

# Structural damage in the cities of Reggiolo and Carpi after the earthquake on May 2012 in Emilia Romagna

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**Abstract** This paper addresses the structural damage to the main buildings of the cities of Reggiolo and Carpi after the primary earthquake shocks on May 20th and 29th, 2012, in Emilia Romagna. The damage survey, performed via form-based methods, highlights the different seismic behaviour of several types of buildings, especially those having historical features, and the consequences of the damage in terms of costs. Moreover, an analysis of some failure mechanisms activated in Reggiolo enables the evaluation of the local peak ground acceleration, due to the soil amplification.

**Keywords** Emilia earthquake · Collapse mechanism · Damage survey · Masonry construction

## 1 The earthquakes in Emilia Romagna

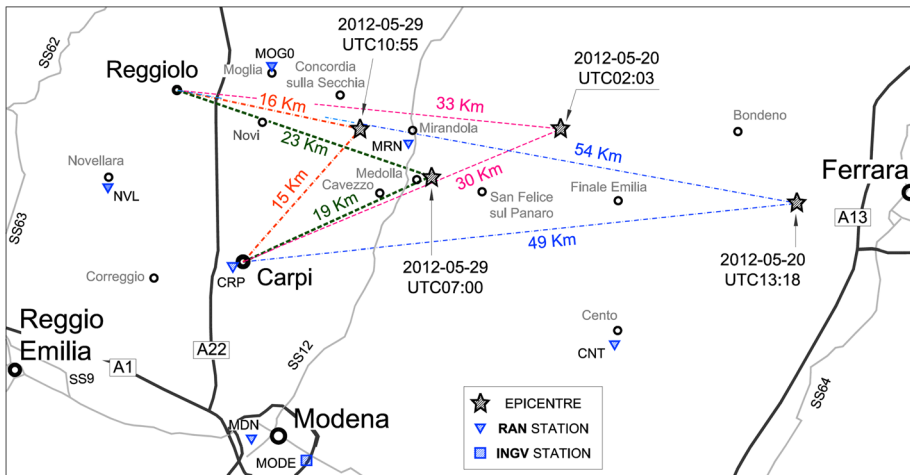
The series of earthquakes that hit the Emilia Romagna Region of Italy on May 20th (02:03 UTC MI = 5.9–13:18 UTC MI = 5.1) and on May 29th 2012 (07:00 UTC MI = 5.8–10:55 UTC MI = 5.3) involved an area of about 9,000 km<sup>2</sup>, traditionally considered with low seismic hazard (Fig. 1). Overall, the sequence caused 26 victims, and induced significant damage to public and private, historic and industrial constructions, and had a substantial impact on the economy of the region.

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**Fig. 1** The epicentral area of the May 2012 sequence

In the past, the area between Ferrara and Novi di Modena had already been affected by seismic events, some of them were quite destructive, such as those in 1570 and in 1796. The former, with epicentre in Ferrara, occurred with several replicas and presented features very similar to the 2012 earthquakes in terms of magnitude and qualitative effects on buildings and the soil (Galli et al. 2012), as demonstrated by Paolini et al. (2012). A coeval chronicle dating back to the fourteenth century (Galli et al. 2012) indicates that a strong earthquake also hit Ferrara in 1346. A comparison of the damage surveyed in 2012 with that produced by the two historical earthquakes of 1570 and 1796, performed by Paolini et al. (2012) based on the report of Arcoraci et al. (2012), demonstrated that the effects of the 2012 earthquakes matched or exceeded the maximum damage levels caused by the historical events. In addition, a recent study (Camassi et al. 2011) indicates the occurrence of an earthquake in 1639 with epicentre in Finale Emilia, although this event has not yet been included in the main Italian parametric catalogues. Other earthquakes occurred in nearby areas in 1986, in 1987 and in 1996, having instrumental magnitudes  $M_w$  of 4.35, 4.56 and 5.41, respectively. It can be therefore concluded that the 2012 sequence was the most severe in the last 500 years (Paolini et al. 2012) and the epicentral area of the 2012 sequence had never experienced earthquakes of such high energy or magnitude. These recent events thus represented the first real seismic test for almost all historic buildings, causing relevant damage to the cultural heritage.

A wide and interesting discussion on the seismic behavior of existing construction in Emilia and the peculiarities of damage to different building types has been carried out by several authors: churches (Sorrentino et al. 2013a), vernacular buildings (Sorrentino et al. 2013b), industrial buildings (Bournas et al. 2013; Liberatore et al. 2013), fortresses (Cattari et al. 2013), reinforced concrete buildings (Manfredi et al. 2013) and masonry buildings (Penna et al. 2013).

The high low-frequency content in the horizontal components of the ground motion of the May 29th event (Bordoni et al. 2012) caused many collapses to production facilities (Bournas et al. 2013). The affected area, whose seismicity has been codified only recently, is characterized by a high density of industrial buildings that are made up of precast r. c. elements for the most part and were not designed to withstand seismic actions. In many cases it was found the inadequacy of the fastenings between non-structural and structural elements, the



**Fig. 2** Warehouse in Medolla

absence of connections between the structural elements, the recurrent lack of any redundancy even in the main structure. The most frequent damage was due to the formation of a plastic hinge at the base of the columns, the short-column failure, and the failure at the top as well as the unseating of the simply supported beams (Liberatore et al. 2013).

As emblematic case, a heavily damaged warehouse near Medolla is reported in Fig. 2 which shows an excavator used to provide additional support to the reinforced concrete (r. c.) panels left standing. Besides the collapse of the precast building structure with heavy r. c. panels, the high flexibility of the vertical elements of the interior steel stand, which were heavily loaded and insufficiently braced, triggered a second order P- $\Delta$  effect, which in turn produced considerable lateral displacements of the metallic structure and strong deformation of the vertical braces.

The damage to many precast concrete industrial plants represents a new aspect in seismic prevention, in which regard the Department of Civil Protection (DPC = Dipartimento di Protezione Civile), together with the Italian Consortium of Earthquake Engineering Laboratories (ReLUIS = Rete dei Laboratori Universitari di Ingegneria Sismica) and the Italian Superior Council for Public Works (CSLLPP = Consiglio Superiore dei Lavori Pubblici), has issued specific new construction standards concerning vulnerability evaluations and retrofitting procedure for production facilities in seismic areas (Magliulo 2012).

The damage has been increased by the significant vertical component of ground motion, which is another feature of these earthquakes. The vertical acceleration was considerable and increasing towards the epicentre: the maximum horizontal acceleration measured in the epicentral area (in Mirandola) during the May 29th event at 07:00 UTC is 0.29 g, while the maximum vertical acceleration is 0.92 g. Some damage modes highlight the strong influence of the vertical shaking, which is common for a near-fault earthquake with an inverse focal mechanism. In particular, in many failures the debris was rather close to the construction's original position, as observed by Decanini et al. (2012a, b) in the case of the *Rocca Estense fortress* at Finale Emilia.

Besides industrial prefabricated buildings, the most vulnerable structures were mainly some historic and old masonry constructions which are a significant part of the building stock in the earthquake affected area and also the large majority of the residential buildings.

Old masonry structures generally exhibited a mainly global behaviour governed by the in-plane wall response, with damaged piers and spandrel beams. Buildings with typical defects and lack of proper detailing were the most damaged, as well as those with low quality mortar. The lack of nearby limestone quarries is probably the reason of the low strength of the mortar that in some cases has been evaluated through PNT-G penetrometer test (Gucci and Barsotti (1995)), as described below. Nevertheless, brickwork grants an overall quality of masonry (Sorrentino et al. 2013b).

The occurrence of out-of-plane failure modes are limited to some specific cases, i.e. in presence of instable or thrusting roofs, poor connections to wall edges, combinations of large wall slenderness or unrestrained wall lengths (as the city hall in Sant'Agostino) and structural irregularity.

Nevertheless, modern masonry buildings which are low-rise, regular and built in accordance with the more recent detailing principles have evidenced mainly a good seismic performance without any significant damage (Penna et al. 2013). In both old and modern masonry buildings peculiar non-structural damage frequently occurred: roof tiles displacement, damage to balustrades, chimneys and pinnacles, which are very dangerous for the safety of people outside the building.

Earthquakes seriously hit the cultural heritage in the epicentral area, fortresses, churches, bell towers. Fortresses, which are characterised by an irregular shape both in plan and in elevation, exhibited a high vulnerability due to the interaction of the towers with the fortress main body and with the perimeter walls (Cattari et al. 2013).

Among the historic buildings, churches presented the worst collapses. The façade mechanism was the most common (Sorrentino et al. 2013b), especially in the upper part, where the connections between walls become less effective, due to the reduction of gravity loads and consequently of the frictional forces. Other frequent mechanisms are those involving together the clerestory walls and the upper vaults. The bell towers, in turn, have been frequently damaged, but also induced significant cracks, when connected to the church. Many cracks to domes, drums and tiburium were occurred as a consequence of flexural and torsional modes of vibration.

In many cases the effect of the sequence of the main shocks was quite significant and the final condition of the building was the result of damage accumulation (Penna et al. 2013; Sorrentino et al. 2013b).

Finally, r. c. building stock, characterized by low/mid-rise constructions designed for gravity loads only, showed in general slight to medium damage that involved non-structural elements such as masonry infills and only in the epicentral zone. In few cases brittle failures in r. c. elements, either caused by local interaction with infills, or by poor reinforcement detailing, were the main cause of severe structural damage (Manfredi et al. 2013).

Emilia earthquakes have somewhere also induced secondary environmental effects as soil liquefaction and ground cracks (Carydis et al. 2012), with alteration of the stability of the slopes in the same sites.

During the initial stages, all-important roles were carried out by the National Fire Corps and the DPC, which contributed to emergency management and ensured constant assistance and support to the population.

