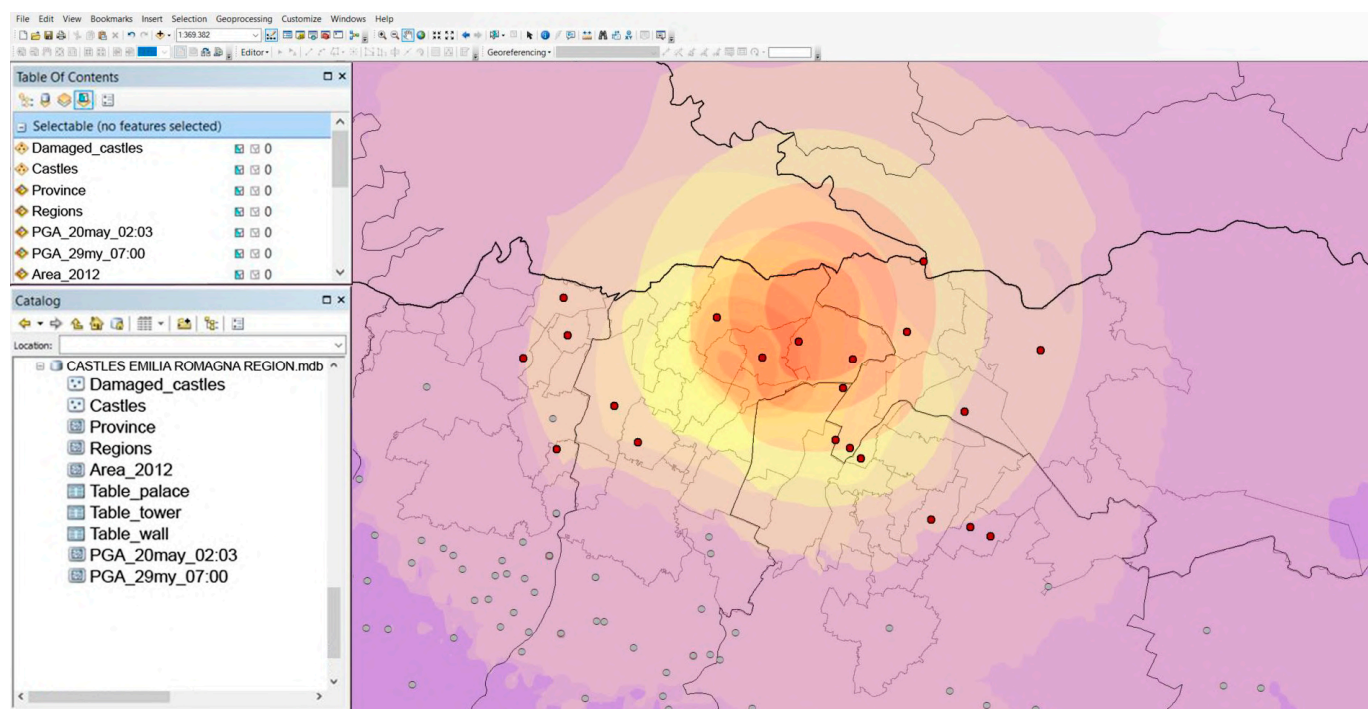


Figure 3. A screenshot of the GIS software (ArcGIS 10.3), which shows the structure and the main components of the geodatabase. The figure also shows the shakemaps of 20th and 29th May 2012, the damaged castles (red points) and undamaged castles (gray points).

Table 2. Data about the 2012 seismic shocks with magnitude greater than 5, whose shakemaps have been entered with GIS.

Date	UTC Time	Local Time	Latitude	Longitude	Magnitude
20 May 2012	02:03:52	04:03:52	44.889	11.228	5.9
20 May 2012	02:07:31	04:07:31	44.863	11.370	5.1
20 May 2012	03:02:47	05:02:47	44.86	11.15	5.0
20 May 2012	13:18:02	15:18:02	44.831	11.490	5.1
29 May 2012	07:00:03	09:00:03	44.851	11.086	5.8
29 May 2012	08:25:51	10:25:57	44.86	10.95	5.0
29 May 2012	10:55:57	12:55:57	44.888	11.008	5.3
29 May 2012	11:00:25	13:00:25	44.879	10.947	5.2
3 June 2012	19:20:43	21:20:42	44.899	10.943	5.1

3.2. Modeling

- Definition of the logical data model: In this geo-relational model (Figure 4), relationships between feature classes are established through a common field in the attribute table. Specifically, the Damaged_Castles feature class acts as the ‘parent’ feature class, to which other feature classes and attribute tables are linked, with a join relationship. More specifically, the tables Palace, Tower, and Curtain Wall are connected to the ‘parent’ feature class via the primary entity field associated with the Heritage Department code, thereby establishing one-to-many (1:M) relationships.

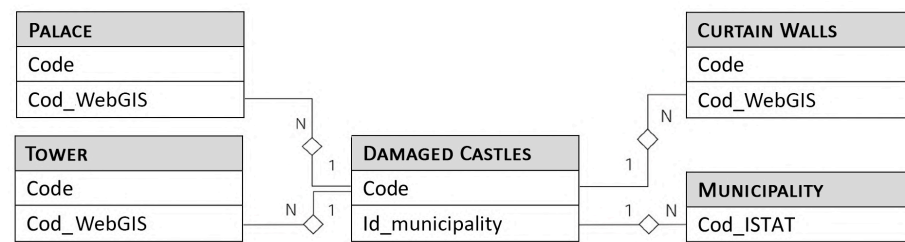


Figure 4. Logical data model of the designed geodatabase, showing the one-to-many relationships between the feature classes.

- Definition of the physical data models: this model describes the implemented fields for attribute tables. In particular, it was developed for the feature class Damaged_Castles (Table 3) and the attribute tables of the component assets (Palace, Tower, and Walls). The frame of reference used is the WGS84 UTM32.

Table 3. Physical data model of the feature class Damaged castles, represented as points. In the table, the attributes are described.

Name of the Field	Description	Type	Consistency
Code	The primary key is an alphanumeric code that uniquely identifies the listed asset. This code is made up of the ISTAT code of the municipality, an underscore and a whole number identifying the asset.	Text (10)	
Province	The province where the listed asset is located.	Text (12)	
ID municipality	ISTAT code of the municipality where the listed asset is located	Number	Whole number consisting of 6 digits.
Municipality	The municipality where the listed asset is located.	Text (22)	
Palace	Presence or absence of the Palace component asset within the complex asset.	Text (3)	Domain: -YES -NO
Tower	The number of towers within the complex asset. In case of absence, enter the number 0.	Number	
Curtain Wall	Presence or absence of the Curtain Wall component asset within the complex asset.	Text (2)	Domain: -YES -NO

3.3. Implementation and Management

- Component assets attribute table: the organization of the attribute tables of the aforementioned three component assets was carried out according to the physical model. An alphanumeric code was assigned to each component asset. In particular, for each macro-element, the possible damage mechanisms and the damage levels were associated.

