

Analysis of damage mechanisms suffered by Italian fortified buildings hit by earthquakes in the last 40 years

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Abstract This paper presents an empirical approach to studying the seismic behaviour of fortified buildings, including castles, fortresses, and citadels. The first step for a focused preventive intervention on this building typology, characterised by the presence of towers, defensive walls and other particular elements, is to identify recurring vulnerabilities. Over 750 castles and 7 seismic events which have hit Italy in recent decades have been considered, including the earthquakes in Central Italy in August and October 2016. For each seismic event, the characteristics of the earthquake have been described by means of shake maps, while the castles in the area have been identified and inserted in a specifically formulated geographic information system. Subsequently, a thorough archival and bibliographical research on the damage suffered by the most significant case histories allowed the comparison of the damage observed in the castles with different characteristics in terms of soil, materials, building typologies and conservation status. A previously proposed table of damage mechanisms was adopted and verified on a larger number of castles, suggesting some modifications. Lastly, statistical analysis on these data was conducted in order to inspect possible connections between building features, peak ground acceleration and damage mechanisms. The results have shown a good agreement with the existing vulnerability curve and the small amount of numerical analyses proposed in the literature for the same building typology.

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1 Introduction

The earthquakes that have hit Italy in the past few decades have caused considerable damage to the country's widespread architectural heritage, including a large number of castles, fortresses, and fortified villages. "Castles" are defined as complex fortified buildings usually composed of towers with surrounding walls and secondary buildings, sometimes characterised by unique architectural elements. With respect to other building typologies, like churches (Doglioni et al. 1994) and palaces (D'Ayala and Speranza 2003), castles have been the subject of a limited number of studies on specific seismic damage, mainly focused on single case histories (Tiberti et al. 2016; Castellazzi et al. 2015; Coisson et al. 2016a; Meschini et al. 2015; Barrile et al. 2016; Leoni et al. 2015). At a territorial scale, some works have analysed the vulnerability of isolated towers and belfries (Sepe et al. 2008; Mirabella Roberti et al. 2012; Bartoli et al. 2016; Valente and Milani 2016). In these studies, the assessment of seismic vulnerability was usually performed by means of finite element models, adopting modal response spectrum analysis (Barrile et al. 2016), nonlinear static analysis (Tiberti et al. 2016; Valente and Milani 2016; Castellazzi et al. 2017), and nonlinear dynamic analysis (Tiberti et al. 2016). In some cases, kinematic analysis was used to study local mechanisms (Leoni et al. 2015; Coisson et al. 2016a; Bartoli et al. 2016; Tiberti et al. 2016).

The first work that analysed a group of castles in order to find a relation between building features and damage was Cattari et al. (2014), which included a first proposal for a table cataloguing the main damage mechanisms identified in the castles struck by the 2012 Emilia earthquake. However, this table was defined considering only a limited number of cases from the Emilia region, thus it has a limited range of possible applications for cataloguing damage caused by future earthquakes and—most importantly—for the identification of the vulnerable elements in order to undertake preventive conservation.

In Coisson et al. (2016b) the authors extended the study to two strong Italian earthquakes (Irpinia 1980 and Emilia 2012), thus including a larger number of cases from different areas, implicitly considering different earthquake characteristics, soil types, distances from the epicentre, building typologies, materials and technologies, and conservation status. A geographic information system (GIS) was adopted to collect, catalogue, and analyse this large amount of data. The application of the damage table to both the 2012 Emilia earthquake and 1980 Irpinia earthquake allowed some improvement to the damage table definition and a first comparison of different behaviours in the two regions.

In the present paper, the number of seismic events considered was extended further, also including the 2016 Central Italy earthquakes. The improved damage table was applied to the following seismic events: Friuli 1976, Irpinia 1980 (Campania and Basilicata regions), Umbria-Marche 1996, Emilia 2008, Abruzzo 2009, Emilia 2012, and Central Italy 2016 (Umbria, Marche, Lazio, and Abruzzo regions). For completeness, a map of the examined regions is shown in Fig. 1, together with the epicentres of the main shocks. The 2008 Emilia earthquake was included despite being secondary, because it damaged some significant fortresses, allowing a wider statistical analysis of the data collected and a more significant comparison between the various regions and building features.

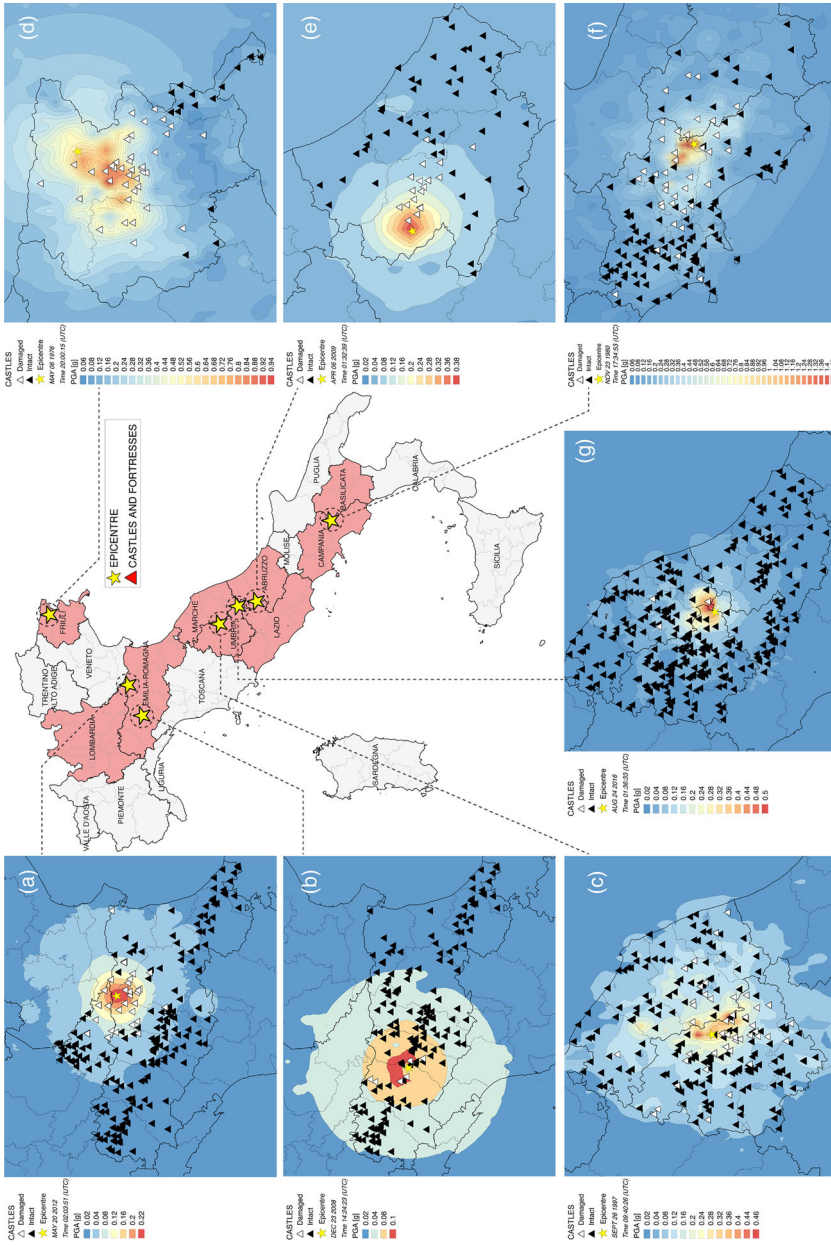


Fig. 1 Castles and fortresses and main shake maps of the most severe earthquakes examined: **a** Emilia 2008, **b** Emilia 2008, **c** Umbria-Marche, **d** Friuli, **e** Abruzzo, **f** Friuli, **g** Central Italy (Umbria, Marche, Lazio, and Abruzzo regions)

The results permitted the inspection of the relationships between the seismic input data, in terms of peak ground acceleration (pga), and the seismic effects in terms of damage to each castle, with its individual characteristics.