In the following sections it has been reported on the surveys performed in the municipalities of Reggiolo and Carpi, two cities located on the western side of the stricken area, both outside the epicentral area and almost equidistant from each of the four epicentres that moved from east to west during the sequence of main shock events (Fig. 1). The macroseismic intensity,  $I_{MCS}$ , evaluated by Tertulliani et al. (2012) as cumulative damage up to June 3rd 2012 is VII in Reggiolo and VI in Carpi.

A large number of teams composed by volunteer engineers visited the entire area, in order to classify the damage and evaluate the usability of the buildings. The authors, appointed by the DPC, were involved in several inspections in Reggiolo, to check the usage safety of ordinary buildings. In addition, the authors have been part of the Operating Unit for the Historic Artistic Heritage (N.O.P.S.A. = Nuclei Operativi Patrimonio Storico Artistico), established by the Regional Service of the Ministry of Cultural Heritage (MiBAC = Ministero per i Beni e le Attività Culturali). This group consists of various experts, MiBAC officers, structural engineers and National Fire Corp members, with the assignment to assess the damage level of some historic buildings and to estimate the cost of their restoration.

It is worth noting that, despite the similar distances of the two cities from the epicentres (Fig. 1), the damage suffered by the two centres was quite different. This finding is based on the results of the authors' surveys and from the damage data provided by the two municipalities.

In order to assess whether the different damage is due to the lower construction quality or to the higher seismic shaking in Reggiolo, where no accelerometric records are available, a rough estimation of the peak soil acceleration has been performed by using extremely simplified methods.

Moreover, the data recorded at the nearby stations of the Italian Accelerometric Network (RAN = Rete Accelerometrica Nazionale) offers interesting insights regarding the evaluation of the soil amplification in both cities.

## 2 The form-based assessment

Over the last 20 years, quick inspection methods have been developed to assess the usability, damage level and vulnerability of structures after an earthquake by means of damage indicators that can be appraised through visual-only inspection and simple tools (Dolce 1998; Grünthal 1998; Bernardini 1999; SSN/GNDT 1998).

The “usability” judgment is a first step evaluation performed by the surveyor, based on visual inspection and data which can be easily collected. The aim is to simply determine whether buildings affected by a seismic event can still be used with a reasonable safety level (Baggio et al. 2007). It does not however represent a safety assessment, nor does it have a precise objective in terms of risk.

A specific assessment tool for post-earthquake usability evaluation of ordinary buildings is the so-called AeDES form (AeDES = Agibilità e Danno nell'Emergenza Sismica = Usability and Damage in the Seismic Emergency) (Baggio et al. 2007). It was originally developed in Italy in 1997 by the National Seismic Survey (SSN) together with the National Group for the Defence against Earthquakes (GNDT = Gruppo Nazionale per la Difesa dai Terremoti). Subsequently, the experience acquired in the further seismic emergencies lead to the drafting of a second version of the form (1998) and finally to the 2000 version, formulated specifically for ordinary buildings by the Working Group DPC-GNDT-SSN (Goretti and Di Pasquale 2004).

The usability survey form is based on assessment data regarding important properties of the structure and the site, as well as the extent of damage to structural and non-structural elements, supplemented by qualitative information concerning the soil and foundations needed for the geotechnical risk evaluation. The novelty of the latest version of the form is the introduction of the external risk posed by other constructions along with some short term countermeasures (e.g. temporary supports, propping) to help inspectors implement measures to reduce risk in the post-earthquake phase. Moreover, the form indicates the mean vulnerability level with

reference to possible configurations of structural element types and materials, according to the European Macro seismic Scale EMS-98 (Grünthal 1998).

Depending on the intensity of structural damage detected, the inspector evaluates the risk conditions of the building, without any mathematical correlation. The final judgment regarding the safety of a given structure is driven by the risk assessment, but the final outcome depends largely on the inspector's opinion. In particular, the procedure is to consider the building safe if it can be expected to survive another shock of the same intensity as the main shock which has occurred.

The usability classification of a building provides for six possible outcomes, from A to F, where A denotes usable, B temporarily unusable (partially or totally) but usable after short term countermeasures, C partially unusable, D temporarily unusable, requiring a more detailed investigation, E unusable, F unusable due to external risk. As the AeDES form is a first-level of assessment, it does not provide for either a damage index, or vulnerability level for a building.

Similar assessment tools for post-earthquake damage surveys, specifically dedicated to historic structures, are contained in special form versions for palaces and churches. MiBAC forms, unlike AeDES for ordinary buildings, allow to take into account the peculiarities of damage which occurs to certain types of historic buildings during the earthquake. Formulation of the latter was prompted since 1976 by observations of the seismic damage to churches (Doglioni et al. 1994), culminating in its first draft in 1987 (GNDT—S3 model). Through it, an inspector can summarize the damage modes of the church through a certain number of fundamental collapse mechanisms of macroelements (parts of the building with independent seismic behaviour). This original version was further tested in post-earthquake scenarios and, in 2006, gave rise to new survey forms, elaborated by the DPC and approved by the MiBAC (PCM-DPC-MiBAC 2006), which were suitable for recognition of damage to the cultural heritage comprised of artistic assets. The survey form for masonry churches, the A-DC model, identifies 28 possible kinematic mechanisms and grades the damage on five levels, according to the EMS-98 scale. The outcome of the form is a damage index,  $i_d$ , with a value between 0 and 1, which quantifies the average damage level suffered by the church. The damage index is expressed as

$$i_d = \frac{d}{5n}, \quad (1)$$

where  $n$  is the number of possible mechanisms activated by the seismic actions and  $d$  is the overall intensity, sum of the damage levels of all activated mechanisms.

Afterwards, the form requires the judgement of usability, similar to that of AeDES form, with six possible outcomes: usable, unusable, partially usable, usable after short term countermeasures, temporarily unusable, unusable due to external risk. As with the AeDES form, the usability judgment is still largely the opinion of the surveyor, but, in this case, it is not even related to the degree of risk.

The damage index is not directly connected to the macroseismic intensity, however, it is relevant for the outcome of usability. Although it is impossible to fix a threshold value for the damage score directly associated with usability, Lagomarsino and Podestà (2004a, b) showed that, after the Umbria-Marche earthquake, almost all churches with  $i_d \geq 0.3$  were judged unsafe. The damage index allows also a concise estimation of the costs of the restoration, as will be explained below.

Analogously, the form for palaces, the B-DP model, enables determining the damage index by evaluating the critical factors of a masonry structure, all related to the possible occurrence of 22 collapse mechanisms. Moreover, the simultaneous occurrence in every macroelement

of a principal mechanism as well as secondary ones is taken in account. The damage index is once again determined by Eq. (1), where  $n$  is the number of principal mechanisms alone.

Finally, a similar form, specifically designed for artistic assets, is the C-DM model, which allows identification of artistic frescos, mosaics, stuccoes, wooden or plaster false ceilings, thin light plaster vaults, decorated tiles, altars, sculptures, and pulpits. In this case no numerical indices are obtained; the form provides only for an estimation of restoration costs.

In contrast to the AeDES forms, all MiBAC forms require an evaluation of the costs associated to building repair, seismic strengthening including non structural elements and the short-term countermeasures to be adopted. Nevertheless, the nature of the quick, visual-only inspection makes realistic estimation difficult. In fact, it involves having to formulate restoration solutions dealing with the historical and artistic value of a building, which makes the problem quite complex. For this reason, MiBAC officers have adopted rough indications on the correlation between damage index and costs. In particular, the formula attached to MiBAC forms for costs assessment of building repair and seismic reinforcement of churches  $C_{s-c}$  is as follows

$$C_{s-c} = \alpha_{s-c} V i_d, \quad (2)$$

where  $V$  is the volume in  $\text{m}^3$  of the building and  $\alpha_{s-c} = 300 \text{ €}$ . Instead,  $C_{s-p}$ , for palaces is calculated via

$$C_{s-p} = \alpha_{s-p} A i_d, \quad (3)$$

where  $A$  is the ground surface in  $\text{m}^2$  and  $\alpha_{s-p} = 1000 \text{ €}$ .

Similarly, the costs associated to finishing and installing facilities for churches  $C_{fw-c}$  can be calculated as follows

$$C_{fw-c} = \alpha_{fw-c} V i_d c_c, \quad (4)$$

where  $\alpha_{fw-c} = 90 \text{ €}$ , and  $c_c$  is a coefficient varying from 1 to 2 expressing the artistic value of the particulars. The analogous index for palaces,  $C_{fw-p}$ , is expressed by

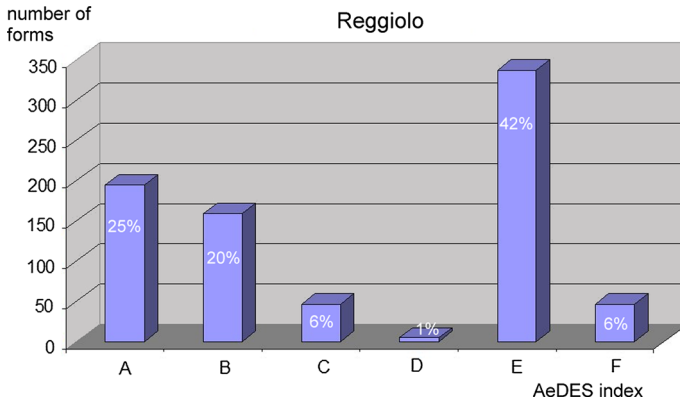
$$C_{fw-p} = \alpha_{fw-p} A i_d c_p, \quad (5)$$

where  $\alpha_{fw-p} = 900 \text{ €}$ , and  $c_p$  is a coefficient varying from 1 to 2 expressing the artistic value of the particulars.