- Data upload: the shapefiles and attribute tables, with the data about the component assets, were uploaded; the feature classes were linked together, according to the logical model.
- Statistical analysis and main results: cross-referencing the collected data through spatial and attributes queries and statistical analysis was performed to define new original information, which will be described more in detail in the next paragraph.

4. Results

4.1. Vulnerability: A Statistical Approach

Once the GIS database was populated, it was possible to generate original information through spatial (select by location) and attribute (select by attributes) queries. The spatial queries were of significant importance in establishing a correlation between the PGA values and the 21 castles in the exam (feature class *Damaged_castles*). Shakemaps are essential for establishing this correlation. These maps, available in shapefile format on the INGV website [31], graphically represent the distribution of ground seismic actions, recorded by seismometers deployed throughout the region at seismic stations of both the National Seismic Network and the National Accelerometric Network. The data collected from these stations are then interpolated to create shakemaps for the entire area affected by the earthquake. The reliability of these maps increases with the number and quality of instrumental recordings made at the time of the event. For instance, following the first strong shock on May 20th, additional temporary stations were installed across the region to monitor aftershocks. Therefore, it can be reasonably assumed that the maps of subsequent seismic events are more reliable [46]. From an operational point of view, it was possible to assign a PGA value to each castle through a select-by-location operation. This query allowed for the identification of the castles situated within specific polygons of the shakemaps. In fact, each polygon in the shakemap corresponds to a value of PGA. Specifically, the shakemaps of the 9 shocks with a magnitude ≥ 5 were taken into account (Table 2). This decision was based on the observation that, despite the occurrence of only two significant magnitude earthquakes (on May 20th and May 29th), the 2012 seismic swarm is distinguished by a linear displacement of individual epicenters, extending from east to west for up to 50 km. This scenario, in addition to a significant expansion of the earthquake area, has also resulted in certain assets, located far from the epicenters of the two major shocks, experiencing higher acceleration values due to minor shocks, with closer epicenters. However, in most of the cases examined, the highest accelerations was related to the seismic events of May 20th and May 29th. The identification of the maximum acceleration values suffered by the castles under study was crucial for the statistical analyses, that will be subsequently illustrated. The attribute queries, on the other hand, provided evidence of correlations between constructive morphological features and mechanism activation. In this regard, the paper focused on the three mechanisms illustrated in Section 2.2, related to towers and merlons.

4.1.1. Towers

As previously illustrated, the Emilian castle typology is typically characterized by quadrangular corner towers and by a gate tower at the entrance to the complex. Instead, isolated towers are rare. For this reason, the frequency of the above-mentioned damage mechanisms typical of the main body and of the top of the tower was analyzed and compared with the different types of tower positions, shown in Figure 5. For these analyses, 60 towers, from 21 damaged castles, were considered.

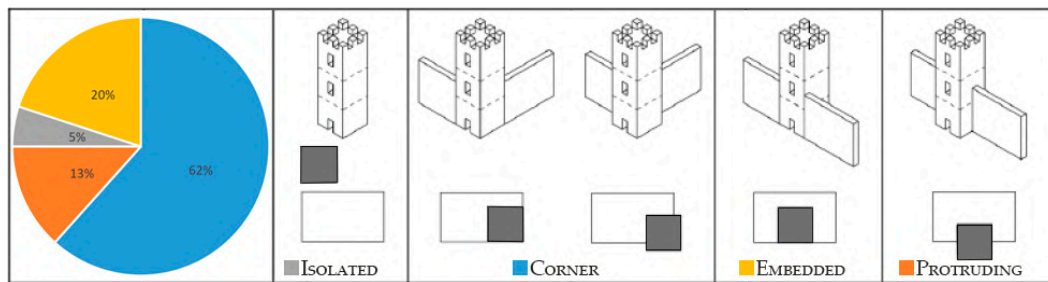


Figure 5. Different positions of the towers of Emilian castles.

In particular, by analyzing the mechanism of shear crack in the main body of the tower, it was possible to verify that the protruding towers show a severe crack pattern (DL 5), while the corner and embedded towers mostly show medium levels of damage (DL 3–4) (Figure 6). This is probably due to the strong asymmetric constraint at the base, which characterizes the protruding towers and some corner towers, and which leads to the occurrence of flexural-torsional stresses. There is also a change in stiffness at the point where the tower becomes freestanding which can trigger damage. On the other hand, in the cases considered, isolated towers are undamaged, probably because they can oscillate without hammering effects with adjacent structures. However, too few isolated towers belonging to fortified complexes have been surveyed for statistical purposes.

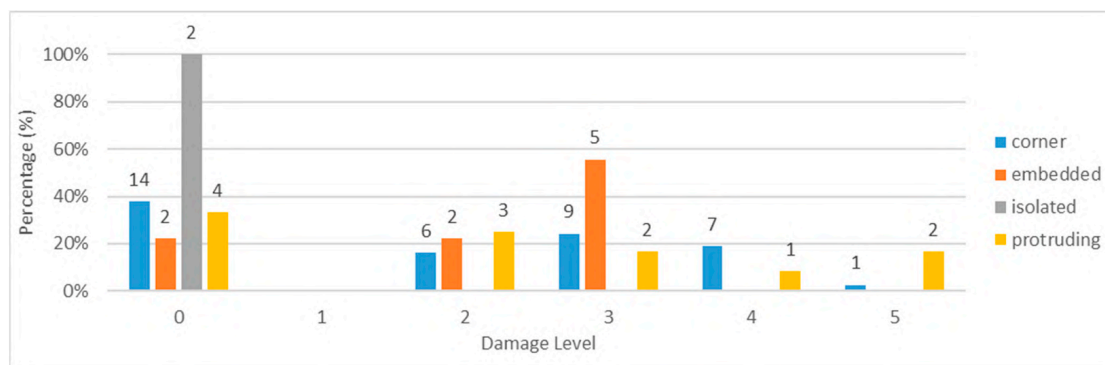


Figure 6. Mechanism of shear crack in the main body of the 60 examined tower in relation to its position.

Regarding the shear mechanism in the freestanding upper part of the tower, 57 towers are taken into account, excluding the single isolated tower and those that do not extend beyond the adjacent structures. The least damaged towers are those that protrude from the main structure (Figure 7). The most severely damaged ones are the corner towers and embedded towers, probably because these towers have a better connection of the main body to the complex than the protruding towers. In fact, if the lower part of the tower is better connected, there could be a greater change in stiffness at the point where the tower starts to rise, which could lead to more severe damage in the upper part. It should be noted that isolated towers were excluded from the analysis of this mechanism, as in this case only the portion of the tower protruding with respect to the adjacent buildings is taken into consideration.