2 Italian castles hit by recent earthquakes

2.1 Typologies of Italian castles

In Italy, as in most parts of Europe, the encastellation phenomenon spread during the Middle Ages, mainly as a consequence of the onset of the feudal system. In the Early Middle Ages, the first rudimentary form of defence construction was the so-called motte-and-bailey castle, composed of a small artificial hill with a surrounding palisade in timber and a tower (usually also in timber) inside. In Italy there are traces of this type of fortification mainly in Sicily, dating from the Norman period, but this kind of fortification was also employed in other areas, e.g. on the Po plain in Northern Italy (Settia 1997). Starting from the mountain areas, given the difficulty of digging a ditch or planting a palisade, the wooden elements were soon replaced with stone, with the spread, from the eleventh century, of a large number of stone masonry donjons, sometimes with an external wall. In these donjons the first characteristic features of fortified architectures were introduced and developed: the crenelated parapet with merlons (Fig. 2a), the wooden hoarding (which was



Fig. 2 Typical features of Italian fortified architectures from different historical periods: **a** crenelated parapet with merlons; **b** machicolations; **c** an aerial view of a typical fifteenth century castle; **d** a fortified citadel; **e** a fortress with bastions, introduced to withstand attacks with firearms, from the sixteenth century; **f** a medieval castle transformed into residential palace

later replaced by permanent masonry machicolation, Fig. 2b), the arrow-slits (Lepage 2002). Starting from the thirteenth century, the architecture of castles became more complex and sophisticated, with the spread of external curtain walls reinforced by wall-towers and corner-towers (Fig. 2c). The interaction between these elements is one of the vulnerabilities inspected and it is also dependent on whether the towers and the defensive walls were built together or at different times. In the same period, many Italian villages and cities built or rebuilt fortified walls, with features similar to the curtain walls and towers of the castles (Lepage, 2002) (Fig. 2d). The last significant evolution of fortified building techniques occurred in the sixteenth century, when the spread of firearms forced a change from a passive form of defence to an active one. The main changes regarded the curtain walls—built with a lower height-to-thickness ratio in order to increase stability against horizontal actions—and bastions (Fig. 2e), added for more complete protection and for the installation of defensive artillery (Duffy 1979). In more recent times, most castles were adapted to residences, with an increase in the number of openings, insertion of roofs over the battlements, sometimes with the transformation of crenels into windows (Fig. 2f), and changes in the inner space organisation.

Of course, not all castles in Italy have the same features, not only because of the different historical settings but also for the different importance each of them has and, mostly, for the different natural settings in which they stand, which clearly influenced their development. Nevertheless, some similarities can be found among fortified architectures within the same areas, as they share a common general history and, most of all, the same territorial morphology and materials availability. In the regions taken into consideration in the present work, it is possible to identify the following main characteristics:

- Friuli is characterised by a hilly landscape, with castles made of stone, which is usually squared, with a main tower, sometimes surrounded by minor buildings and/or a curtain wall; battlements are frequent, although many castles have in time turned into palaces, losing part of their specific features.
- Irpinia is a mountain area between the regions of Basilicata and Campania, thus most castles are on a hilltop or hill slope and made of stone masonry. The building technique is different from the one adopted in Friuli: the blocks are mostly rounded, small to medium sized, arranged in three-leaf walls. The area is characterised by a large number of small castles, sometimes just a donjon and a wall, quite frequently in a state of abandonment or complete ruin even before the earthquake, and the typical fortification elements were generally already lost.
- The central regions of Umbria and Marche are also on the Apennine mountains, but here castles can be made of stone or brick masonry, sometimes mixed, depending on the location. The spatial configuration is usually more complex, with a main donjon, often with merlons and protruding elements, walls with corner towers, fortified gateways and other buildings added over time.
- The area of the Emilia Romagna region hit by the 2008 earthquake lies between low hills and the Po plain. The castles in this region are made of bricks or mixed masonry, with the use of round pebble stones from the nearby rivers.
- In Abruzzo, similarly to Irpinia, castles are mainly made of irregular unsquared stone masonry, and located on hill slopes. Frequently towers are rounded and with unique architectural elements, such as merlons and machicolations, even if sometimes only their traces remain. The state of conservation is variable, from archaeological remains to buildings still in use.

- The part of the Emilia-Romagna region hit by the 2012 earthquake is, instead, on the Po plain: castles are all made of brick masonry, with a minor use of river pebble stones. Most of these castles, even if already present in a primitive shape since the Middle Ages, were intensively enlarged and reshaped in the fifteenth century, with insertion of new curtain walls and towers, machicolation, battlements and even later, with the addition of roofs on all these previously uncovered structures.
- The wide area hit by the most recent earthquake in Central Italy is located between the Umbria, Marche and Abruzzo regions, where castles present features similar to the ones previously described for these areas.

2.2 GIS based data collection of castles and fortresses

The first step of the work consisted in georeferencing the castles and fortresses affected by seismic events. The geodatabase created in Coïsson et al. (2016b), using the open source software QGIS version 2.12 (QGIS Development Team 2015), was here adopted and extended. The localisation of the castles, together with the boundaries of the regions examined, are represented in Fig. 1. Over 750 castles and fortresses were identified and localised in the considered areas through consultation of general reference books (e.g. Ebhardt 1917), websites (MiBAC 2016; I Luoghi del Silenzio 2016; Icastelli 2016; Mondi Medievali 2016) and of the following bibliographies on the regions struck by the seven earthquakes: Friuli 1976 (Biasatti 2003; Fantoni 2006; Gazzola 1976), Irpinia 1980 (MiBAC 1994; Santoro 1978), Umbria-Marche 1996 (MiBAC 2007), Emilia 2008 (Perogalli 1972), Abruzzo 2009 (Latini 2000; Chiarizia et al. 2002), Emilia 2012 (Perogalli 1972; MiBAC 2015; Monti 2006), Central Italy 2016 (Amoni 1999; Mauro 1992). Only the more significant castles and fortresses were included, disregarding single isolated towers and castles transformed into palaces, with consequent loss of their particular features. Most of the castles in ruins were also discarded, since it is difficult to distinguish the pre-existing damage from the damage caused by the earthquake; moreover, the damage could be influenced by the lack of building portions and thus be less representative of the typical behaviour. Successively, the fortresses were located and catalogued by means of the Google Earth satellite views and their geographical coordinates (latitude, longitude, and altitude).

The data regarding the 7 main earthquakes and the 21 aftershocks were considered, reporting magnitude (M_I), hypocentre depth, and date and time of each earthquake. All these data are summarised in Table 1.

2.3 Shake maps and castles in the affected areas

Shake maps in terms of peak ground acceleration (pga) of the 7 main earthquakes are reported in Fig. 1, representing with a colour map the pga values distribution. Data for the shake maps were inserted in the GIS and castle locations were superimposed. The yellow star represents the epicentre while the triangles symbolise the fortresses.