Inspections of the ordinary buildings in Reggiolo were performed with the help of the AeDES form, while those on the historic and artistic buildings in both Reggiolo and Carpi were performed using the MiBAC forms for churches, palaces and artistic assets. In Reggiolo the authors filled out about 60 AeDES forms regarding both public and private ordinary buildings, over 20 MiBAC forms were completed for historic buildings, of which 6 in Reggiolo, 10 in Carpi and the others in Concordia sulla Secchia, Fossoli and Cortile. In this regard, we observed that the judgements of viability obtained for the same building with the two methods does not vary, despite using different survey forms for ordinary and historic buildings. Although the MiBAC forms involve greater awareness in judging damage to a specific building, the outcome of the viability assessment is always up to the opinion of the surveyor.

### 3 Report on Reggiolo (RE)

Reggiolo is a city of about 9,200 inhabitants covering a territory of about  $43 \text{ km}^2$ . It has medieval origins and therefore some important historical masonry buildings, such as the medieval fortress (“la Rocca”) (Fig. 4), the old Town Hall (Fig. 5) and the Municipal Theatre



**Fig. 3** Distribution of the AeDES index in Reggiolo

(Fig. 6), located in the city centre. Clay units and limestone mortar is the main construction material used for churches, palaces, residential and rural buildings, due to the absence of stone quarries in the Po valley.

A large number of masonry and r. c. constructions, mainly for housing, were added during the urban expansion in the 1900s, together with several buildings with precast r. c. elements for public services (social centres, schools, sport activities etc.) and industrial plants. Almost all r. c. buildings are masonry infilled r. c. frames up to six storeys and exhibited no collapses.

About one quarter of the buildings in Reggiolo were built before 1945, one half between 1945 and 1980 and the remainder after 1980. Most r. c. buildings in Reggiolo were built between the 50 and 70 s, during a period when the lack of seismic standards resulted in some of the most vulnerable structures in the area. This has been confirmed by the wide-ranging survey campaign performed by the authors and other experts on public buildings in Tuscany (Ferrini et al. 2008; De Stefano et al. 2012), as well as throughout Italy (Ferrini et al. 2004; Fabbrocino et al. 2004; Cosenza et al. 2002).

A survey of Reggiolo's private buildings provides some valuable insights on the level of damage and the inhabitants' sense of initiative. Based on the data kindly provided by the technicians of the Municipality, of the nearly 800 structural units inspected, approximately 45% were usable or repairable through emergency measures, but more than 42% were completely unusable, as shown in Fig. 3.

About 55% of the constructions inspected were masonry buildings, whereas 45% were r. c. buildings. About half of the A + B outcomes involves masonry buildings, whose construction took place mostly before 1980, and the remaining half of the A + B outcomes involved r. c. buildings. In turn, 60% of the E outcomes were masonry buildings (26% of the global number of inspected buildings) and 40% regarded r. c. buildings (16% of the global number of inspected buildings). The number of the E outcomes for masonry buildings is higher than for r.c. structures, despite the low quality of the latter. Table 1 reports the number of structural units for different outcomes and different periods of construction.

Table 2 summarises the survey AeDES or MiBAC outcomes of the inspections performed by the authors in Reggiolo. The outcomes marked with a double asterisk (\*\*) are those obtained from the MiBAC forms and called with the same letters used in the AeDES form.

The wide-spread damage to masonry buildings caused by the earthquake exhibited similar features: characteristic cracking patterns on facades and the internal parts of buildings, and failure of thin brick vaults or reed mat false vaults, mainly at the highest floors. Clearly, the



**Table 1** AeDES outcomes and construction period for completed forms in Reggiolo

Year	Before 1919	1919–1945	1945–1980	After 1980	No date
<i>Outcome</i>					
A	24	13	100	39	19
B	32	15	36	34	43
C	6	1	18	10	12
D	1	1	0	1	2
E	86	12	69	25	146
F	4	1	22	10	10

major damage was always found at the upper levels, where the walls are commonly thinner and the vertical load is lower than at the lower levels, while the pounding of the wooden roof beams often damages the walls and masonry lintels. A large part of masonry constructions exhibited collapse of chimneys, pinnacles, merlons and sliding of the roof tiles.

Even if the number of buildings inspected does not allow for meaningful statistical analyses, it can clearly underline the high-level damage resulting from the survey of historic masonry buildings in the Reggiolo centre, as shown in Table 2, which reports all unusable structures with outcome E.

Many damage mechanisms are clearly visible from the outside, including out-of-plane rotations of wall portion, masonry corners or entire façades and, less frequently, collapse of the outer leaf of walls. A large number of buildings have been declared unusable, even though lacking any significant failures. Some examples of old constructions with striking damage are “*la Rocca*” (Fig. 4a), the old Town Hall (Fig. 5) and the retirement home *Santa Maria delle Grazie* (Fig. 6). *La Rocca* was built in the early thirteenth century by the Municipality of Reggio Emilia to defend the city against Mantova. It is a squared brick masonry fortress with four towers at the corners and a main 34 m-high central tower, now the property of the Municipality. The structure was damaged by the 1985 earthquake, restored in 1995 and until 2012 earthquake had been used for guided tours and public events. The damage caused by the earthquake are significant: collapse of merlons and free walls made it completely unusable (Fig. 4b, c).

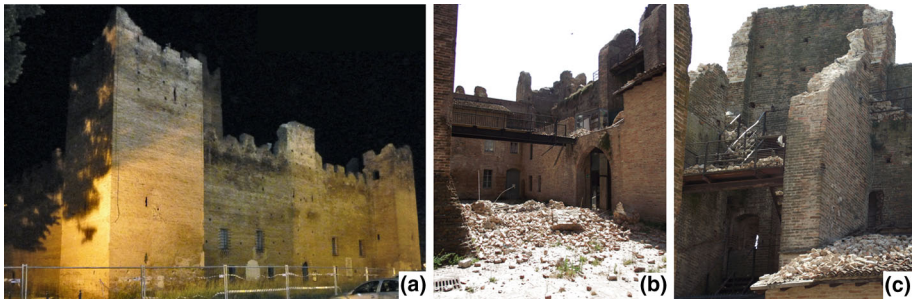
The old Town Hall (*Palazzo Sartoretti*) on the southern side of the square of *Piazza Martiri* (Fig. 5) is an L-shaped brick masonry construction built in the sixteenth century. The three-storey building with a higher central part holds paintings dating back to the 1700–1800s, giving it a neoclassical atmosphere. It was largely refurbished in 2003 and then again in 2009: although no structural interventions were made, the state of conservation before earthquakes was good. The first floor holding the city library is now severely damaged, revealing in plane shear collapses, overturning of the corners, unseating and pounding of the roof beams, and heavy damage to the brick vaults. Figure 5 shows the main façade with heavy damage.

The retirement home *Santa Maria delle Grazie* is an historic villa built between the eighteenth and nineteenth century. The two-storey masonry building has a central higher part and double symmetrical configuration. Noticeable in- and out-of-plane wall collapses, accompanied by the crumbling of plasters, portions of the reed mat false vaults and chimneys, together with sliding of the roof tiles occurred in consequence to the earthquakes.

In all three cases the damage is severe, despite the fact that the construction techniques used complied fully with the best practice of the time. Most of the cracking clearly runs along the mortar joints (Fig. 6c)—a clear sign of weak mortar. In order to evaluate the

**Table 2** Public buildings inspected by authors in Reggiolo (RE)

Name	Position	Typology	n° floors	Ground area (m <sup>2</sup> )	Volume (m <sup>3</sup> )	Height (m)	Age	AEDES safety index	MiBAC damage index
1 Municipal Healthcare Civic Centre	Isolated	Masonry	2	350	3,200	9	1930	B	
2 Kindergarten Giotosa	Isolated	Masonry	3	750	6,975	3	1962/1971 and 1992/2001	A	
3 Kindergarten Bambi-Peter Pan	Isolated	R.C.	1	550	1,710	3	1972/1981 and 2002	B	
4 Multi-purpose Social Centre	Extremity	R.C.	2	850	7,750	12	>2002	B	
5 Municipal Bowls Centre	Extremity	R.C.	1	1,000	5,250	8	1972/1981	B	
6 Sports hall Magnani	Isolated	R.C.	1	1,100	5,250	10	1992/2001	C	
7 City Hall	Extremity	R.C.	6	270	4,500	19	1962/1971	E	
8 Middle School Carducci-Auditorium	Extremity	R.C.	4	350	1,470	12	1992/2001	B	
9 Middle School Carducci-Principal building	Extremity	Masonry	2	850	6,600	10	<1919	E**	0.63
10 Social Health Centre-building 32	Isolated	Masonry	2	1,100	6,300	9	1919/1945 and 1962/1971	E	
11 Elementary School DeAmicis-Principal building	Extremity	R.C. and R.C.	2	1,450	8,400	7	1962/1971	B	
12 Elementary School DeAmicis-Refectory	Extremity	R.C.	2	220	1,140	7	>2002	C	
13 Elementary School DeAmicis-Sports hall	Extremity	R.C.	1	600	2,875	9	>2002	E	
14 Kindergarten Hansel e Grete1	Isolated	R.C.	1	250	1,113	4	1972/1981 and 2002	C	
15 Kindergarten Parrucchia Maria Immacolata	Isolated	Masonry	2	580	3,450	8	1962/1971	A	
16 Sartoretti Palace	Extremity	Masonry	4	1,020	13,260	14	1800	E**	0.60
17 City Theatre Rinaldi	Isolated	Masonry	3	520	5,150	6	1800	E**	0.49
18 Medieval Rocca	Isolated	Masonry	2	1,900	38,000	4	1200	E**	0.86
19 Municipal Cemetery	Isolated	R.C.	2	2,470	17,297	7	1930	C**	0.10
20 Villanova Cemetery	Isolated	Masonry	1	130	1,040	8	1950	E**	0.37
21 Municipal warehouse	Isolated	R.C.	1	480	2,250	8	1972/1981	A	
22 Ex officina IPSIA Social Centre	Isolated	R.C.	1	220	600	4	1972/1981	B	
23 Retirement home; Cantone street	Isolated	Masonry	2	700	5,600	8	1920	E	



**Fig. 4** The medieval fortress *la Rocca di Reggiolo*—**a** external view; **b**, **c** masonry fragments after the collapse



**Fig. 5** *Palazzo Sartoretti*—the old Town Hall (the main façade heavily damaged)

mortar strength, some drilling tests were performed with the PNT-G technique, an indirect non-destructive method (RILEM TC 177-MDT D.1. 2004) for determining the mortar load capacity in situ by measuring the amount of energy required to drill a small bore hole in the joint. The method, developed by Gucci and Barsotti (1995) and by Gucci et al. (1995), showed satisfactory correspondence with direct compressive tests of low quality mortars, as in two previous blind tests on large scale buildings, the TREREM project at ENEA Casaccia (Gucci et al. 2006) and TREESLAB at EUCENTRE (Sassu et al. 2008), and in a recent on site experimental campaign (Andreini et al. 2014). The great advantage in the case of weak mortar (with compressive strength lower than approximately 4 MPa) is that the correlation between drilling work and mortar compressive strength is independent of both the aggregate type and the grain size distribution. When the mortar compressive strength is high, a specific calibration curve for every mortar type is required. Limitations of the technique are achieved in the presence of weak aggregate.