4.1.2. Merlons

Statistical analyses—carried out on 37 crenelated parapets—have shown that the presence or absence of a roof, i.e., a top constraint, has a significant effect on the seismic behavior of the merlon. In fact, as can be intuitively imagined, merlons which are constrained only at the base are more subject to out-of-plane overturning mechanisms (Figure 8a). On the other

hand, merlons supporting a roof on top, and therefore constrained also at the top, are more vulnerable to in-plane shear damage (Figure 8b). However, some exceptions have been noted. In particular, the overturning of the merlons with a roof on a tower of the Castle of Finale Emilia (Figure 9a) and of one of the curtain walls of San Felice sul Panaro Castle (Figure 9b) is probably due to an inadequate connection between the masonry and the elements of the roof, which therefore did not act as a constraint, or especially in the second case—due to the thrust of the roof elements, which not only did not prevent the mechanism from being activated but also contributed to it. Of course, there are other factors that may worsen the crack pattern of the merlons, such as their slenderness and position in height. On the other hand, there seems to be no significant correlation between the onset of the damage mechanism and the shape of the merlon (guelph or ghibelline).

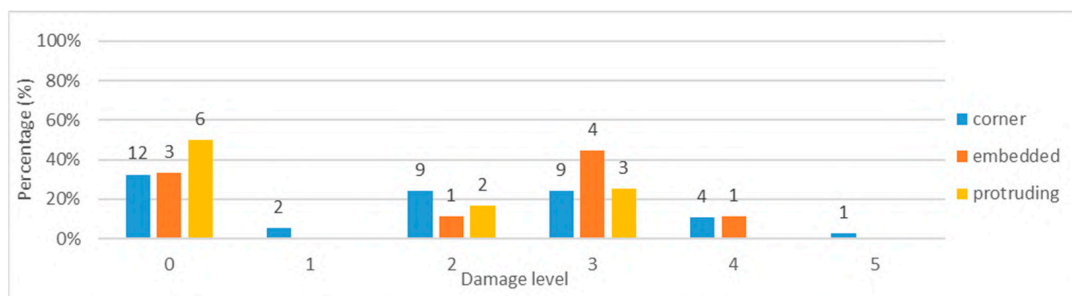
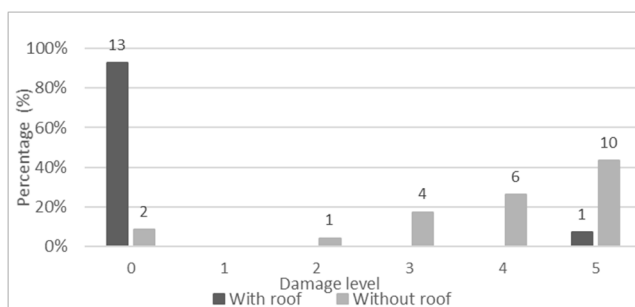
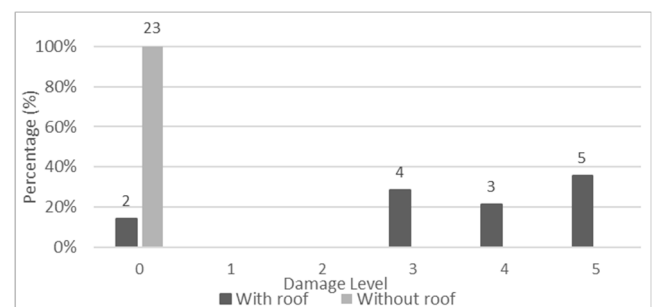


Figure 7. Mechanism of shear crack in the freestanding part of the tower in relation to its position.



(a)



(b)

Figure 8. Merlons with or without a roof: **(a)** frequency of activation of out-of-plane overturning mechanism; **(b)** frequency of activation of in-plane shear mechanism.



(a)



(b)

Figure 9. Two examples of overturning of the merlons with roof: **(a)** merlons of a tower of the Castle of Finale Emilia; **(b)** a merlon of the curtain walls of San Felice sul Panaro Castle.

4.2. Fragility Curves

Fragility curves have been defined for the three damage mechanisms considered. These functions graphically represent the seismic risk and are now widely used in the scientific field for its assessment at the territorial scale, both for ordinary buildings and for architectural heritage [32,35,47]. It is possible to develop fragility curves numerically or empirically. In the proposed procedure the latter has been chosen, based on the statistical analysis of data collected on-site, for fortified architectural typology. In particular, fragility curves were not defined for the entire complex, but only for the three mechanisms of towers and merlons. This choice has already been made for other masonry typologies. Historical masonry buildings tend to be damaged by local rather than global mechanisms. In fact, within the same building, following an earthquake, some macro-elements may collapse, whereas others may suffer no damage. Consequently, according to [34,48,49], the fragility curves can exhibit significant variability across different mechanisms. In fact, certain mechanisms demonstrate higher vulnerability than others, supporting a mechanism-based approach, over the global assessment methods. The development of fragility curves for each mechanism can therefore aid in providing more accurate risk assessments. For each of the three mechanisms, the following graphs (Figures 10–12) show the data expressed both in terms of numerical frequency—i.e., for each PGA range the actual number of mechanisms activated according to the relative damage levels is shown—and in terms of relative frequency—i.e., for each PGA range the percentage of damage levels is shown. The graphs, based on the data about 60 towers and 37 crenelated parapets, show that as PGA values increase, the percentages of D0 and D1 damage levels (green colors) tend to decrease, while those of the more severe D4 and D5 levels (red-orange colors) tend to increase. In the case of the mechanism of overturning the merlons, it was necessary to merge different damage levels in order to have a more significant amount of data.

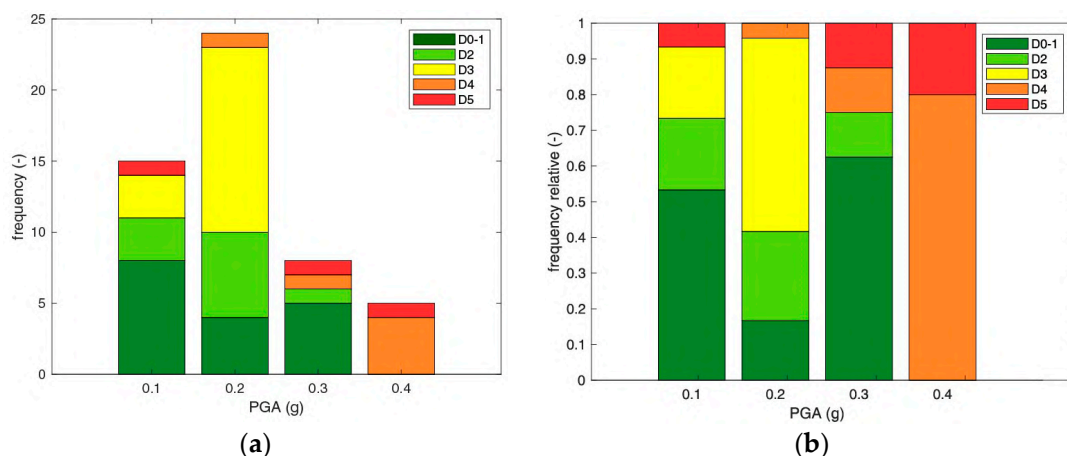


Figure 10. Shear cracks in the main body of the tower: (a) graph in terms of numerical frequency; (b) graph in terms of relative frequency.