A shake map is a representation of the ground shaking produced by an earthquake on each point of the surface. The ground shaking levels at sites throughout the region depend on the distance from the earthquake, on the rock and soil conditions at the sites, and on variations in the propagation of seismic waves from the earthquake due to complexities in the structure of the Earth's crust. For the present study, the shake map data were taken from

Table 1 Seismic events considered

ID	Region	M_L	Date	Time (UTC)	Depth (km)
1	Friuli	6.5	05/06/1976	20:00:15	20.9
2		5.9	05/07/1976	09:41:19	33
3		5.2	05/11/1976	22:44:01	7.2
4		5.2	06/17/1976	14:28:51	25
5		5.5	09/11/1976	16:31:12	4.2
6		5.4	09/11/1976	16:35:03	12.3
7		6.0	09/15/1976	03:15:20	0.9
8		5.9	09/15/1976	09:21:19	9.7
9		5.7	11/23/1976	07:30:27	33
10	Irpinia	6.9	11/23/1980	17:34:53	6.9
11		4.9	11/30/1980	07:42:01	15.1
12	Umbria-Marche	5.7	09/26/1997	00:33:14	8
13		6.0	09/26/1997	09:40:26	6
14		5.3	10/03/1997	08:55:23	10.3
15		5.5	10/06/1997	23:24:55	13.8
16		5.9	10/14/1997	15:23:12	14.1
17	Emilia 2008	5.3	12/23/2008	14:24:23	28.9
18		5.0	12/23/2008	20:58:26	13.4
19	Abruzzo	6.3	04/06/2009	01:32:39	8.8
20		5.5	04/07/2009	17:47:37	13.4
21	Emilia 2012	6.0	05/20/2012	02:03:51	8.3
22		5.8	05/29/2012	07:00:03	9.0
23		5.5	05/29/2012	10:55:57	9.9
24	Central Italy	6.0	08/24/2016	01:36:32	8.1
25		5.3	08/24/2016	02:33:29	5.0
26		5.4	10/26/2016	17:10:36	8.7
27		5.9	10/26/2016	19:18:05	7.5
28		6.5	10/30/2016	06:40:17	9.2

the USGS archives (USGS 2016) for all the cases, except the Central Italy earthquake, whose shake maps were taken from the INGV archive (Shakemap Working Group 2016).

The GIS also allowed the analysis of the shake maps and the automatic extraction of the maximum values of pga suffered by each castle for the single seismic event. In some cases, the same castle was hit by more than one seismic event, among the ones considered. In this case, considering that the castles were normally subjected to restoration works between the different events, the effects on the castles were analysed separately for each earthquake.

The results are unavoidably affected by the approximations of the shake maps, which depend on the number and type of the seismic stations (Cultrera et al. 2014), therefore the oldest data and the first shocks have a higher degree of inaccuracy.

2.4 Relation between damage and pga

Unfortunately, to our knowledge, no official lists of the damaged castles and fortresses are public. For this reason, in order to link the pga to the damage, we searched for lists of

buildings that were restored with public funding after the earthquakes. These lists have been cross-linked with the scarce number of available publications, but they most probably remain incomplete. Some damaged fortresses may therefore have been overlooked and in some cases the seismic damage might have been confused with pre-existing damage phenomena. Furthermore, the adopted approach leads to a binary definition of damage (no damage vs. damage) since, especially for the oldest cases, the data are insufficient to differentiate between damage levels, as usually done, for instance, when dealing with vulnerability curves (e.g. no damage, slight, moderate, heavy, very heavy, and collapse). However, in the cases in which damage was identified by funding of interventions, it is reasonable to assume that the damage level was at least moderate.

Following this procedure, 192 damaged fortresses were detected. In particular, 40 in Friuli, 38 in Irpinia, 45 in Umbria-Marche, 6 in Emilia for the 2008 earthquake, 18 in Abruzzo, 30 in Emilia for the 2012 earthquake, and 15 in Central Italy for the 2016 earthquake. The damaged castles identified are represented with white triangles in Fig. 1.

Figure 3 shows a detail of the Abruzzo 2009 earthquake shake map, in which the dots represent reporting stations and the triangles refer to the castles and fortresses, together with their identification number, which are analysed in Table 7.

The relative frequency of damaged castles subjected to a given value of the maximum pga is represented in Fig. 4. Bins of amplitude 0.1 g were adopted. Labels provide the ratio between the number of damaged and undamaged fortresses for a certain interval of pga . Some fortresses were hit by two or more earthquakes (e.g. Umbria-Marche 1997 and Central Italy 2016), therefore the number of cases considered (1241) is larger than the number of castles. Since damage was not reported for a pga less than 0.04 g, this value was

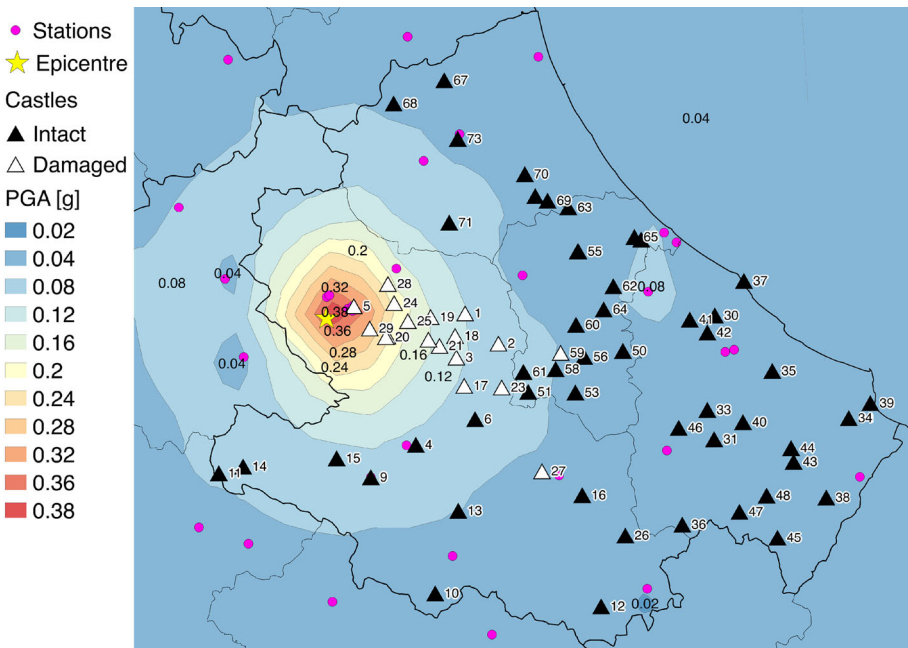
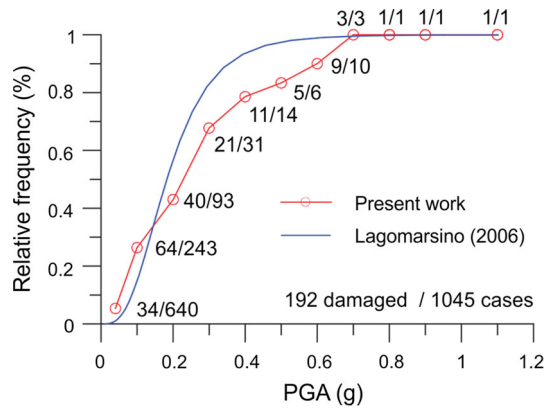


Fig. 3 Detail of the shake map of Abruzzo 2009 Earthquake with the seismic reporting stations, the damaged fortresses (in white) and the undamaged ones (in black). Numbers permit the localisation of the castles in Table 7

Fig. 4 Relative frequency of damaged fortresses as a function of pga compared with the vulnerability function for castles proposed by Lagomarsino (2006)



chosen as a threshold and fortresses subjected to a lower pga were not considered in the analysis for counting the undamaged fortresses, reducing the total number of cases considered from 1241 to 1045. In Fig. 4 the curve is compared to the vulnerability curve for castles proposed in Lagomarsino (2006), choosing a moderate damage level (D2). Since the vulnerability curve was defined as a function of the macroseismic intensity I, it was necessary to transform I to pga by means of the equation proposed in Guagenti and Petrini (1989) specifically for the Italian earthquakes. Results show a good agreement between the two curves, notwithstanding the considerable number of uncertainties, such as: (a) the lack of information about the real damage level; (b) the transformation from I to pga; (c) the different typology of castles (e.g. squat fortresses with bastions display a better seismic behaviour than medieval castles with tall towers).

3 Table of seismic damage mechanisms of castles

The previous analyses allow the identification of the castles that were damaged in relation to the pga suffered, but for prevention purposes it is necessary to apply an empirical approach that goes deeper into detail by also inspecting the type of damage.