The resulting compressive strength values of the mortar detected in the three buildings were between 0.3 and 0.7 MPa—quite low for ordinary limestone mortar. Chemical-physical analyses were also carried out on mortar. In particular, petrographic analysis and x-ray diffractometry showed an earthy mixture consisting of a clay matrix having a sandy component with size below 0.3 mm. This mortar can therefore be referred to as a raw mixture of clay and sand (Fig. 7).

A particular traditional type of constructions in an agricultural area is represented by a rural masonry building, consisting of dwellings and stable-haylofts. Such houses are usually two or three storeys high, separated from the hayloft and sometimes fronted by a large portico.



Fig. 6 Retirement home—a external view; b PNT-G tests; c crack pattern

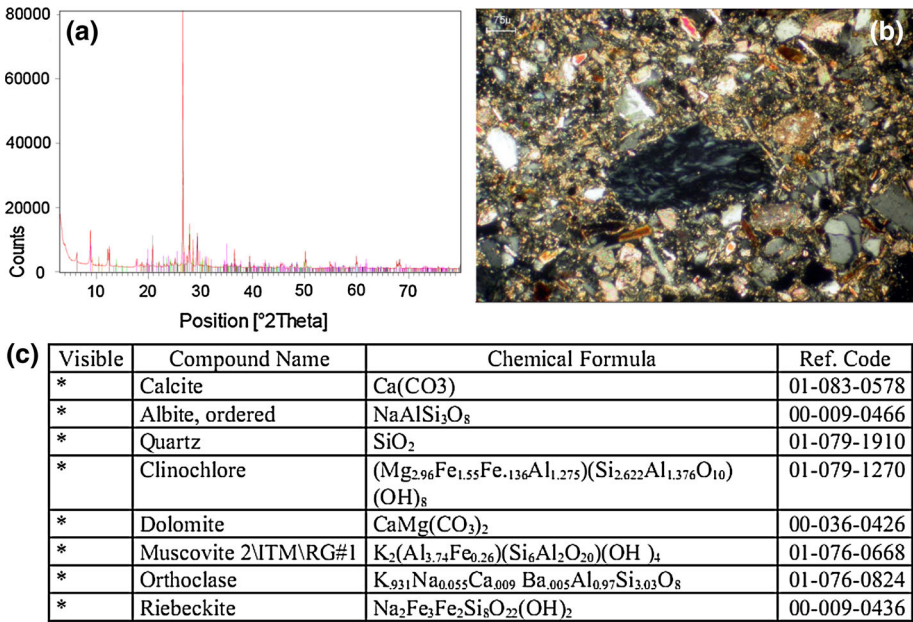


Fig. 7 Retirement home—chemical analysis on mortar a diffractometric analysis; b 100× image; c chemical components of mortar

The main structure is constructed using clay bricks and timber beams. Figure 9 shows an example of such a rural house in Reggiolo.

Sometimes adobe is present on the upper floors: in ancient times unfired bricks were rather common, because the fuel necessary to fire the bricks was rather in short supply and thus expensive. Fired bricks were once used only up to the expected height of a flood and only in the nineteenth and twentieth centuries they came to be predominant (Ortolani 1953). In addition, earth mortar made up of a special river silt was often used.

The observed damage has shown that rural dwellings were much less weakened than stable-haylofts and local canopies. In fact, porticos and haylofts present typically external hollow brick walls and isolated masonry piers or masonry walls which support the roof (Figs. 8b, 9). These elements constitute a major source of vulnerability due to the slenderness of the



**Fig. 8** **a** a typical rural house in Reggiolo; **b** the portico with collapsed hollow brick wall and cracked masonry pillar



**Fig. 9** Different structures of the roof in the haylofts—arrows indicate damage

columns and the poor connections with the wooden roof beams. In addition most of these buildings are little used or abandoned. So, due to overall layout, constructive details, poor maintenance and severe ground motion, the seismic performance of vernacular buildings was very poor (Sorrentino et al. 2013a).

The authors examined a number of residential and office buildings consisting in masonry infilled r. c. frames with no shear wall structural systems. No heavy damage was found in these cases.

It is worth noting that most r. c. constructions—generally built after the 60s—underwent damage to non-structural elements, especially in the external clay unit panels. Since the survival of r. c. structures during the earthquakes has sometimes been ensured by the presence of infill walls (Decanini et al. 2012a, b); their cracking, although slight, had sometimes determined a bad usability outcome. The most frequently activated collapse mechanisms are out-of-plane ones and slight in-plane cracking. Often damage is mostly concentrated at the ground storey, due to irregular distribution of the infills. In some cases, the hollow brick walls sustaining the coverage elements collapsed and caused damage to the roof, as in the Social Centre (*ex officine IPSIA*, Fig. 10).

There are no serious collapses in r. c. precast structures, but the vulnerability of some public buildings is evident, such as the *Bambi-Peter Pan* Kindergarten. As for the Social Centre and the Magnani sports hall (Fig. 11), incipient tilting of the external panels is avoided only by thin metal bars.



**Fig. 10** Social Centre—**a** external view; **b** overturning of the upper masonry roof walls



**Fig. 11** Magnani sports hall—**a** general view; **b**, **c** details of the connections of the panels

Figure 12 shows a reinforcement added to the support of a precast beam in a textile factory in Reggio: in order to return to work as soon as possible, the owners repaired the damaged structural elements before the arrival of DPC inspectors.



**Fig. 12** Textile factory in Reggiolo: reinforcement added to the support of a precast beam after the earthquake

The responsiveness of the population is also demonstrated by the large number of consolidation project proposals that had already been filed by August 25th 2012: 138 projects, of which 45 regarded manufacturing activities.

#### 4 Report on Carpi (MO)

The city of Carpi has about 70,000 inhabitants and hosts an important cultural heritage. Its historic centre covers about 1.5 sq. km and it is made up of three or four-storey brick masonry buildings. Floor and roof structures are generally comprised of wooden beams or trusses and clay bricks. A typical architectural element found in the old city is the portico, generally one-storey high, covered by cross vaults with underlying arcades spanning from 4 to 5 m. Figure 13 shows the arcades of the *Portico Lungo* in the *Piazza Martiri* (Italy's 3rd largest square) and the *Portici del Grano* after the 2012 earthquakes.

Many small r. c. and masonry buildings are found just outside the historic centre, while more recent industrial precast buildings are located in the city's outskirts.

After the seismic events, 1842 AeDES forms were completed by the Italian Civil Protection Department. Figure 14 shows the distribution of the AeDES index in Carpi, as per the data kindly furnished by the officers of the Municipality: approximately 53 % of all structural units were usable or repairable by means of emergency measures, while 34 % were completely unusable.

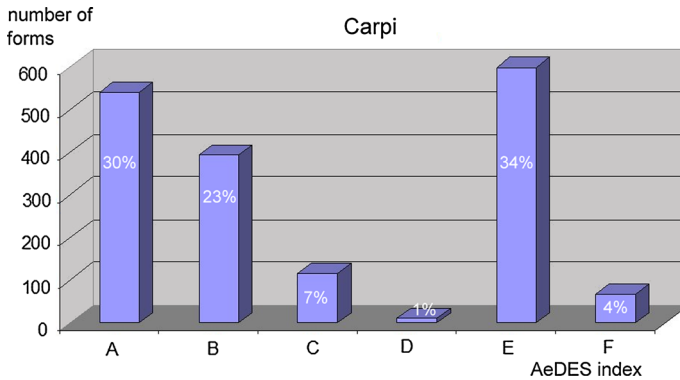
The breakdown accordingly to usage is as follows: 1.138 housing units, 68 production facilities, 172 combined residential and production units and 509 with other uses.

The percentage of masonry structural units is slightly higher in Carpi than Reggiolo: about 57 % of all units inspected are masonry, whereas 43 % are r. c.. It can be observed that over half of the A+B outcomes refer to masonry buildings constructed mostly before 1980, and the rest are r. c. buildings. In addition, as in Reggiolo, 3/5 of the E outcomes were masonry units (16 % of all inspected units) and 2/5 r. c. units (10 %). Once again, the number of the E outcomes for masonry units is higher than for r. c. structures, and the ratio between the two types is the same as for Reggiolo. Table 3 reports the number of structural units for each outcome and construction period.