From the data thus processed, it was possible to define empirical fragility curves. Specifically, the fragility curves shown below were defined according to the function (1) with log-normal distribution, as previous studies [35] have confirmed that this is the most appropriate one to represent the observed damage data. The specific function used is:

$$P[DS \geq PGA] = \Phi\left(\frac{\ln(PGA) - \mu}{\beta}\right) \quad (1)$$

where Φ is the log-normal cumulative distribution function (CDF), μ is the log mean, a parameter that can be any real number, and β is the standard deviation, which must be a

positive number. In particular, the parameters μ and β used, shown in Table 4, have been defined using the method of maximum likelihood estimation (MLE), i.e., by maximizing the likelihood function (2), which, already studied and published [50], is shown below:

$$\text{Likelihood} = \prod_{j=1}^m \binom{N_j}{n_j} p_j^{n_j} (1 - p_j)^{N_j - n_j} \quad (2)$$

where p_j is the probability of damage, n_j is the number of damaged buildings and N_j is the total number of buildings. As shown in Table 4, a different parameter μ was assumed for each obtained curve, while the parametric parameter β was kept constant, in order to avoid the curves crossing each other, as illustrated in [51].

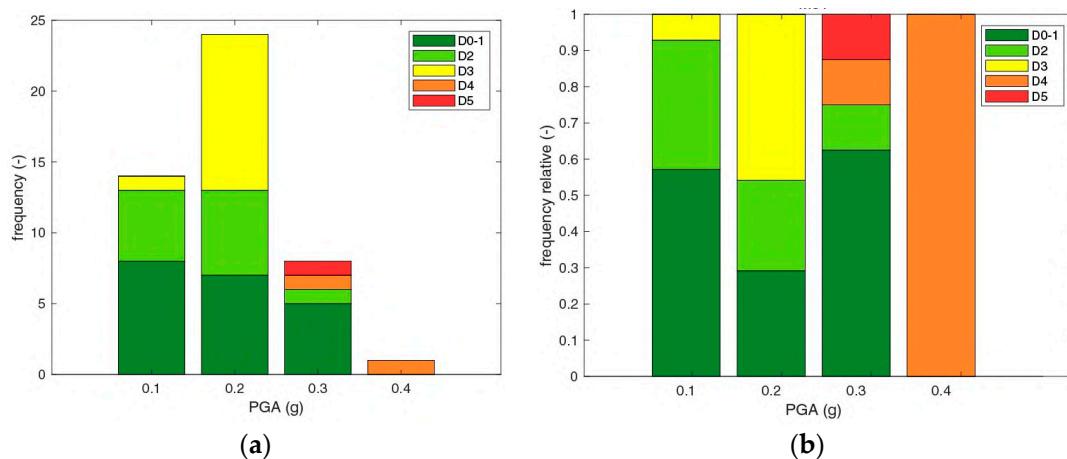


Figure 11. Shear cracks in the upper part of the tower: (a) graph in terms of numerical frequency; (b) graph in terms of relative frequency.

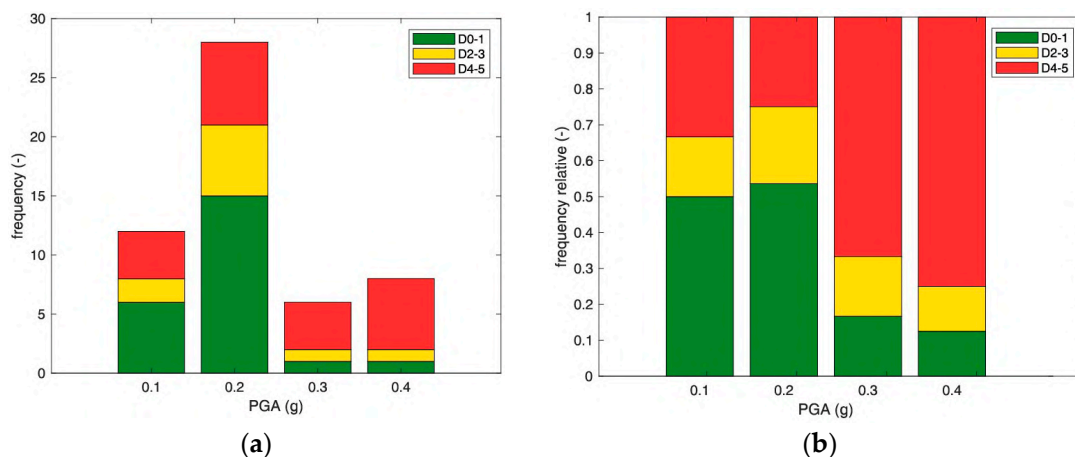


Figure 12. Out-of-plane overturning of the merlons: (a) graph in terms of numerical frequency; (b) graph in terms of relative frequency.

The estimated fragility curves, shown simultaneously on the same graph (Figure 13), express the probability of reaching the given damage levels, for each macro-element, on varying the PGA values, based on the observed damage levels (points in Figure 13). As the acceleration values increase, the probability of high damage obviously increases. Furthermore, for each acceleration value, the probability of low-medium damage levels—2 or 3—is always greater than the probability of severe damage levels—4 or 5. For example, at acceleration values of 0.1 g, the probability of tower collapse is very low. While merlons

already have a 20% probability of collapse at this value, rising to 35% for minor low-medium damage levels.

Table 4. Parameters of the logarithmic function (1).

	μ D2	μ D3	μ D4	μ D5	β
Shear cracks in the main body of the tower	−2.2129	−1.6209	−0.5140	0.1969	1.1211
Shear cracks in the upper part of the tower	−1.9282	−1.2045	−0.0007	0.5249	1.0240
Merlons overturning	−1.8788		−1.2315		1.3078

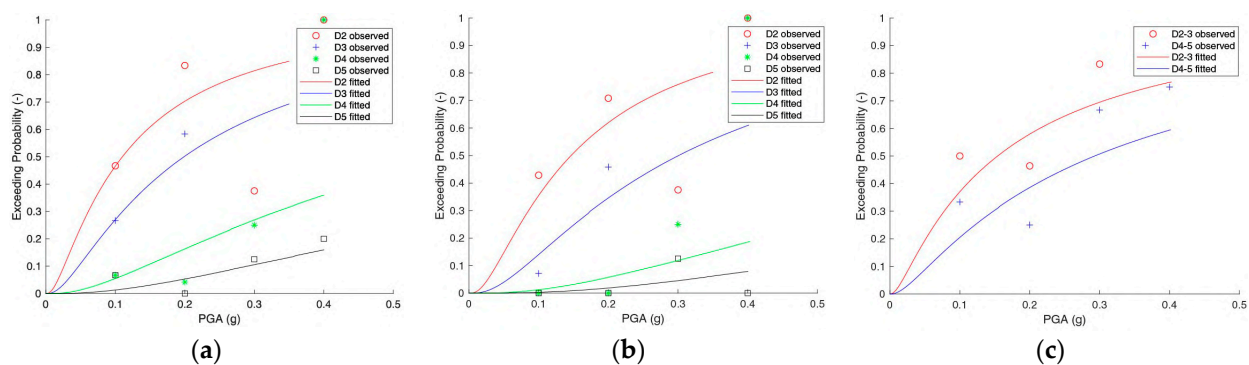


Figure 13. Fragility curves of three typical damage mechanisms: (a) shear cracks in the main body of the tower; (b) Shear cracks in the upper part of the tower; (c) overturning of the merlons.