This empirical approach bases the comprehension of the seismic behaviour of buildings on the observation of the real damage, given the existence of recurring damage mechanisms for the different building typologies. The 1976 Friuli earthquake was probably the first occurrence in which this approach was applied in the field, with the surveying and cataloguing of the damage mechanisms of churches undertaken by Doglioni et al. (1994).

The subsequent developments led to the introduction of the damage mechanism table for churches in the latest Italian technical code for the protection of the cultural heritage from seismic risk (Guidelines 2007). More tables were then developed for other types of buildings, like palaces and villas (PCM-DPC-MiBAC 2006). The present work aims to pursue this strand of research, focusing on the fortified constructions. Indeed, as shown in Coïsson and Ottoni (2012), defining a priority list by damage mechanisms rather than by whole buildings allows the interventions to be focused on the most vulnerable elements, thus retrofitting a larger number of buildings within a given budget. In order to apply this type of approach, the table of damage mechanisms proposed in Coïsson et al. (2016b) was here adopted, with some changes both in the graphic output and in the definition of some specific mechanisms.

The table is shown in Fig. 5. The damage mechanisms are defined as:

- Masonry
 - Crumbling of masonry (1a);
 - Delamination of the cladding (1b), especially in three-leaf masonry;
- Walls
 - Cracks caused by the different dynamic behaviour between tower and wall (2a);
 - In plane shear cracks (2b);
 - Out of plane overturning (2c) of the entire wall or of its portions;
- Main body of the tower
 - Damage at the base of the tower, due to combined compressive and bending cracks or to soft storey (3a);
 - Shear cracks in the main body of the tower (3b), with possible torsional effects if the tower is asymmetrically connected to the walls;
 - Shear cracks in the upper part of the tower (3c), standing out from the fortress or walls;
- Merlons
 - In plane flexural or shear cracks (4a);
 - Overturning (4b);
- Protruding elements
 - Damage to the battlements (5a), possibly exacerbated by the vertical component of the acceleration;
 - Damage to protruding turrets (5b);
 - Damage to sentry-boxes, pinnacles and other protruding elements (5c);
- Roof
 - Damage in the tower corners or at the top of the fortress wall, in case due to the roof thrust (6a);
 - Shear damage between the roof and the walls (6b), particularly when stiffening interventions have been carried out in the past;
- Floors
 - Damage to floors (7a) of different typologies, usually caused by slippage of the beam from the supports or collapse of deteriorated beams;
 - Damage to the vaults (7b) of different types, usually caused by movements of the supporting elements;
- Foundations
 - Fall of the foundation rock or settlements of the soil (8a);
 - Overturning of walls caused by the dynamic thrust of the earth (8b).

With respect to the damage table published in Coisson et al. (2016b), it was observed that damage 6a occurs even when the roof is absent. Furthermore, settlement due to liquefaction (which, to the authors' knowledge, has never been recorded in castles) was