**Fig. 13** **a** The *Portico Lungo* in *Piazza Martiri* seen from the south; **b** an overview of the *Piazza Martiri* arcades from the north; **c** *Portici del Grano* in *Via Alberto Pio*: arrows indicate the columns that have been consolidated





**Fig. 14** Distribution of the AeDES index in Carpi

**Table 3** AeDES outcomes and construction period for completed forms in Carpi

Year	Before 1919	1919–1945	1945–1980	After 1980	No date
<i>Outcome</i>					
A	38	49	49	263	76
B	53	54	54	130	55
C	17	11	11	39	25
D	1	0	0	0	0
E	102	65	65	104	40
F	6	6	6	19	8

As in Reggiolo, the citizens of Carpi exhibited a strong spirit of initiative: by the end of 2012, 350 applications for construction procedures had been filed, and 526 safety inspections were conducted on production facilities (360 on r. c. buildings and 166 on masonry buildings).

After the earthquake—just one day after the last strong ground motion of 29th of May 2012—the municipal government issued a decision to prohibit access to the entire city centre for ten days. Thus, the management of the emergency restoration activities enabled the city centre to be re-opened in a very short time and normal activities to be completely resumed by late September.

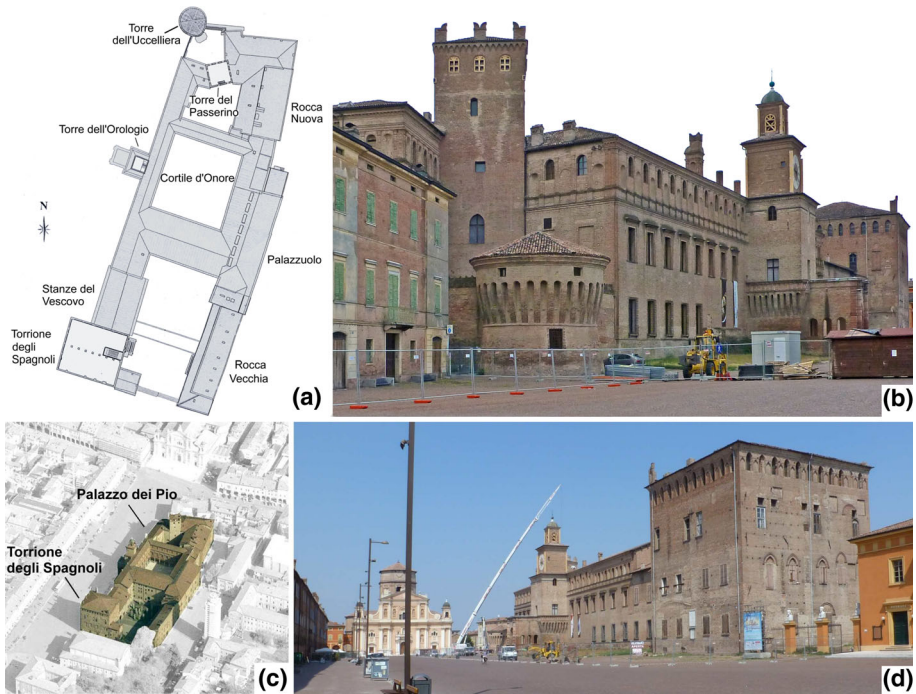
The centre area, where the majority of masonry buildings are located, exhibited the typical damage to walls, as well as a large number of overturned secondary elements, such as chimneypots, merlons, pinnacles and small towers, which had no efficient connections to the roofs. In addition, serious crack patterns have affected domes, vaults and apses, as can be seen in the church of San Nicolò (Figs. 15a, b). In this regard, the *Assunta* Cathedral serves as a representative example (Fig. 15c–e). In this case, ornaments falling from the facade caused severe damage to the structure. In particular, the cross at the top of the facade fell with two marble spheres, breaking the roof and the underlying brick vault. The dome turned out to be the most damaged element: in spite of previous consolidation with internal tie rods, the shaking triggered local mechanisms, with collapse of the window lintel and wall below.

The earthquakes did not cause noticeable damage to the porticos, thanks to the transverse and longitudinal tie rods. The arcades of the age-old *Portici del Grano* were also undamaged, but following the earthquakes the columns were nonetheless consolidated with alternating external metal hoops (Fig. 13c).



**Fig. 15** **a** Rear side of *San Nicolò* church; **b** new and existing damage in the barrel vault in *San Nicolò*; **c–e** cathedral of *Assunta*: fallen ornaments and damage to roof and dome

The authors inspected the main historic buildings of Carpi, near *Piazza Martiri*: the *Palazzo dei Pio* building (Fig. 16), the *Torrione degli Spagnoli* tower (Figs. 16, 20, 21), *il Mattatoio* (i.e., slaughterhouse Fig. 22), the former Synagogue (Fig. 23), and the *Santa Chiara* Church



**Fig. 16** *Palazzo dei Pio*—**a** scheme; **b** view from north, in front of the *Torre dell'Uccelliera*, after the earthquakes; **c** axonometric view of the complex **d** view from south, in front of the *Torrione degli Spagnoli* after the earthquakes

with the Clarisse monastery (Fig. 24). Table 4 shows the outcomes for these structures of the 1st level damage survey forms for Cultural Heritage Buildings.

Inspections were also conducted on the *Campo di Fossoli* (a concentration camp during the deportation of Jews) (Fig. 25) and on the old cemeteries of Fossoli and Cortile.

#### 4.1 Palazzo dei Pio

*Palazzo dei Pio* (Fig. 16), a large masonry complex of about 20.000 sqm with 140 m × 60 m in extension, was transformed from a defensive castle (twelfth century) into a royal palace and became public property in the twentieth century; it has been recently restored to cultural centre, hosting three museums, the historic archives, a library and a centre for children (Rossi and Svalduz 2008).

It is composed by many structural units of various ages, different in height and shape, but similar in terms of materials and construction techniques.

The material is brick masonry throughout, with thick basement walls (from 0.60 to 1.20 m). The floors are sustained by wooden beams, brick cloisters or cross vaults. Reed mat false vaults with frescoes are quite common, while the pavilion roofs are sustained by wooden trusses.

The oldest part of the complex is the five-storey, 30 m-high *Torre del Passerino*. Nearby, in the northern part of the complex, stands the *Torre dell'Uccelliera*, a low-rise brick masonry tower with circular section (Fig. 16).

**Table 4** Historic buildings inspected in the centre of Carpi

Building complex	n° of floors	Ground area (m <sup>2</sup> )	Volume(m <sup>3</sup> )	Height (m)	Age	AeDES safety index	MIBAC damage index
1 Ancient Mattatoio	1	170	833	4,9	1800	B **	0.15
2 Monastery of the Clarisse	3	689	8,268	4	1400	C **	0.31
3 Santa Chiara church	1	420	4,032	9,6	1500	B **	0.2
4 Former Synagogue	3	750	13,500	6	1700	C **	0.06
5 Torrione degli Spagnoli	4	460	11,000	6	1400	E **	0.6
6 Palazzo dei Pio	3	4,000	80,000	20	1300–1600	B **	0.19

Dimensional data of the central building  
The indexes are referred to the whole aggregate



**Fig. 17** *Palazzo dei Pio*—**a** frescoes with cracks. **b** extraction of a roof beam on the upper level of *Torre del Passerino*

The *Rocca Nuova* (i.e. new fortress), in the north-east edge, is a residential area (Fig. 16a), a three-storey rectangular building that incorporates the nucleus of the original complex dating back to the twelfth century.

The *Torre dell’Orologio* (clock tower) forms the main entrance of *Palazzo dei Pio* (Fig. 16a, b). It is composed of overlapping structures, which decrease in volume towards the top, and ends in a small bell-tower with four arches. The entrance leads to the *Cortile d’Onore*, (courtyard of honour), a squared cloister with a 800 sqm gallery (Figs. 16a, 19b). The portico, with marble columns and round arches, is surmounted by closed lodges on the two upper storeys.

The late fifteenth-century *Rocca Vecchia*, (old fortress) is a three storey located in the south-eastern area of the complex (Fig. 16a), containing the municipal archive. The *Palazzuolo* (small palace) is a three-storey rectangular building located between *Rocca Vecchia* and *Rocca Nuova*, on the complex’s eastern side (Fig. 16a). Lastly, an apartment called “*Le Stanze del Vescovo*” (Bishop’s rooms), adjacent to the *Torrione degli Spagnoli* in the southern area (Fig. 16a), consists of large rooms with reed mat false vaults decorated by frescoes.

The main seismic damage was frequently located on the higher floors: diagonal cracking on the walls caused by in-plane mechanisms, local damage due to structural dishomogeneity (chimney flues or infilled material) or structural discontinuities (different adjacent unconnected structures), cracking of the vaults and punching of the wooden beams. Sliding failures occurred in the upper parts of some low-quality walls (historical archive), together with cracks on vaults (Fig. 17a) and small sliding movements of the supports of wooden roof structures (Fig. 17b). The upper outer walls of the *Torre del Passerino* exhibited a few new inclined cracks and some damage to the openings, despite the presence of tie rods. In most buildings, many sub-vertical walls cracks on the lower floors had already arisen before the earthquakes and were re-opened by the seismic shaking.

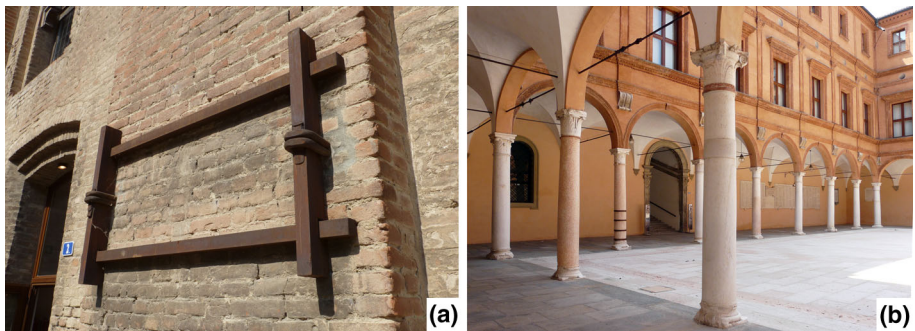
Lastly, the bell-tower atop the *Torre dell’Orologio* underwent sliding collapse (Fig. 18a) and many tower elements such as chimneys and pinnacles overturned (Fig. 18b).