The functions described above represent a preliminary achievement, but further improvement is possible in the future through: the extension of the damage survey in order to increase the reliability of the analyses and thus of the relative predictions; the detailed study of the geometric-constructive features or the presence of seismic-protection elements (e.g., tie rods, hooping etc.) that could influence the activation of the mechanism.

5. Discussion on the Proactive Application of the Results

Accurate seismic risk assessment at the territorial scale is essential for the definition of mitigation strategies and for the management and planning of appropriate conservation interventions for the built heritage. The main challenge is the definition of risk, which is the product of three parameters [52]: hazard, vulnerability, and exposure. Seismic hazard describes the frequency and the magnitude of future earthquakes in an area. Vulnerability refers to the susceptibility of a building to be damaged by an earthquake. Exposure is related to the assets exposed to the risk, such as loss of human lives, and economic and cultural heritage damage.

Two of these aspects are particularly addressed by the outlined proactive methodology: hazard and vulnerability. In particular, the methodology takes into account the expected accelerations, in terms of PGA, as estimated by seismic hazard maps [36] and compares them with the foreseen vulnerabilities. To this aim, this methodology focuses on the construction and morphological characteristics of fortified architecture, specifically highlighting three frequent mechanisms, described in the previous section, for which fragility curves have been defined. Therefore, by correlating the expected accelerations of the seismic hazard map with the acceleration values identified by the fragility curves, it is possible to highlight the macro-elements at risk—in this case, towers and merlons—in order to intervene before the damage occurs. In fact, vulnerability remains the only parameter on which action can be taken, through preventive interventions, aimed at improving the seismic resistance of the

most vulnerable macro-elements through local actions, in compliance with the principles of minimum intervention and material conservation for the preservation of CH. In addition, the adopted proactive methodology ensures the possibility of drawing up a list of priority interventions in order to optimize the use of economic resources.

The proposed proactive methodology was then validated by applying it outside the 2012 seismic area, i.e., where no damage had occurred. The Province of Parma was chosen, because the fortified architectures of this area have similar constructive and morphological characteristics and chronology to those belonging to the 2012 seismic area. In particular, in the province of Parma, there are 30 fortified architectures in a good state of conservation. These assets were included in the GIS database by creating a new feature class, whose macro-elements were cataloged in the related attribute table. Once the study cases in Parma were geo-located, it was possible to associate them with the expected acceleration values, expressed in PGA, derived from the seismic hazard map, adopted by the Italian regulation [44]. Specifically, the used map reports values of peak ground acceleration (PGA) with a 10% probability of exceedance in 50 years, based on stiff soil conditions [36,44]. The map, available from the INGV website in Excel or text file format, contains the coordinate data of a regular grid of points. Each point is associated with a corresponding ground acceleration value. The text files were imported into the GIS environment, where the relevant grid points were interpolated to generate a raster file representing the spatial distribution of ground accelerations over the territory of the Province of Parma. This procedure allowed the assignment of an expected acceleration value to each castle by means of a spatial query. By applying the cumulative log-normal distribution function, which describes the previously illustrated fragility curves, it was possible to define the probabilities that the tree mechanisms in the exam would occur for each asset in the Province of Parma in the event of future earthquakes.

From the analyzed data, it was possible to define the following risk scenarios. As expected, the macro-elements at greater risk are located in the Apennine area, in the south of the Province, where the expected accelerations are higher (Figures 14 and 15). Specifically, the probabilities that the freestanding portion of the tower collapses (D5) or is very heavily damaged (D4) due to shear cracks, in the Province of Parma, are significantly low (Figure 14a). Instead, the probability of moderate damage is around 50%. However, among the assets with the same expected accelerations, it would be reasonable to focus future risk prevention interventions on embedded towers—which are more vulnerable to this mechanism—such as the towers of the Gallinella and Scipione castles in Salsomaggiore Terme and Montechiarugolo. The probabilities of heavy damage (D4–D5), due to shear cracks with torsional effect in the main body of the tower appear instead to be more relevant (Figure 14b). Specifically, among the assets with the same expected acceleration, it would be recommended to give priority—for an in-depth analysis and then for an intervention if necessary—to those with protruding towers, as they are more vulnerable to this mechanism.

The probability that the overturning mechanisms of merlons activate, in this scenario resulted to be particularly high. For 10 out of 17 assets, the probability of this mechanism manifesting in a moderate way (D2–D3) is around or over 50% (Figure 15a), and over 30% in a heavy way (D4–D5) (Figure 15b). However, as illustrated in the previous paragraphs, the likelihood of overturning for a merlon constrained at the top by the roof is rare. It is therefore recommended to apply more urgent preventive actions on freestanding merlons. More in detail, the order of priority for the interventions on merlons is the following: the Castle of Tabiano in Salsomaggiore Terme, the Fortress of Castelguelfo in Noceto, the San Vitale Fortress in Fontanellato, the Fortress of Rossi in San Secondo Parmense and the Castle of Busseto. The results derived from the definition of a potential seismic risk scenario will require further development in future work to incorporate the effects of local site conditions.

Specifically, the seismic hazard map used in this study indicates that lowland areas are generally at lower risk compared to mountainous regions. However, it does not account for the amplification effects associated with softer soil conditions [53–55]. Nevertheless, the proactive methodology proposed in this study offers a valuable framework, which, when further developed through additional case studies and the integration of more precise and reliable data, has the potential to effectively inform the implementation of targeted strategies of planned conservation [56,57], which includes both territorial-scale interventions for the prevention and the management of risks, as well as building interventions to mitigate vulnerabilities.