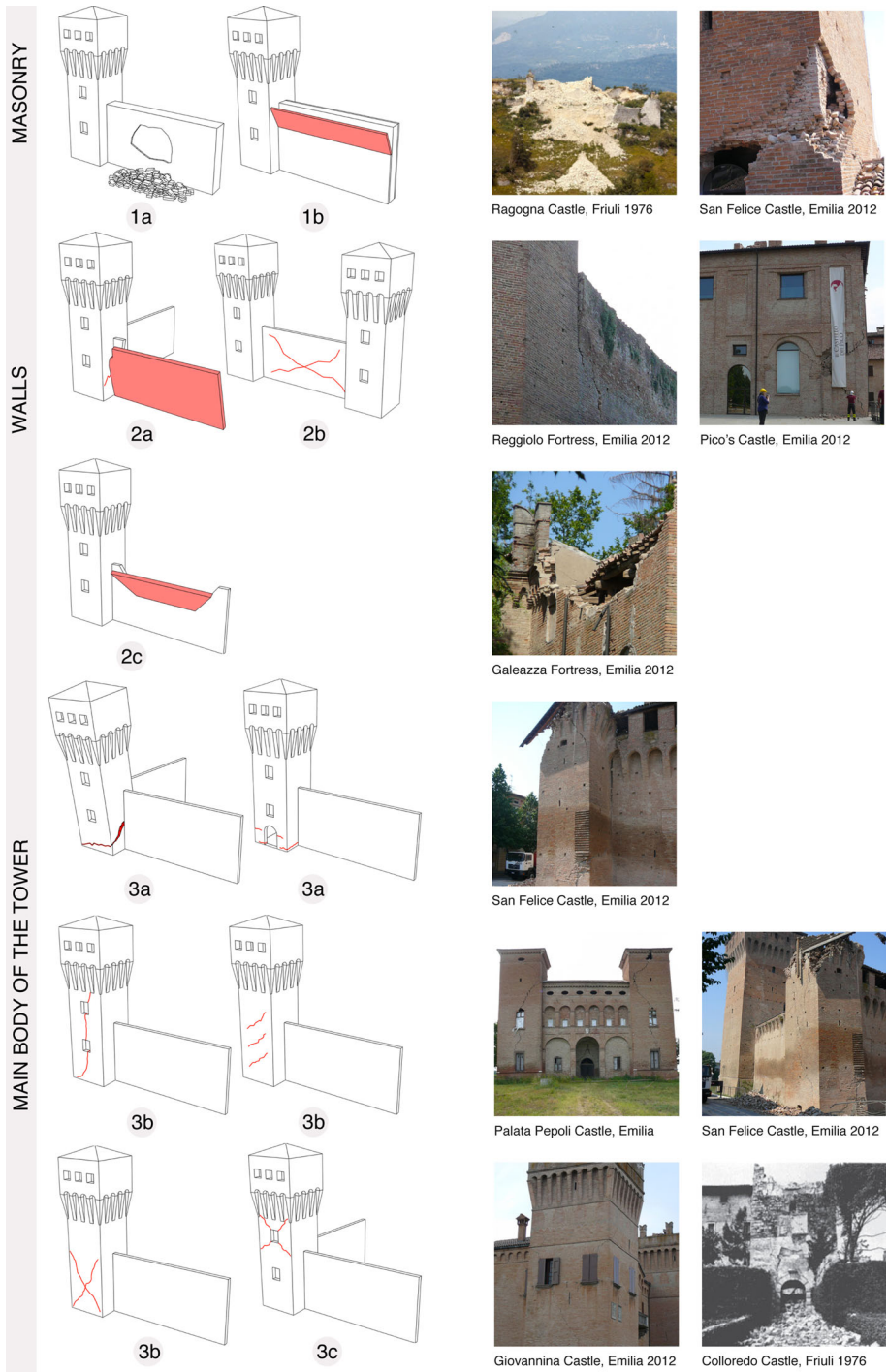


Fig. 5 Table of damage mechanisms and explicative photos

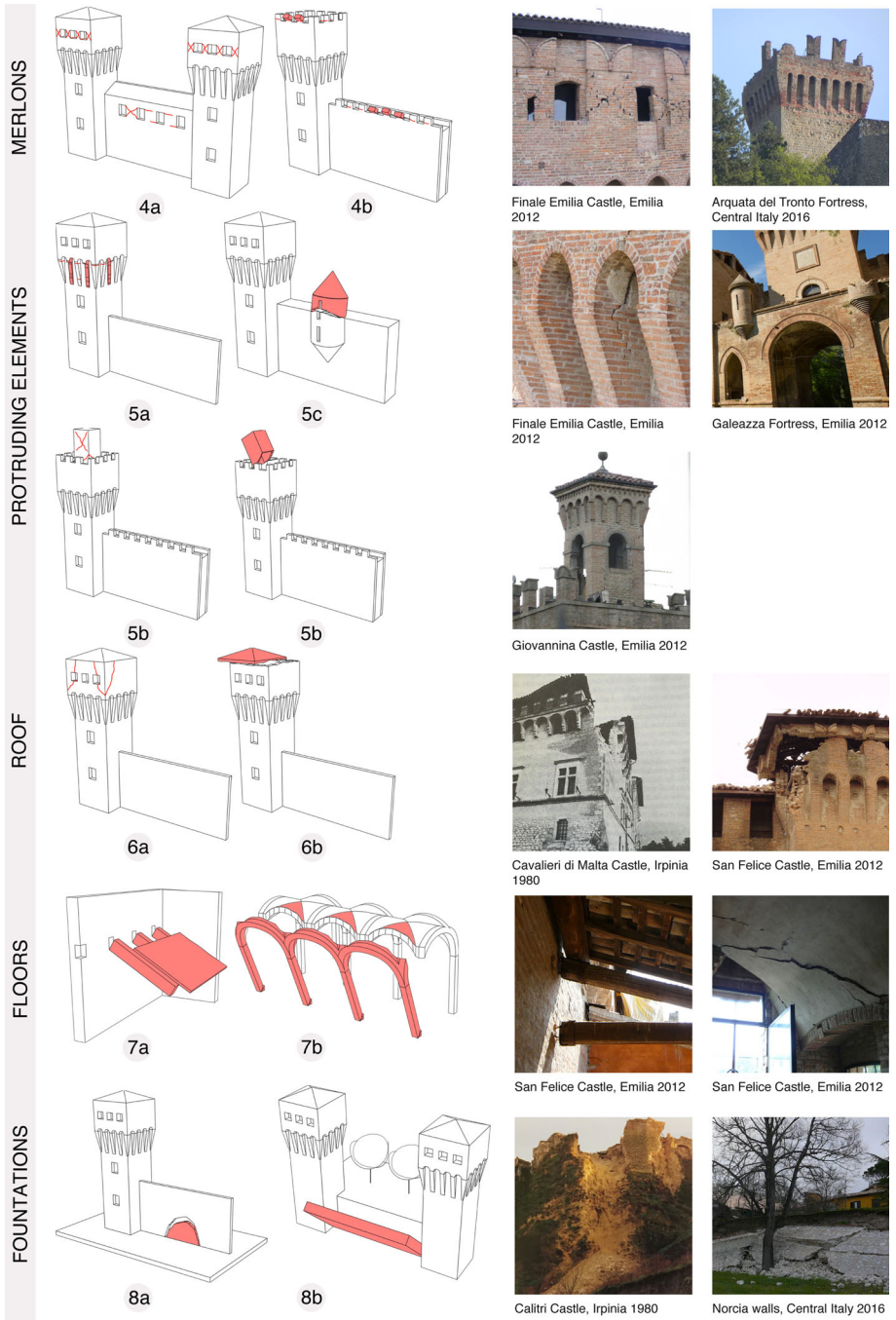


Fig. 5 continued

replaced with the overturning of the defensive walls that also act as earth retaining walls, as occurred in the Norcia city walls in October 2016.

4 Analysis of the damage mechanisms distribution

4.1 Identification and cataloguing of damage mechanisms

Once the table of damage mechanisms was defined, it was possible to analyse the damage to each castle and to classify it with respect to the table. These analyses were used to make some considerations about the distribution of the different mechanisms on the territorial scale. This part of the study turned out to be extremely difficult, especially for non-recent events, because of the lack of specific reliable documentation. Drawings and reports of the restoration projects after the earthquakes were not available since they are stored in the archives of the municipalities or Ministry (MIBACT) and are not public. Books, papers and photos were the main sources of information. Unfortunately, often the photos of the castles soon after the earthquake are absent and the written descriptions are not exhaustive, as far as the type of damage is concerned, as they generically cite the occurrence of collapses. Moreover, in the case of extensive damage, it is impossible to distinguish the single mechanism, since the result is an undefined pile of rubble. This is particularly true for mechanism 1a. For these reasons, in this work, only a subset of all the damaged cases were analysed. The references that were found are reported in Table 2, together with the number of fortresses studied with respect to the total number of damaged ones. For Central Italy, because of the repeated aftershocks that are still ongoing, the work is in progress and the results are not conclusive.

The results are shown in Tables 3, 4, 5, 6, 7, 8 and 9, reported in the “Appendix”. The tables contain the province in which the castle is located, its identification number (ID) and its complete name. The identification number allows location of the castles in the maps (e.g. Fig. 3). The prevailing type of masonry (solid clay bricks, stone units or rubble masonry, tuff units, mixed) and the geometry of the towers (none, circular, rectangular,

Table 2 Number of analysed fortresses with respect to the hit and total ones

Events	References	Total	PGA > 0.04 g	Hit	Analysed
Friuli 1976	Biasatti (2003), Fantoni (2006), Gazzola (1976), Badan (2013), Moretti (2008)	57	57	40	17
Irpinia 1980	MiBAC (1994), Santoro (1978)	154	154	38	17
Umbria-Marche 1997	MiBAC (2007), Chiarizia et al. (2002), Regione Umbria (2015), MIBAC (MiBAC 1998)	225	225	45	5
Emilia 2008	Direct survey by the Authors	177	126	6	4
Abruzzo 2009	Binda et al. (2011), Cialone and Copersino (2013)	73	73	18	3
Emilia 2012	Cattari et al. (2014), Cattari et al. (2012), Andreini et al. (2014), Saisi and Terenzoni (2014)	224	125	30	17
Central Italy 2016	Direct survey by the Authors, Lenticchia and Coisson (2017)	331	285	15	10
Total		1241	1045	192	73

irregular) are also reported, together with the presence of merlons and protruding elements. The state at the time of the earthquake (ruin, used, abandoned) was considered. The value of $p_{ga\ max}$ was obtained by querying the GIS for the maximum p_{ga} recorded in the specific site during the main shock and the considered aftershocks (Table 1). Soil morphology (plain, soft slope, strong slope, and crest) is also reported. Finally, the table is populated by dots, which represent the type of damage. To fill the table, the damage was inferred from photos, technical drawings, or through on-site surveys.

Table 3 shows that the Friuli castles are mainly built with stone masonry and often characterised by the presence of merlons (Fig. 6a, b): these vulnerable elements were damaged in nearly all the cases studied, mainly due to overturning (mechanism 4b). Furthermore, it is possible to notice that the buildings which suffered complete collapse due to masonry crumbling (mechanism 1a) were abandoned or in a state of ruin: once again, we have confirmation of the positive effects of maintenance on the preservation of monuments, even from the seismic view point.

The castles of Irpinia (Table 4) were built in stone, rubble masonry and tuff masonry (Fig. 6c, d). It is worth noting that, at the time of the earthquake, these castles were generally unused or in ruins. The poor condition of the masonry, together with high accelerations, explains the severe damage they suffered. The descriptions of damage reported in MiBAC (1994) rarely comment on merlons, battlements, and protruding elements. In addition, the frequent damage to the floors and roofs are described in general terms and it is unclear whether it is caused by rotation of the walls or their deterioration. In the case of ruins, roofs could even have been absent before the earthquake. Some foundation problems (mechanism 8a), usually due to rockfalls, are present, because most of the castles were built on hilltops, as can be seen in Table 4.



Fig. 6 Typical castles hit by the earthquakes in Friuli (a, b), Irpinia (c, d) and Emilia 2008 (e, f)

The fortresses analysed for the Umbria-Marche 1997 earthquake (Table 5) were hit by relatively low p_{ga} , showing limited damage. Nevertheless, the data collected on this seismic event are still limited and further research is needed.

The castles in the western part of Emilia, hit by the 2008 earthquake (Table 6), are characterised by massive walls in bricks and cobblestones. Despite their apparent strength, even if subjected to low p_{ga} they all suffered shear damage (mechanism 3b) in the tower walls and consequent damage to the vaults (mechanism 7b) (Fig. 6e, f).

In Abruzzo many castles had been transformed into palaces, with the incorporation of curtain walls and merlons: the damages shown therefore are similar to the typical damage to palaces (D’Ayala and Speranza 2003) with the frequent overturning of walls and damage to the roof structures (Fig. 7a). The small number of cases analysed and the limited information on the crack pattern indicate the need for further research on this specific event.