On the whole, the seismic response of *Palazzo dei Pio* was satisfactory, also thanks to the recent consolidation operations: the installation of new tie rods, roof consolidation with substitution of deteriorated elements. In particular, the tie rods surely limited the extent of vault cracking and avoided out-of-plane mechanisms.

The average damage index value for the complex is 0.19, with an usability outcome of B (Table 4), meaning the building is partially temporarily unusable: despite the limited damage to structure, it is justified by the presence of a number of important artistic features. The total



**Fig. 18** *Palazzo dei Pio*—**a** bell tower atop the *Torre dell’Orologio* **b** collapsed merlon on the *Torre del Passerino* **c** consolidated merlon on the main façade

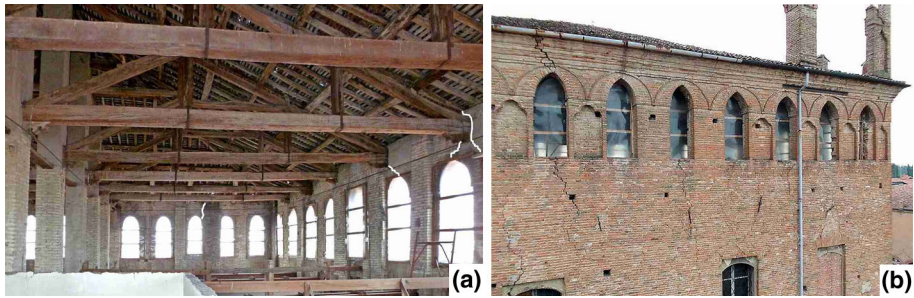


**Fig. 19** *Palazzo dei Pio*—**a** tie rod anchor system recently installed on the *Rocca Nuova* **b** old and recent tie rods in the *Cortile d’Onore*

costs assessment, inclusive of building repairs, seismic strengthening and finishing, according to formulas (3) and (5), originally amounted to about € 2 million, though a subsequent, more accurate evaluation has raised the overall cost estimate to € 3.5 million (Fig. 19).

#### 4.2 Torrione degli Spagnoli

This tower was created in 1450 by joining two adjacent towers. It is connected to the *Palazzo dei Pio* (Fig. 16a) along the north-eastern side. The four-storey brick masonry building is rectangular in section, 20m × 23 m. The floors are mainly supported by brick vaults, often decorated, and the roof is sustained by large wooden trusses resting on the outer walls and isolated columns (Fig. 20a). The building has always been state-owned, but it is currently abandoned and in a poor state of maintenance. Only the lower floors were partially consolidated after the 1996 earthquake. During the two shocks of May 2012 the *Torrione* suffered further damage to its interior walls, with some frescoes and vaulted ceilings with decorated plasters. However, few additional diagonal cracks appeared on the walls and vaults: the recently installed tie rods helped to contain out-of-plane mechanisms. The most cracks are located at the top of the building, on the outer walls, particularly vulnerable to the presence of a great number of openings (Fig. 20b). Moreover, the roof trusses (Fig. 20a), some of which were in conditions of incipient collapse, produced local damage to the walls, due to punching actions during the seismic oscillations. Indeed, many out-of-plumb sections are noticeable on the upper part of the walls.



**Fig. 20** *Torrione degli Spagnoli*: damage at the top of the building—**a** interior view; **b** exterior view

In addition, after May 20th, some tower elements (Fig. 21a) were in conditions of incipient collapse, although they have recently been reinforced with steel bars anchored with resins (Figs. 18b, 21c). In order to avoid risks to the underlying structures, most of them were removed and stocked on the ground (Fig. 21b, c) or demolished (Fig. 21d)

The temporary consolidation works to repair wooden collapsed elements and close some openings at the upper level have been finalized.

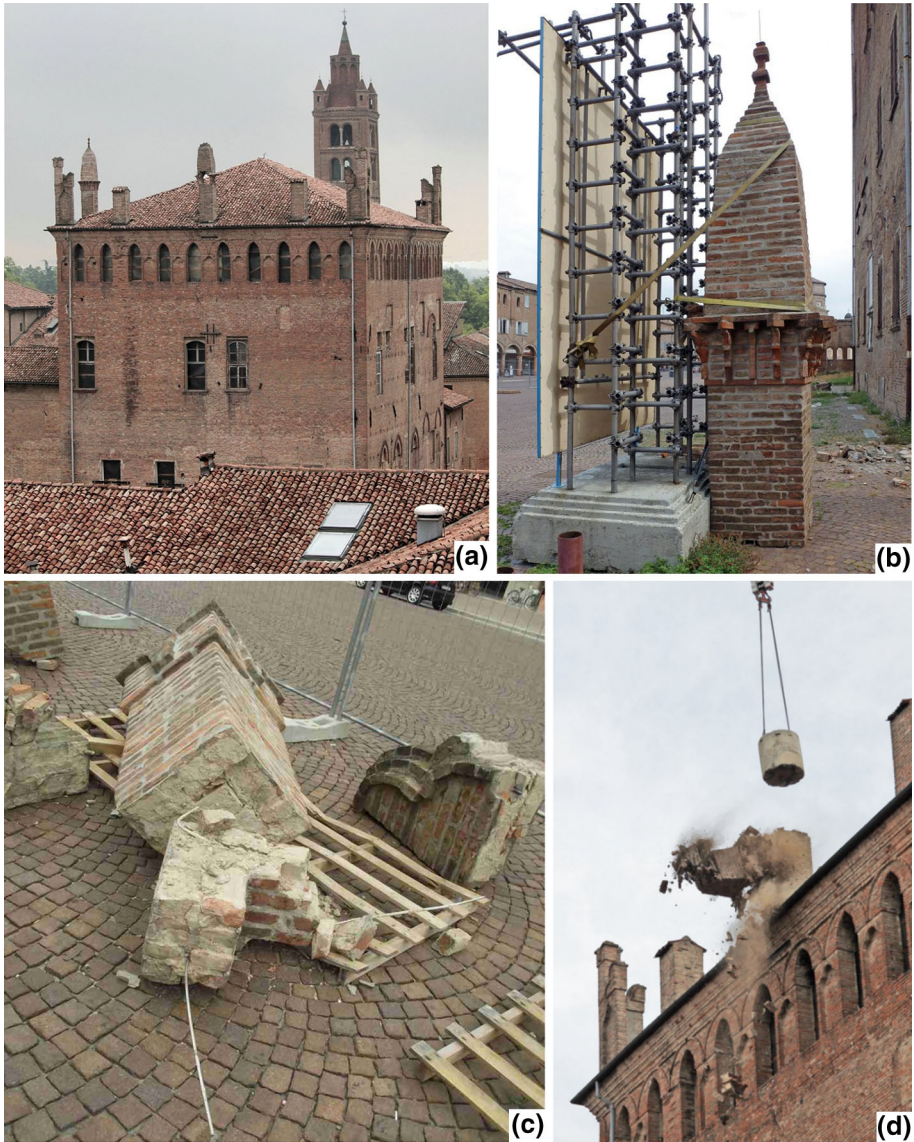
The outcome of the MiBAC form is E: the building is totally unusable, due to the previous and further seismic damage. The total cost for a complete restoring is about € 4.6 million, whereas using expressions (3) and (5), the amount is lower than 1 million Euros.

#### 4.3 The old Mattatoio

This single-storey masonry building, dating back to nineteenth century, was once the town's slaughterhouse, though it now hosts a pub. It is regular in shape, with a 5.5 x 31 m rectangular plan, and is well constructed (Fig. 22a). The earthquakes produced little damage to the walls: only an in-plane crack on the arch, as shown in Fig. 22b. However, the hipped roof has an inherent vulnerability due to some broken trusses: in the past, the roof was repaired as shown in Fig. 22c. A source of vulnerability is the Perret ceiling, fragile and locally damaged by humidity. Moreover, as shown in Fig. 22d, marked sliding of the roof tiles occurred. The usability outcome was B, and the damage index 0.15. The estimated total cost for the restoration was about € 100,000, though applying expressions (3) and (5) the amount was reduced of about 50%.

#### 4.4 The former Synagogue

The old Synagogue is located on the top floor of the 1722 building which includes the *Portico del Grano* (Fig. 13c). The new neoclassical Synagogue, the result of nineteenth-century modifications, is instead located on the first floor. The three-storey building housing the two temples is made up of brick masonry; the floors are sustained by wooden beams and the roof by wooden trusses. The rooms are covered by decorated reed mat vaults. After the earthquake, many pre-existing vertical cracks on the walls re-opened and some new inclined cracks were formed. Figure 23a shows a pre-existing vertical crack on the new Synagogue wall, while Fig. 23b shows a portion of the earlier cracking pattern in the ancient Synagogue, with local collapse of the reed mat vault. No out-of-plane collapses took place, but due to the punching action of the wooden roof beams, expulsion of the wall plastering occurred frequently (Fig. 23b).



**Fig. 21** *Torrione degli Spagnoli*—a tower elements after May 20th; b, c removal of previously consolidated elements; d demolished elements

As the seismic behaviour of the complex was overall quite good, the resulting damage index was only 0.06, despite the serious damage in the old Synagogue. The usability outcome was C, specifically, the building was deemed partially unusable in its upper rooms. The estimated total restoration cost for the complex amounts to € 900,000.