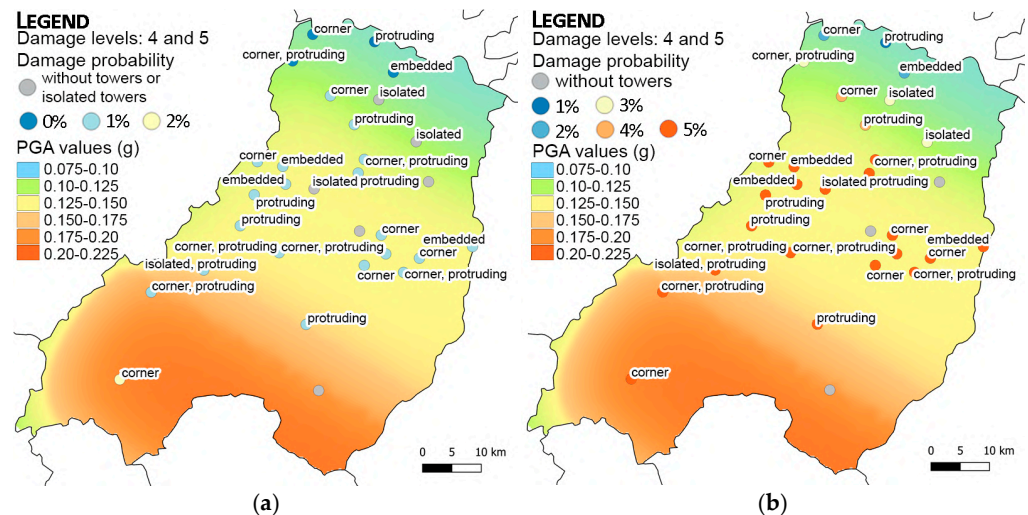


Figure 14. Positions of the towers and scenario of the probability of occurrence—in heavy way (D4–D5)—of the two mechanisms in exam: (a) shear cracks in the upper part of the tower; (b) shear cracks in the main body of the tower.

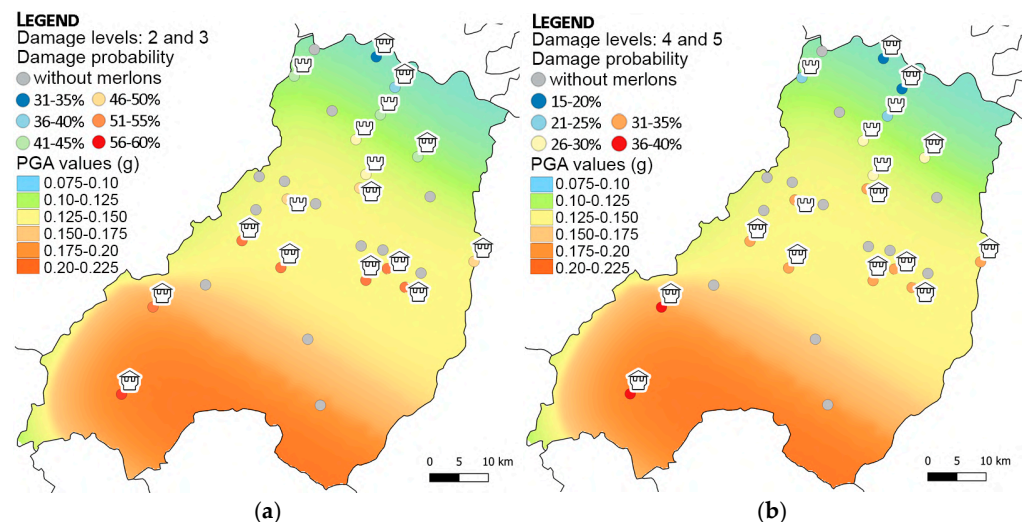


Figure 15. Scenario of the frequency of the overturning mechanism of merlon with or without a roof (as highlighted by the symbols): (a) the probability of occurrence of the mechanism in a moderate way (D2–D3) is around or over 50%; (b) and over 30% in a heavy way (D4–D5).

6. Conclusions

This research selected fortified structures as an example of the seismic vulnerability of masonry-built heritage, which tends to be damaged through typical and local mechanisms. In particular, the paper focused on three seismic damage mechanisms commonly observed

after the 2012 earthquake, with the aim of defying a possible proactive methodology for their prevention in other areas.

The implementation of this methodology, within the GIS environment, allowed for the achievement of preliminary results. In particular, statistical and georeferenced analyses enabled the identification of correlations between constructive features and the occurrence of specific collapse mechanisms. Moreover, the fragility curves made it possible to establish a quantitative correlation between the damage levels of each mechanism and the ground acceleration (PGA), derived from shakemaps. In addition, the proactive methodology, when applied to the area of the Province of Parma, outside the 2012 earthquake area, allowed the identification of the vulnerabilities at a territorial scale and helped prioritize assets for intervention based on their higher seismic risk, considering both hazard and vulnerability. The proposed methodology thus has the potential to optimize the management of limited economic resources and to preserve the CH through the application of planned conservation strategies.

The results illustrated in this paper set the basis for future developments. In particular, the designed geo-database is suitable for further implementation and expansion. It is essential that the tool can interoperate with existing regional [22] and national [30] databases, in order to serve as an effective instrument for the optimization of heritage management procedures, both before and after earthquakes, and for the definition of strategies and intervention priorities for seismic risk reduction.

Furthermore, the geo-database could be expanded to include additional architectural typologies, that present similar damage mechanisms, such as isolated towers, civic towers, city gates, and urban walls. The addition of these typologies would increase the number of examined cases, thereby optimizing the fragility curves that have been defined. Additionally, the PGA values of the seismic hazard map must be modified according to local site conditions, as outlined in the literature [53–55]. Such data implementation would serve to enhance the reliability of the statistical outputs, providing a basis for more accurate predictions regarding the onset of kinematism. This would allow for the definition and application of targeted preventive interventions to improve the material conservation of architectural heritage.

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Data Availability Statement: The original data presented in the study are partly openly available in [22,31,36,45] and partly obtained from the Archive of the Heritage Department of Bologna. These latter data are available upon request and with permission from the respective owners of the castles.

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References

1. Decreto-Legge. n. 74—06/06/2012. Interventi Urgenti in Favore Delle Popolazioni Colpite Dagli Eventi Sismici che Hanno Interessato il Territorio Delle Province di Bologna, Modena, Ferrara, Mantova, Reggio Emilia e Rovigo, il 20 e il 29 Maggio 2012; In Gazzetta Ufficiale n. 180—03/08/2012: Rome, Italy, 2012. Available online: https://www.gazzettaufficiale.it/atto/serie_generale/caricaDettaglioAtto/originario?atto.dataPubblicazioneGazzetta=2012-06-07&atto.codiceRedazionale=012G0096 (accessed on 26 April 2025).
2. Coisson, E.; Ferrari, L.; Ferretti, D.; Rozzi, M. Non-Smooth Dynamic Analysis of Local Seismic Damage Mechanisms of the San Felice Fortress in Northern Italy. *Procedia Eng.* **2016**, *161*, 451–457. [CrossRef]