Table 8 shows that for the Emilia 2012 case all the castles were built in solid clay brick and at the time of the earthquake they were in use, usually as museums, council offices, or private dwellings. Towers are generally rectangular. Observing the damage mechanisms, we can see that the masonry usually had no problems of crumbling. Instead, damage was localised on towers, merlons and protruding elements (Fig. 7b). Fortunately, although the area presented several cases of soil liquefaction, the castles were spared from this phenomenon.

The damage recorded in the latest Italian seismic events, in Central Italy, are reported in Table 9. The inspections have not been completed yet, but it can be noticed that the masonries have variable characteristics, depending on the area. In the mountains, castles



(a) Forte Spagnolo, Abruzzo 2009



(b) San Felice sul Panaro Castle, Emilia 2012



(c) Arquata del Tronto Castle, Central Italy 2016



(d) Norcia walls, Central Italy 2016



(e) Castelraimondo Castle, Central Italy



(f) Capodacqua Castle, Central Italy

Fig. 7 Typical castles hit by the earthquakes in Abruzzo (a), Emilia 2012 (b), and Central Italy (c–f)

are built in stone masonry, while in the hills solid clay masonry prevails. The building technique has a correlation with the occurrence of crumbling and delamination of the masonry. Merlons are sometimes present and, in most cases, were damaged. Frequent shear damage on the towers was also reported. This is particularly true for fortified buildings that present a tower built on a massive prismatic base (Fig. 7e). Battlements built with stone slabs did not usually present signs of damage (Fig. 7f). Aftershocks are still occurring, therefore the results reported in Table 9 are provisional.

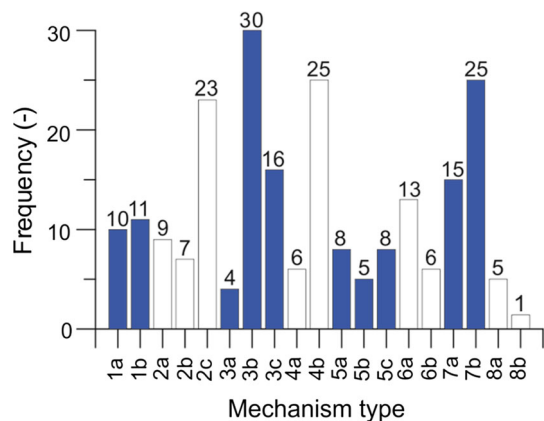
4.2 Statistical analyses on the frequencies of the damage mechanisms

Considering the eight main damage typologies, it is possible to record the number of recurrences reported in Tables 3, 4, 5, 6, 7, 8 and 9. The bar chart presented in Fig. 8 shows the number of cases for each damage mechanism. It is evident that the most common damage mechanisms affect towers, floors and merlons. In the case of floors, the data are inaccurate because the interiors of the castles hit by the recent earthquakes are still off limits and, consequently, this kind of information is lacking in many cases. Furthermore, most of the photos regard only the exteriors, which is also the case for past events.

For these reasons, only the damage to the trunk of the towers (mechanism 3b) and the overturning of the merlons (mechanism 4b) were analysed in detail in the bar charts of Fig. 9a, b, respectively. Here, the level of p_{ga} was plotted in descending order for the cases examined in Tables 3, 4, 5, 6, 7, 8 and 9. For mechanism 3b it is possible to identify in Fig. 9a a minimum threshold of $p_{ga} \approx 0.1$ g corresponding to the onset of damage. The damage level was not recorded but it is reasonable to assume that it was at least moderate, since it was identified by recognising cracks visible in photos that were not usually taken in close-up. Mechanism 3b has also been analysed for some case studies taken from the literature, where seismic assessment was performed by means of finite elements analysis (Castellazzi et al. 2017; Valente and Milani 2016). The values of p_{ga} computed by these authors (for the seismic assessment performed according to the Italian standards) are reported, for comparison, in Fig. 9a. It is possible to notice a substantial agreement between the quantitative values defined via structural analyses and the threshold previously defined qualitatively.

Similarly, mechanism 4b was examined in Fig. 9b. In this case, too, it is possible to identify a minimum threshold of $p_{ga} \approx 0.10$ – 0.15 g related to the damage, but unfortunately, the data do not distinguish between the activation of the mechanism and the

Fig. 8 Frequency of the different damage mechanisms



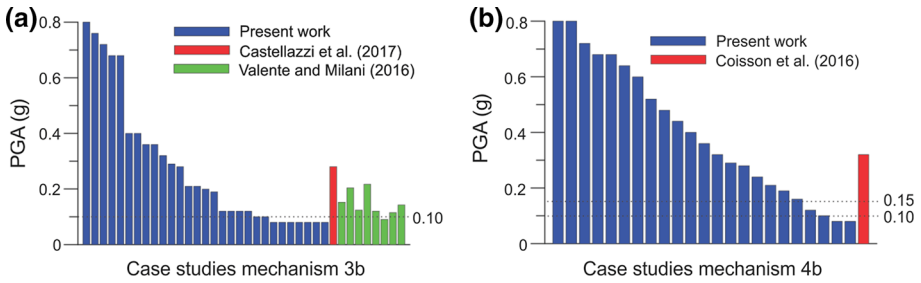


Fig. 9 Values of pga that hit the case studies (obtained from the shake-maps) compared with the values obtained from mechanical analyses: **a** damage to the tower (mechanism 3b); **b** overturning of merlons (mechanism 4b)

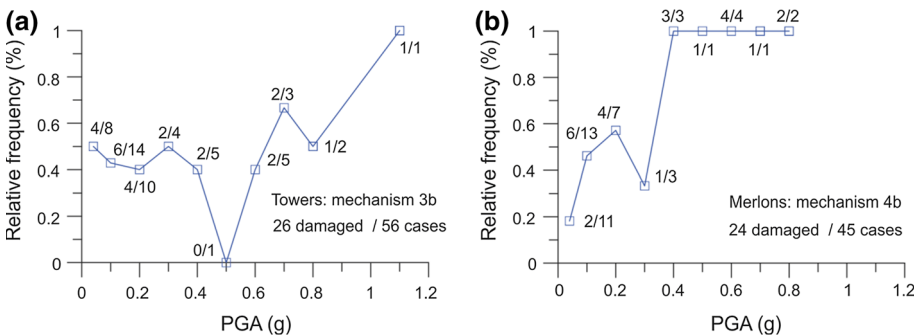


Fig. 10 Relative frequencies of damage as a function of pga: **a** shear cracks in the main body of the tower (mechanism 3b); **b** overturning of the merlons (mechanism 4b)

complete overturning of the merlons. To the authors’ knowledge only one study in the literature has dealt with the overturning of merlons covered by a roof (Coisson et al., 2016a). The numerical result of this seismic assessment, which is superimposed in Fig. 9b, does not contradict the qualitative results, but it is insufficient for general conclusions. In the future, an extensive study on the overturning of merlons, considering not only their geometry but also the possible presence of an overlying roof and the filtering effect of different underlying structures, will certainly be desirable.

In Fig. 10 the number of fortresses hit by a specific acceleration, for each level of acceleration, was indicated and the relative frequency of the damage mechanism examined was calculated. As expected, the trend increases quite regularly, although there are some anomalies due to the limited number of cases examined. The presence of damage to towers for very low values of pga can also be explained by the presence of pre-existing cracks.

Introducing a classification of the damage levels for each damage mechanism would make it possible to proceed from the graphs of Fig. 10 to specific vulnerability curves (Simões et al. 2015; Bernardini and Lagomarsino 2008; Jaiswal et al. 2011; D’Ayala 2013; Roca 2012). As the number of cases examined for each damage mechanism grows, the results will become increasingly reliable and meaningful. The results will then be inserted in the GIS and this will allow cross-examination of the damage mechanisms in relation to the seismic action, location, building techniques, materials, etc.