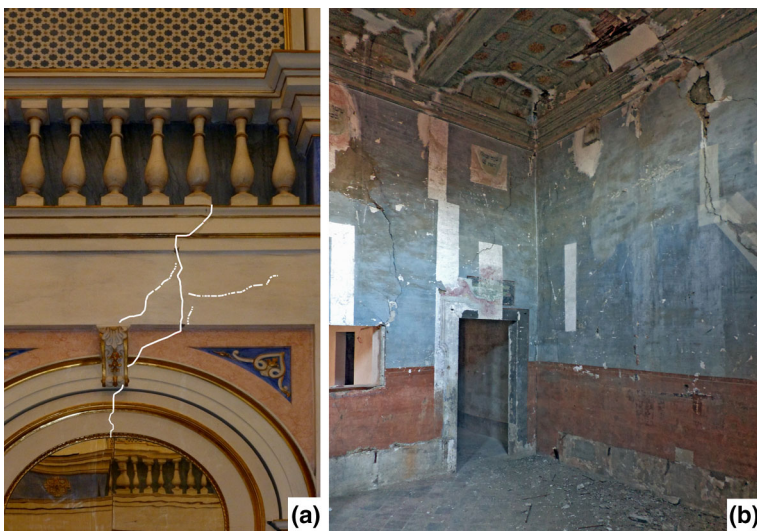
#### 4.5 The Clarisse monastery and the Church of Santa Chiara

This brick masonry complex comprises the fourteenth-century monastery of Clarisse and the adjacent church of Santa Chiara (Zarri 2003). The monastery extends over a surface area of

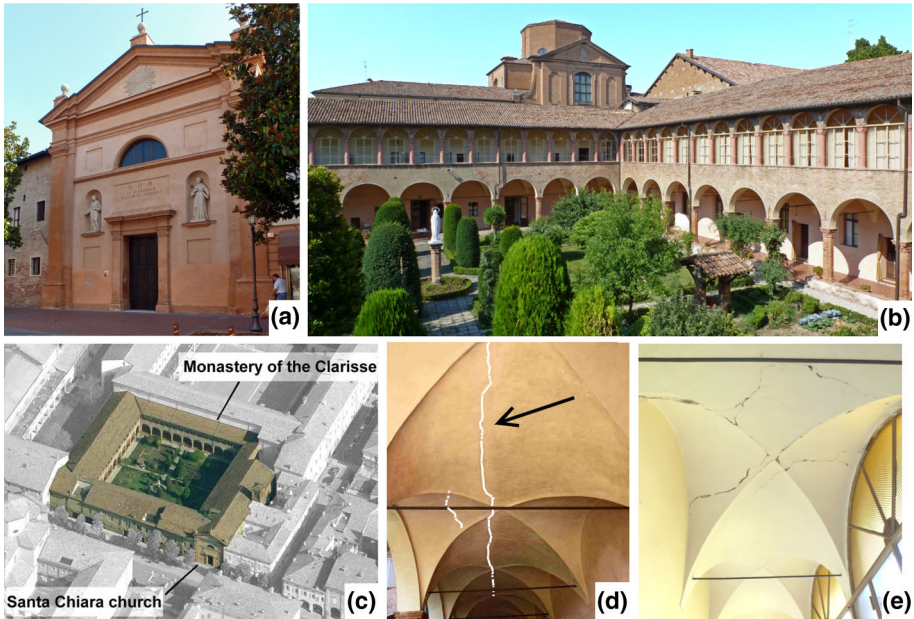




**Fig. 22** The *Mattatoio*—**a** lateral view; **b** cracking of the arch opening; **c** critical situations on roof truss; **d** roof tiles displacement



**Fig. 23** The two Synagogues—**a** an earlier crack in the new Synagogue; **b** cracking pattern in the old Synagogue



**Fig. 24** The Clarisse Monastery and the Church of Santa Chiara—**a** church facade; **b** the cloister; **c** the Clarisse complex; **d** damaged cross vaults of the cloister; **e** damaged cross vaults in the corridor at the first level

about 3,000 m<sup>2</sup> and surrounds a cloister with garden within. The two-storey complex consists of a four-sided portico, surmounted by closed lodges on the upper floor that hosts the cloister cells and services quarters. The floors are supported by wooden beams or brick vaults.

The church is a 10 m-high, 10 m x 40 m rectangular building, with a small annexed bell tower. The interior area is divided into two halls by a transverse wall: one is covered by a cross vault and the other by a decorated barrel vault. The roofs are made up of wooden trusses.

The most damaged macroelements are the inner and outer walls and the vaults. There is a great deal of shear cracking on the walls, especially over the openings. The vaults (Fig. 24e) show various cracking pattern. The damage, however, is most pronounced on the upper floors and in the attic, where expulsion of the plastering occurred due to the oscillating roof beams that punched the walls. The cross brick vaults are traversed by an evident longitudinal crack due to an older static event (Fig. 24d). It was caused by the presence of an overlaying longitudinal wall, placed in the mid-span of the vault and delimiting the upper corridor (Fig. 24e). Due to the seismic vertical shaking, the cracks re-opened and increased, which occurred despite recent consolidation designed and carried out with the sole purpose of conserving the structure: a reinforced concrete slab was cast on the extrados, just below the hallway, without however covering the entire surface of the vault. Such a measure only increases the weight, without achieving any benefits in terms of improved bearing capacity. Fortunately, as in the previously discussed cases, the presence of transverse tie rods avoided the worst damage. Other visible cracks, which are mainly pre-existing, affected the external walls of the cloister and interior areas.

The damage index of the monastery was 0.31 and the viability outcome was partial usability limited to a few rooms on the lower floor and a portion of the cloister.



**Fig. 25** Campo di Fossoli—**a** restored barrack used as visitor and exhibition centre; **b** damaged barrack

In the absence of precious decorations, the total cost of restoration was estimated to be € 1.6 million. According to the formulas suggested by MiBAC, the total cost is approximately one quarter of said value.

As for the church, it presents a few large diagonal shear cracks in the external walls and internal transverse wall. The barrel vault is cracked along the transverse direction. Even the small bell tower bears widespread damage.

The damage index for the church was 0.2 and the viability outcome was usability after temporary countermeasures to avoid falling fragments from the damaged barrel vault. The repair costs were estimated at € 850,000, though once again evaluation with the MiBAC formulas (2) and (4) yields a value half that.

#### 4.6 Campo di Fossoli

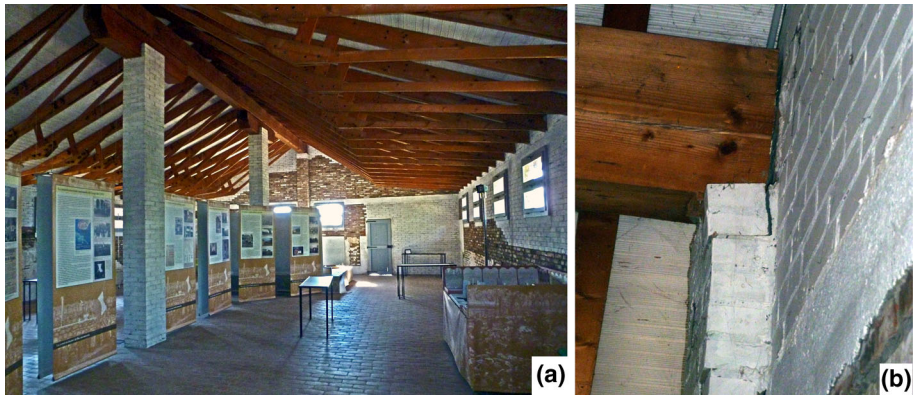
This complex, originally built in 1942 as a camp for war prisoners, in 1944 was converted into a “police and transit camp” for political and racial deportees, Ori (2008) and today is an Holocaust Memorial and WW II Museum.

The camp was arranged in a series of barracks—single-storey brick masonry buildings (Fig. 25a) with wooden trusses. Before the 2012 earthquake, many structures were abandoned with most of the roofs falling apart and hence underwent severe damage. Following the May 2012 collapse events increased, adding further external risks for the visitors to the museum (Fig. 25b).

One of the 20 barracks has been recently restored to its original arrangement (Fig. 26a) and is now used as a visitors and exhibition centre. The building has an elongated rectangular shape, 40 m x 12 m, and is covered by a gable roof sustained by timber trusses resting on the external walls and free-standing central pillars (Fig. 26a).

Conserving this valuable memorial site, together with the authenticity of its structures, is a rather unusual, difficult-to-solve restoration problem, due especially to the high costs involved, coupled with the lack of available financial resources and the absence of artistic value. Thus, as an alternative to a costly rebuilding of the entire complex, the work group proposed restoring the collapsed portions of the facades, using metal propping inside to ensure stability. Maintenance of the external appearance of most of the barracks would be ensured, though access to their interiors would be prohibited. Complete restoration could then be undertaken only on a selected number of barracks. The estimate of the restoring cost has not been reported herein because the technical solution is so preliminary in this phase that it is difficult to execute a reliable cost assessment.

Although not vast, the degree of damage to the previously restored barrack justifies an outcome of unusability: the unseating of the ridge beams (Fig. 26b), damage to the support pillars and the slight in-plane cracking of the gable walls increase the building’s vulnerability



**Fig. 26** *Campo di Fossoli* visitors centre **a** interior view; **b** unseating of wooden ridge beam

to the point that it could easily collapse under the actions of an earthquake similar to those of May 2012.

## 5 Strong ground motion and damage

During the May 29th event the peak ground accelerations at the epicentre (Mirandola) were around 0.3 g, approximately double the design acceleration prescribed by the INGV (INGV 2012). In fact, as per the seismic hazard maps drawn up by Meletti and Montaldo (2007), the predicted peak ground acceleration values for a 10 % exceedance probability within 50 years vary from 0.125 to 0.15 g in the epicentral area. The higher actual values reached are probably due to the features of the soil and their ability to produce amplification effects. The specific geology in the Padana plain area is dominated by compressional tectonics forming thrust belt type structures such as the Apennine Mountains, with asymmetric folds and thrust and reverse faults verging north-northeast (Ioannou et al. 2012). The epicentral area is characterized by a flat morphology with geomorphic features typical of the areas that rise locally from the plain (Bordoni et al. 2012): river levees and anthropic fillings. The superficial geology of the area is dominated by paleo-river-bed sediments, mainly sand, sand-silty and silty-clay sediments, whereas in the deep sedimentary cover there are some aquifers of regional importance. As demonstrated by Massa et al. (2011), alluvial basins are capable of generating significant seismic amplifications, so that an earthquake with moderate magnitude is able to produce highly destructive effects. In addition, the deep sediments of the Po Plain may have produced the larger low-frequency content in the horizontal components with respect to the average trend expected for the Italian territory (Bordoni et al. 2012).