3. Tiberti, S.; Acito, M.; Milani, G. Comprehensive FE numerical insight into Finale Emilia Castle behavior under 2012 Emilia Romagna seismic sequence: Damage causes and seismic vulnerability mitigation hypothesis. *Eng. Struct.* **2016**, *117*, 397–421. [CrossRef]
4. Degli Abbati, S.; D’Altri, A.M.; Ottonelli, D.; Castellazzi, G.; Cattari, S.; De Miranda, S.; Lagomarsino, S. Seismic assessment of complex assets through nonlinear static analyses: The fortress in San Felice sul Panaro hit by the 2012 earthquake in Italy. In Proceedings of the 6th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Rhodes Island, Greece, 15–17 June 2017; pp. 2290–2299. [CrossRef]
5. D’Altri, A.M.; Castellazzi, G.; De Miranda, S. Collapse investigation of the Arquata del Tronto medieval fortress after the 2016 Central Italy seismic sequence. *J. Build. Eng.* **2018**, *18*, 245–251. [CrossRef]
6. Valente, M.; Milani, G. Earthquake-Induced damage assessment and partial failure mechanisms of an Italian Medieval castle. *Eng. Fail. Anal.* **2019**, *99*, 292–309. [CrossRef]
7. Milani, G.; Acito, M.; Chesi, C.; Di Francesco, C.; Martines, G. A multidisciplinary insight into the collapse causes of the masonry clock tower and castle in Finale Emilia. In Proceedings of the SAHC2014—9th International Conference on Structural Analysis of Historical Constructions, Mexico City, Mexico, 14–17 October 2014; pp. 14–17.
8. Acito, M.; Bocciarelli, M.; Chesi, C.; Milani, G. Collapse of the clock tower in Finale Emilia after the May 2012 Emilia Romagna earthquake sequence: Numerical insight. *Eng. Struct.* **2014**, *72*, 70–91. [CrossRef]
9. Zanutti Fragonara, L.; Boscatto, G.; Ceravolo, R.; Russo, S.; Ientile, S.; Pecorelli, M.L.; Quattrone, A. Dynamic investigation on the Mirandola bell tower in post-earthquake scenarios. *Bull. Earthq. Eng.* **2017**, *15*, 313–337. [CrossRef]
10. Castellazzi, G.; D’Altri, A.M.; De Miranda, S.; Chiozzi, A.; Tralli, A. Numerical insights on the seismic behavior of a nonisolated historical masonry tower. *Bull. Earthq. Eng.* **2018**, *16*, 933–961. [CrossRef]
11. Torelli, G.; D’Ayala, D.; Betti, M.; Bartoli, G. Analytical and numerical seismic assessment of heritage masonry towers. *Bull. Earthq. Eng.* **2020**, *18*, 969–1008. [CrossRef]
12. Cima, V.; Grande, E.; Lirer, S. Proposal for an expeditious seismic vulnerability evaluation of the Italian medieval defensive walls. *Bull. Earthq. Eng.* **2024**, *22*, 5147–5171. [CrossRef]
13. Doglioni, F. *Codice di Pratica (Linee Guida) per la Progettazione Degli Interventi di Riparazione, Miglioramento Sismico e Resaturato dei Beni Architettonici Danneggiati dal Terremoto Umbro-Marchigiano del 1997*; Regione Marche—Bollettino Ufficiale: Ancona, Italy, 2000.
14. Doglioni, F.; Moretti, A.; Petrini, V. *Le Chiese e il Terremoto*; Lint Ed.: Trieste, Italy, 1994; ISBN 888-617-936-7.
15. Lagomarsino, S. Damage assessment of churches after L’Aquila earthquake (2012). *Bull. Earthq. Eng.* **2012**, *10*, 73–92. [CrossRef]
16. D’Ayala, D.; Speranza, E. Definition of collapse mechanisms and seismic vulnerability of historic masonry buildings. *Earthq. Spectra* **2003**, *19*, 479–509. [CrossRef]
17. Cattari, S.; Degli Abbati, S.; Ferretti, D.; Lagomarsino, S.; Ottonelli, D.; Tralli, A. Damage assessment of fortresses after the 2012 Emilia earthquake (Italy). *Bull. Earthq. Eng.* **2014**, *12*, 2333–2365. [CrossRef]
18. Coisson, E.; Ferretti, D.; Lenticchia, E. Analysis of damage mechanisms suffered by Italian fortified buildings hit by earthquakes in the last 40 years. *Bull. Earthq. Eng.* **2017**, *15*, 5139–5166. [CrossRef]
19. Zanazzi, E. *Fortezze Fragili: Dall’analisi del Dissesto a Strategie per la sua Prevenzione*; Quasar: Rome, Italy, 2023; pp. 1–243, ISBN 978-88-5491-433-9.
20. Della Torre, S. Italian perspective on the planned preventive conservation of architectural heritage. *Front. Archit. Res.* **2021**, *10*, 108–116. [CrossRef]
21. Decreto-Legge n. 42—22/01/2004. *Codice dei Beni Culturali e del Paesaggio*; In Gazzetta Ufficiale n.45—24/02/2004: Rome, Italy, 2004. Available online: https://www.gazzettaufficiale.it/atto/serie_generale/caricaDettaglioAtto/originario?atto.dataPubblicazioneGazzetta=2004-02-24&atto.codiceRedazionale=004G0066 (accessed on 26 April 2025).
22. WebGIS del Patrimonio Culturale—Emilia Romagna. Available online: <https://www.patrimonioculturale-er.it/webgis/> (accessed on 17 September 2024).
23. Sigec Web. Available online: <https://www.catalogo.beniculturali.it/> (accessed on 28 April 2025).
24. Coisson, E.; Ferretti, D.; Lenticchia, E.; Zanazzi, E. GIS Methodologies for the Management of Seismic Risk and the Damage Prevention on Masonry-Built Heritage. In Proceedings of the International Conference on Structural Analysis of Historical Constructions, Kyoto, Japan, 11–13 September 2023; pp. 1169–1180. [CrossRef]
25. Leggieri, V.; Mastrodonato, G.; Uva, G. GIS Multisource Data for the Seismic Vulnerability Assessment of Buildings at the Urban Scale. *Buildings* **2022**, *12*, 523. [CrossRef]
26. Cara, S.; Aprile, A.; Pelà, L.; Roca, P. Seismic Risk Assessment and Mitigation at Emergency Limit Condition of Historical Buildings along Strategic Urban Roadways. Application to the “Antiga Esquerra de L’Eixample” Neighborhood of Barcelona. *Int. J. Archit. Herit.* **2018**, *12*, 1055–1075. [CrossRef]