5 Conclusions

The work confirms the presence of recurring seismic vulnerabilities in the case of fortified buildings, highlighting the differences in terms of damage mechanisms in relation to the features of the building and introducing statistical evaluations about their relative frequencies.

In particular, the analyses carried out at a territorial scale allow the following conclusions to be drawn:

- The use of a GIS to catalogue and analyse the damage to a large number of fortified buildings, together with the adoption of shake maps, is an effective tool for the application of an empirical approach to the seismic behaviour of cultural heritage.
- The statistical analysis of the recorded damage frequency as a function of the pga showed good agreement with a vulnerability curve proposed in the literature.
- The table of damage mechanisms adopted for fortified architecture, previously proposed only for the Emilia region, was verified on over 70 damaged castles, characterised by different materials and building features, widening its validity, with minor reviews.
- The statistical analyses on the damage typologies in relation to the features of the building have highlight that the most frequent damage regards the trunk of the tower and the typical summit merlons, which are subjected to overturning even for very low values of pga. These results are confirmed by comparisons with the few specific numerical studies published in the literature.
- Some considerations can also be made on the relation between the specificities of each area considered, in terms of the features of the building and the damage suffered. In particular, the type of masonry, which is strictly connected to the local resources available in the area, strongly influenced the damage mechanisms, e.g. the crumbling of masonry was clearly concentrated in specific geographic areas like Irpinia and Central Italy where the stone arrangement in masonry was particularly weak.
- The paper includes the first reports from the recent Central Italy earthquake, specifically for the damage to fortified architectures.

Future developments of this research will benefit from an increase in the number of castles analysed, including other areas, and from inspecting more documents on the damage suffered in past seismic events. Nevertheless, the results obtained in this study are already significant, as they allow the identification of which elements may be subjected to a higher risk, in relation to the features of the building and to the local seismicity. This can provide useful indications for specific preventive measures aimed at the conservation of these important elements of our landscape and cultural identity.

Acknowledgements Wide-ranging research like this requires the contribution of many people in order to make the documentation about buildings all over Italy dating back to decades ago available. This work wouldn't have been possible without the data provided by Rosa Carafa, Livio Fantoni, Vittorio Foramitti, Alberto Moretti, Simona Patrizi, and Alberto Pugliese. Their contribution is thus gratefully acknowledged by the Authors. Furthermore, the Authors would like to thank Sergio Lagomarsino for his precious advice and for providing data on vulnerability curves.

Appendix

See Tables 3, 4, 5, 6, 7, 8 and 9.

Table 3 Friuli 1976 earthquake: analysis of damage mechanisms in some fortresses

PROVINCE	ID	CASTLE/FORTRESS	Building Technique B: brick, S: stone, T: tuff MX: mixed	Presence of towers N: no, C: circular, R: rectangular	Presence of merlons Y: yes, N: no	Presence of protruding elements Y: yes, N: no	Current state R: Ruin, U: Used, A: Abandoned	PGA Max (\bar{g})	Soil morphology T1: plain, T2: soft slope, T3: strong slope, T4: crest	1 MASONRY			2 CURTAIN WALLS			3 TOWERS			4 MERLONS			5 PROTRUDING ELEMENTS			6 ROOFS			7 FLOORS			8 FOUNDATIONS									
										1a	1b	2a	2b	2c	3a	3b	3c	4a	4b	5a	5b	5c	6a	6b	7a	7b	8a	8b												
UD	1	Castello di Colloredo, Colloredo di Montalbano	S	R	Y	N	U	0.60	T2																															
	2	Castello di Cassacco	S	R	Y	Y	U	0.40	T1																															
	5	Castello di Villalta - Castello di Fagnana	M	R	Y	N	U	0.28	T3																															
	7	Castello di Prampero, Magnano in Riviera	S	R	Y	Y	A	0.68	T2																															
	8	Castello Sarvognan di Artegna	S	R	Y	N	U	0.80	T3																															
	10	Castello di Susans, Majano	S	R	N	N	U	0.68	T1																															
	12	Castello di Zogliacco, Treppo Grande	S	R	Y	N	U	0.72	T1																															
	18	Castello d'Arcano, Rive d'Arcano	S	R	Y	N	U	0.48	T1																															
	22	Castello di Gamona	S	R	Y	N	U	0.80	T2																															
	23	Castello di Tricesimo	S	C	Y	N	U	0.32	T2																															
	26	Castello di Toppo, Travesto	S	R	Y	N	R	0.52	T3																															
	31	Castello di Ragogna	S	R	Y	N	A	0.64	T4																															
	35	Castello di Venzone	S	R	Y	N	A	0.68	T1																															
	38	Castello di Sant'Andrea di Melis, Colloredo di Monte Albano	S	R	N	N	R	0.76	T1																															
PN	45	Castello di Spilimbergo	B	R	Y	N	U	0.32	T1																															
	46	Castello di Zoppola	B	R	Y	Y	U	0.16	T1																															
	49	Castello di Maniago	S	R	N	N	R	0.28	T3																															

Table 4 Irpinia 1980 earthquake: analysis of damage mechanisms in some fortresses

PROVINCE	ID	CASTLE/FORTRESS	Building Technique B: brick, MX: stone, T: masonry	Presence of towers N: no, R: rectangular	Presence of merlons Y: yes, N: no	Presence of protruding elements Y: yes, N: no	Current state R: ruin, U: used, A: abandoned	PGA Max (\bar{g})	Soil morphology T1: plain, T2: soft slope, T3: strong slope, T4: crest	1 MASONRY			2 CURTAIN WALLS			3 TOWERS			4 MERLONS			5 PROTRUDING ELEMENTS			6 ROOFS			7 FLOORS			8 FOUNDATIONS								
										1a	1b	1c	2a	2b	2c	3a	3b	3c	4a	4b	4c	5a	5b	5c	6a	6b	7a	7b	7c	8a	8b	8c							
PZ	1	Castello dei Conti Grasoale, Balvano	MX	R	N	N	R	0.40	T3	•																													
	14	Castello di Pirro del Balzo, Venosa	S	R	N	Y	U	0.16	T1	•																													
	17	Castello di Pescopagnano	S	R	N	N	R	0.72	T4																														
AV	20	Castello Normanno, Ariano Irpino	S	C	N	N	R	0.24	T1																														
	21	Castello Ducale, Bisaccia	S	R	N	N	R	0.24	T1																														
	24	Castello di Caliri	S	R	N	N	R	0.40	T3																														
	31	Castello di Monteforte, Monteforte Irpino	S	R	N	N	R	0.36	T4																														
	35	Castello di Sant'Angelo dei Lombardi	S	R	N	N	A	1.16	T3	•																													
	39	Castello di San Barbato, Manocalzati	S	C+R	N	N	U	0.32	T4	•																													
	40	Castello della Leonessa di Montemiletto	S	R	N	N	U	0.36	T2	•																													
	42	Castello del Monte, Montella	S	C	N	N	R	0.36	T4																														
	45	Castello di Avella	S	C+R	Y	N	R	0.20	T4																														
	46	Castello di San Donato, Chianche	S	C+R	N	N	U	0.28	T3																														
SA	86	Castello di Oliveto Citra	S	N	N	N	R	0.36	T2	•																													
NA	89	Castello Aragonese, Bain fraz. di Bacoli	T	C+R	Y	N	R	0.12	T4																														
	92	Castel Cicale, fraz. di Nola	T+R	R	N	N	R	0.16	T3	•																													
CE	140	Castello Fieramosca, Mignano Montelungo	T	C+R	Y	N	R	0.08	T3																														

Table 5 Umbria-Marche 1997 earthquake: analysis of damage mechanisms in some fortresses

PROVINCE	ID	CASTLE/FORTRESS	Building Technique B: brick, Stone, Tuff MX: mixed	Presence of towers N: no, Circular, R: rectangular	Presence of merlons Y: yes, N: no	Presence of protruding elements Y: yes, N: no	Current state R: Ruin, U: Used, A: Abandoned	PGA Max (\bar{g})	Soil morphology T1: plain, T2: soft slope, T3: strong slope, T4: crest	1 MASONRY		2 CURTAIN WALLS		3 TOWERS		4 MERLONS		5 PROTRUDING ELEMENTS		6 ROOFS		7 FLOORS		8 FOUNDATIONS	
										1a	1b	2a	2b	2c	3a	3b	3c	4a	4b	5a	5b	5c	6a	6b	7a
PU	42	Torre civica di Fermignano	MX	R	N	S		0.08	T1																
MC	51	Castello di Lanciano, Castelraimondo	B	R	Y	Y	U	0.16	T1																
	52	Castello di Spindoli, Fiuminata	S	R	N	N	R	0.28	T4																
AP	90	Fortezza di Acquaviva Picena	B	R	Y	Y	U	0.04	T3																
	93	Castello di Rocca Montevarmine	B	R	Y	Y	U	0.08	T3																

Table 6 Emilia 2008 earthquake: analysis of damage mechanisms in some fortresses

PROVINCE	ID	CASTLE/FORTRESS	Building Technique B: brick, Stone, T: mrf MX: mixed	Presence of towers N: no, Circular, R: rectangular	Presence of merlons Y: yes, N: no	Presence of protruding elements Y: yes, N: no	Current state R: Ruin, U: Used, A: Abandoned	PGA Max (\bar{g})	Soil morphology T1: plain, T2: soft slope, T3: strong slope, T4: crest	1 MASONRY		2 CURTAIN WALLS			3 TOWERS			4 MERLONS			5 PROTRUDING ELEMENTS			6 ROOFS		7 FLOORS		8 FOUNDATIONS		
										1a	1b	2a	2b	2c	3a	3b	3c	4a	4b	5a	5b	5c	6a	6b	7a	7b	8a	8b		
PR	89	Castello di Torrechiara	MX	R	Y	Y	U	0.08	T4	•																				
RE	95	Rocca dei Terzi, Sissa	B	R	Y	Y	U	0.08	T1																					
	100	Rocca di Sanvitale Baganza, Sala Baganza	MX	R	N	Y	U	0.10	T1	•																				
	143	Rocca di Bianello, Quattro Castella	MX	R	N	N	U	0.12	T3																					

Table 7 Abruzzo 2009 earthquake: analysis of damage mechanisms in some fortresses

PROVINCE	ID	CASTLE/FORTRESS	Building Technique B: brick, S:stone, T:truff MX: mixed	Presence of towers N: no, C:circular, R:rectangular	Presence of merlons Y: yes, N: no	Presence of protruding elements Y: yes, N: no	Current state R: Ruin, U:Used, A:Abandoned	PGA Max (\bar{g})	Soil morphology T1: plain, T2: soft slope, T3: strong slope, T4: crest	1 MASONRY	2 CURTAIN WALLS	3 TOWERS	4 MERLONS	5 PROTRUDING ELEMENTS	6 ROOFS	7 FLOORS	8 FOUNDATIONS
										1a	2a	3a	4a	5a	6a	7a	8a
										1b	2b	3b	4b	5b	6b	7b	8b
AQ	5	Forte Spagnolo, L'Aquila	S	N	N	N	U	0.36	T1								
	19	Castello di Barrisciano	S	R	N	N	R	0.12	T4	•	•	•				•	
	20	Castello di Ocre	S	R	N	N	R	0.24	T4	•	•						

Table 8 Emilia 2012 earthquake: analysis of damage mechanisms in some fortresses

PROVINCE	ID	CASTLE/FORTRESS	Building Technique B: brick, S:stone, T:truff MX: mixed	Presence of towers N: no, C:circular, R:rectangular	Presence of merlons Y: yes, N: no	Presence of protruding elements Y: yes, N: no	Current state R: Ruin, U:Used, A:Abandoned	PGA Max (\bar{g})	Soil morphology T1: plain, T2: soft slope, T3: strong slope, T4: crest	1 MASONRY		2 CURTAIN WALLS		3 TOWERS		4 MERLONS		5 PROTRUDING ELEMENTS		6 ROOFS		7 FLOORS		8 FOUNDATIONS	
										1a	1b	2a	2b	2c	3a	3b	3c	4a	4b	5a	5b	5c	6a	6b	7a
BO	2	Castello di Palata Pepoli, Crevalcore	B	R	N	Y	U	0.29	T1																
	4	Castello di Galeazza	B	R	Y	Y	U	0.24	T1																
	7	Castello della Giovannina, San Giovanni in Persiceto	B	R	Y	Y	U	0.21	T1																
	15	Castello dei Ronchi, Crevalcore	B	R	Y	Y	U	0.21	T1																
	24	Castello Lambertini, Poggio Renatico	B	R	Y	Y	U	0.09	T1																
	25	Rocca Possente, Stellata di Bondeno	B	N	Y	Y	U	0.17	T1																
MO	52	Castello dei Pio a Carpi	B	R+C	Y	Y	U	0.19	T1																
	53	Rocca di Finale Emilia	B	R	Y	Y	U	0.29	T1																
	57	Castello Pico della Mirandola, Mirandola	B	N	Y	Y	U	0.30	T1																
	65	Rocca di San Felice sul Panaro	B	R	Y	Y	U	0.32	T1																
	67	Rocca Campori a Soliera	B	R	N	Y	U	0.14	T1																
	71	Castello di San Pietro in Elda, San Prospero	B	R	N	N	A	0.20	T1																
RE	145	Rocca di Reggolo	B	R	Y	N	U	0.10	T1																
MN	18	Torre Matildea di Galliano, Governolo	B	R	Y	N	U	0.08	T1																
	36	Palazzo Ducale Gonzagheseo, Revere	B	R	Y	Y	U	0.12	T1																
	41	Torre civica, Serride	B	R	Y	Y	U	0.16	T1																
	47	Torre Prigione, Gonzaga	B	R	Y	N	U	0.12	T1																

Table 9 Central Italy 2016 earthquake: analysis of damage mechanisms in some fortresses

PROVINCE	ID	CASTLE/FORTRESS	Building Technique B: brick, S:stone, T:truff MX: mixed	Presence of towers N: no, C:circular, R:rectangular	Presence of merlons Y: yes, N: no	Presence of protruding elements Y: yes, N: no	Current state R: Ruin, U:Used, A:Abandoned	PGA Max (\bar{g})	Soil morphology T1: plain, T2: soft slope, T3: strong slope, T4: crest	1 MASONRY			2 CURTAIN WALLS			3 TOWERS			4 MERLONS			5 PROTRUDING ELEMENTS			6 ROOFS			7 FLOORS			8 FOUNDATIONS							
										1a	1b	2a	2b	2c	3a	3b	3c	4a	4b	5a	5b	5c	6a	6b	7a	7b	8a	8b										
MC	43	Castello Pallotta, Calderola	MX	R	Y	Y	U	0.12	T2																													
	55	Castello di Brunforte, Loro Piceno	B	R	Y	N	A	0.08	T2																													
	58	Rocca di San Filippo, S. Angelo in Pontano	B	R	Y	Y	A	0.08	T2																													
	59	Castello della Rancia, Tolentino	B	R	Y	Y	U	0.08	T1																													
	60	Mura e porte fortificate, Tolentino	MX	R	Y	Y	U	0.08	T1																													
	66	Castello di Carpignano, San Severino Marche	S	R	N	N	R	0.08	T2																													
	80	Castel Fantellino, Ussita	S	R	N	Y	U	0.52	T4																													
AP	93	Rocca di Arquata del Tronto	MX	R	Y	Y	U	0.44	T1																													
	96	Castel di Luco, Acquasanta Terme	S	N	N	N	U	0.24	T1																													
PG	47	Mura di Norecia	S	R	N	Y	U	0.36	T1																													

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