27. Ferreira, T.M.; Vicente, R.; Mendes Da Silva, J.A.R.; Varum, H.; Costa, A. Seismic vulnerability assessment of historical urban centres: Case study of the old city centre in Seixal, Portugal. *Bull. Earthq. Eng.* **2013**, *11*, 1753–1773. [CrossRef]
28. Lenticchia, E.; Coisson, E. The use of GIS for the application of the phenomenological approach to the seismic risk analysis: The case of the Italian fortified architecture. *ISPRS Arch.* **2017**, *42*, 39–46. [CrossRef]
29. Coisson, E.; Ferretti, D.; Lenticchia, E. Italian castles and earthquakes: A GIS for knowledge and preservation. In Proceedings of the 10th International Conference on Structural Analysis of Historical Constructions SAHC, Leuven, Belgium, 13–15 September 2016; pp. 1489–1496, ISBN 978-131-561-699-5.
30. MiC. Risk Map. Available online: <http://www.cartadelrischio.beniculturali.it/> (accessed on 28 April 2025).
31. ShakeMap Archive. Available online: <https://shakemap.ingv.it/> (accessed on 17 September 2024).
32. Lagomarsino, S. On the vulnerability assessment of monumental buildings. *Bull. Earthq. Eng.* **2006**, *4*, 445–463. [CrossRef]
33. Lagomarsino, S.; Cattari, S.; Ottonelli, D. The heuristic vulnerability model: Fragility curves for masonry buildings. *Bull. Earthq. Eng.* **2021**, *19*, 3129–3163. [CrossRef]
34. Marotta, A.; Liberatore, D.; Sorrentino, L. Development of parametric seismic fragility curves for historical churches. *Bull. Earthq. Eng.* **2021**, *19*, 5609–5641. [CrossRef]
35. Del Gaudio, C.; De Martino, G.; Di Ludovico, M.; Manfredi, G.; Prota, A.; Ricci, P.; Verderame, G.M. Empirical fragility curves for masonry buildings after the 2009 L'Aquila, Italy, earthquake. *Bull. Earthq. Eng.* **2019**, *17*, 6301–6330. [CrossRef]
36. INGV. Seismic Zone. Available online: <http://zonesismiche.mi.ingv.it/> (accessed on 2 March 2025).
37. Cassi Ramelli, A. *Dalle Caverne ai Rifugi Blindati*; Nuova Accademia Editrice: Milan, Italy, 1964; ISBN 978-888-082-232-5.
38. Perogalli, C. *Castelli e Rocche di Emilia e Romagna*; Seregorlich: Milan, Italy, 1972; ISBN 978-884-025-659-7.
39. Karataş, L.; Ateş, T.; Alptekin, A.; Dal M Yakar, M. A systematic method for post-earthquake damage assessment: Case study of the Antep Castle, Türkiye. *Adv. Eng. Sci.* **2023**, *3*, 62–71.
40. Ferretti, D.; Coisson, E.; Lenticchia, E. Seismic damage on merlons in masonry fortified buildings: A parametric analysis for overturning mechanism. *Eng. Struct.* **2018**, *177*, 117–132. [CrossRef]
41. Grünthal, G. *European Macroseismic Scale 1998: EMS-98. European Seismological Commission; Subcommission on Engineering Seismology*; Luxembourg, 1998; p. 15. ISBN 2-87977-008-4.
42. Baggio, C.; Bernardini, A.; Colozza, R.; Corazza, L.; Della Bella, M.; Di Pasquale, G. Field Manual for post-earthquake damage and safety assessment and short term countermeasures (AeDES). In *JRC Sci Technical Reports*; European Commission: Luxembourg, 2007.
43. DPCM. 23/02/2006. In Approvazione dei Modelli per il Rilevamento dei Danni, a Seguito di Eventi Calamitosi, ai Beni Appartenenti al Patrimonio Culturale; In Gazzetta Ufficiale n.55—07/03/2006: Rome, Italy, 2006. Available online: <https://www.gazzettaufficiale.it/eli/id/2006/03/07/06A02214/sg> (accessed on 26 April 2025).
44. OPCM, n. 3519—28/04/2006. Criteri Generali per L'individuazione Delle Zone Sismiche e per la Formazione e L'aggiornamento Degli Elenchi Delle Medesime Zone; In Gazzetta Ufficiale n.108—11/05/2006: Rome, Italy, 2006. Available online: <https://www.gazzettaufficiale.it/eli/id/2006/05/11/06A04427/sg> (accessed on 26 April 2025).
45. ISTAT. Confini Delle Unità Amministrative a Fini Statistici al 1° Gennaio 2022. Available online: <https://www.istat.it/it/archivio/222527> (accessed on 17 September 2024).
46. Michelini, A.; Faenza, L.; Lauciani, V.; Malagnini, L. ShakeMap implementation in Italy. *Seismol. Res. Lett.* **2008**, *79*, 688–697. [CrossRef]
47. Rosti, A.; Rota, M.; Magenes, G.; Penna, A. A procedure for seismic risk assessment of Italian masonry buildings. In Proceedings of the 7th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Crete, Greece, 24–26 June 2019; pp. 1653–1663. [CrossRef]
48. Sisti, R.; Argiento, L.; Casapulla, C.; Ceroni, F.; Prota, A. Empirical fragility curves for macro-elements and single mechanisms of churches damaged during the 2016–2017 Central Italy seismic sequence. *Procedia Struct. Integr.* **2023**, *44*, 1380–1387. [CrossRef]
49. Sisti, R.; Argiento, L.U.; Ceroni, F.; da Porto, F.; Prota, A.; Casapulla, C. Empirical fragility curves for masonry churches and their macro-elements using a large database: Proposal of a new likelihood function. *Structures* **2023**, *57*, 105164. [CrossRef]
50. Baker, J.W. Efficient analytical fragility function fitting using dynamic structural analysis. *Earthq Spectra* **2015**, *31*, 579–599. [CrossRef]
51. Porter, K. A Beginner's Guide to Earthquake Fragility Vulnerability and Risk. *Encycl. Earthq. Eng.* **2015**, 235–260. [CrossRef]
52. Office of the United Nations Disaster Relief Coordinator. *Natural Disasters Vulnerability and Analysis*; Report of Experts Group Meeting; Office of the United Nations Disaster Relief Coordinator: Geneva, Swiss, 1980.
53. Romeo, R.; Paciello, A.; Rinaldis, D. Seismic hazard maps of Italy including site effects. *Soil Dyn. Earthq. Eng.* **2000**, *20*, 85–92. [CrossRef]
54. Crowley, H.; Colombi, M.; Borzi, B.; Faravelli, M.; Onida, M.; Lopez, M. A comparison of seismic risk maps for Italy. *Bull. Earthq. Eng.* **2009**, *7*, 149–180. [CrossRef]

55. Falcone, G.; Mendicelli, A.; Mori, F.; Fabozzi, S.; Moscatelli, M.; Occhipinti, G.; Peronace, E. A simplified analysis of the total seismic hazard in Italy. *Eng. Geol.* **2020**, *267*, 105511. [[CrossRef](#)]
56. Urbani, G. *Intorno al Restauro*, 2nd ed.; Skira: Milan, Italy, 2000; ISBN 978-888-118-512-2.
57. Della Torre, S. A coevolutionary approach as the theoretical foundation of planned conservation of built cultural heritage. In *Preventive Conservation-From Climate and Damage Monitoring to a Systemic and Integrated Approach*; Vandesande, A., Verstrynghe, E., van Balen, K., Eds.; CRC Press: London, UK, 2020; pp. 11–18, ISBN 978-100-300-404-2.

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