In addition, it is interesting to note that the damage in Reggiolo was generally greater than in the surrounding municipalities located closer to the epicentre, as shown (Fig. 27) in the map of the macroseismic survey (Galli et al. 2012).

This fact is probably due to local amplification produced by the soil. A well-known fact is that the surface seismic response generally differs from the shaking in the bedrock and varies from one area to the next depending on the specific geological and morphological conditions of the soil. In addition, in the areas prone to producing local effects, the soil response to different shock levels may be different. In this regard, the current Italian Technical Norms on Constructions (NTC 2008) provide a local amplification coefficient  $S$  to take account of both the soil morphology and topographic effects.

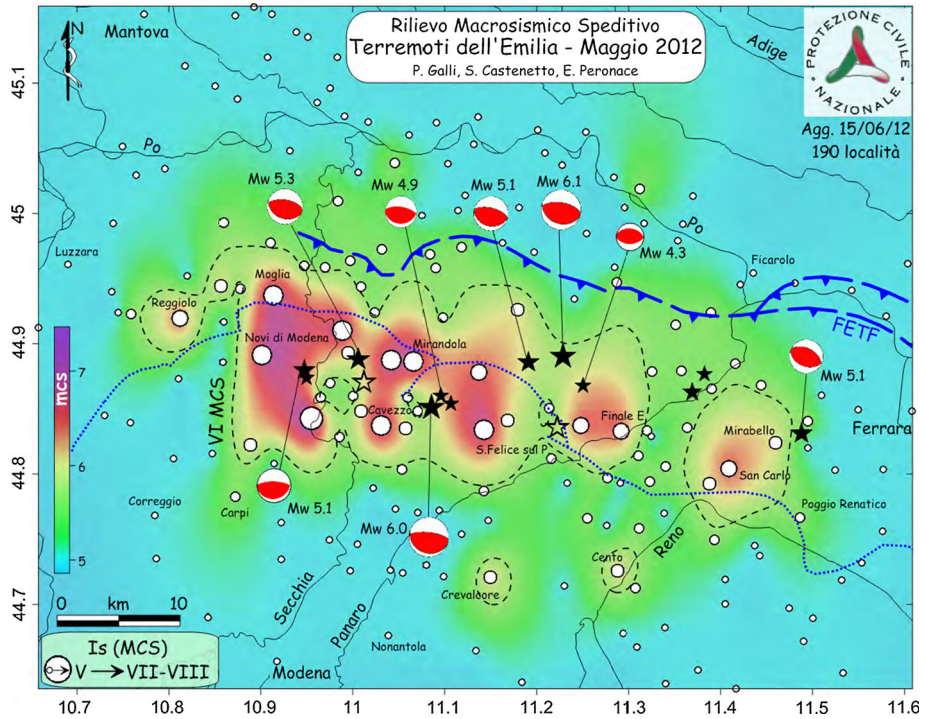


Fig. 27 Macroseismic survey map (Galli et al. 2012)

In order to assess whether the higher damage in Reggio is due to a seismic action greater than in Carpi or to the lower construction quality, it is necessary to evaluate the local peak soil acceleration. The acceleration histories are available at Carpi, but no seismic records are available in Reggio. So an attempt to obtain a rough estimation of the peak soil acceleration at Reggio was made. To this aim, two extremely simplified methods have been used. A first method, which has been proposed by Decanini et al. (1995), offers a correlation between macroseismic intensity  $I_{MCS}$  and effective peak ground accelerations PGA. It allows to infer information about the seismic shaking through data on seismic effects by using the simple relation

$$\log PGA = 0.594 + 0.197 \cdot I_{MCS} \tag{6}$$

A rough estimate of the soil acceleration could thus be deduced from expression (6) and the resulting conventional value of peak soil acceleration capable of producing VII MCS, is about 0.10 g.

Other researchers (Elenas 2000) have moreover presented a method for estimating the interrelation between seismic acceleration parameters and the structural damage. But, as stated by Masi et al. (2011), there is a poor correlation between PGA and damage level: the damage potential of ground motion is linked not only to the PGA, but also to earthquake duration, dominant frequency and seismic shaking energy.

Another method to obtain a rough approximation of the PGA can be deduced by observing the behaviour of simple structural portions of a masonry building, which can be compared to rigid blocks. As demonstrated in Andreini et al. (2012), damage mechanisms may be able to play the role of “earthquake-sensors”. The peak soil acceleration which occurred during the

earthquakes can thus be determined by analysing the damage failure mechanisms with the help of the expressions provided by the Italian Code (Circ. 617/2009). In this regard, it is possible to define three distinct limit states for a collapse mechanism: (i) the state of formation, which involves the friction law on the detachment surface, (ii) the state of activation of oscillation (damage limit state) and (iii) the state of complete overturning (collapse limit state). Because of the many uncertainties about the effectiveness of the connections and the values of the mechanical characteristics involved in the state of formation, as friction coefficient, cohesion of material and width of interlocking, the activated mechanisms are the only ones considered. The activation multiplier  $\alpha_0$  has been computed using simplified rocking block models and taking into account the stabiliser effect of the self-weight and the horizontal inertial forces. In absence of tie rods or r. c. bond beams, the value of the multiplier  $\alpha_0$  that triggers mechanism activation can be simply obtained via the following:

$$\alpha_0 = \frac{M_{RF}}{M_S}, \quad (7)$$

where  $M_{RF}$  is the stabilizing moment of the self-weight and  $M_S$  is the overturning moment due to the seismic forces.

The spectral activation acceleration  $a^*$  at the hinge of the mechanism can be calculated from the multiplier  $\alpha_0$

$$a^* = \frac{\alpha_0}{e^*} g \quad (8)$$

where  $e^*$  is the participating mass ratio, and  $g$  is the gravity acceleration.

When the hinge of the rigid block is located at height  $z$ , the value of the soil spectral acceleration  $a_{0^*}$  that is capable to activate the mechanism is generally lower than  $a^*$ . The values of  $a_{0^*}$  can be evaluated following the suggestion of current Italian NTC 2008. In particular,  $a_{0^*}$  is the minimum value between the one calculated for  $z = 0$ , and the anchorage acceleration of the spectrum having spectral ordinate  $S_e(T_1)$  equal to

$$S_e(T_1) = a^*/(z/h), \quad (9)$$

where  $h$  is the height of the building and  $T_1$  is the period of the building vibration mode involving the mechanism.

In order to deduce an estimation of the PGA which was attained during the main-shocks in Reggiolo, many out-of-plane mechanisms have been analyzed. Since not all the mechanisms showed a clear collapse behaviour from the ground level, the three most significant cases are reported. The following soil spectral acceleration that is capable to activate the mechanism has been obtained:

- *Palazzo Sartoretti*—collapse of the corner—dir. N-S -  $a_{01^*} = 0.16$  g
- the medieval *Rocca*—collapse of a free-standing wall—dir E-O— $a_{02^*} = 0.12$  g
- Retirement home *Santa Maria delle Grazie*—collapse of the façade—dir. E-O -  $a_{03^*} = 0.13$  g.

Thus it can be deduced that the value of the peak soil acceleration in the Reggiolo historic centre has probably overcome 0.16 g in the N-S direction and 0.13 g in the E-W during the main shocks on May 2012. Anyhow, this method does not take into account the contribution of the fore- and after-shocks (i. e. 20th and 29th May) to the development of the failure mechanism.

The PGA in Carpi has been recorded by the CRP station and the components are 0.17 g for the North-South direction, 0.12 g for the East-West direction and 0.085 g for the upwards

direction. In any case, the PGA measured in Carpi was sufficient to activate the mechanisms in Reggiolo.

It is worthwhile noting that the macroseismic intensity at Reggiolo (VI-VII MCS) was higher than at Carpi (V-VI MCS), in spite of Reggiolo’s greater distance from the epicentre. As it can not be incontestably demonstrated that the peak soil accelerations at Reggiolo were higher than at Carpi, it must be recognized that at Carpi, although the North-South PGA component could have been slightly higher than that estimated for Reggiolo (Table 5), the East-West component and the ratio of vertical to horizontal components may have been both lower. This may be the reason for the increased macroseismic intensity at Reggiolo.

Furthermore, in order to appreciate the amplification of the seismic shaking due to the soil effect in Reggiolo, the records of the accelerometric stations (Gorini et al. 2010) in the surrounding area have been analysed by using an appropriate attenuation law. In particular, the PGA in Reggiolo referred to the bedrock has been calculated by processing the anchor accelerations of the different response spectra previously referred to the bedrock. Successively, the amplification coefficient can be inferred by comparing the PGA on the bedrock with the peak soil acceleration deduced by the mechanism analysis.

To this aim, for every registration, the anchor acceleration of the response spectrum has been referred to the bedrock by dividing its value by the local amplification coefficient  $S$ , deduced from the Italian regulation on the base of the typology of the subsoil and the topography of the site.

The PGA values refer to the 7:00 am shock of May 29, with a magnitude of 5.8. Table 5 reports the site data from the RAN stations (Mirandola Earthquake Working Group) (NVL, MRN, MDN, CRP, MOG0), and the INGV station (MODE). An asterisk (\*) marking a soil type means that the determination was performed using Italian geological maps (Soil Type C according to the ground classification of Italian NTC 2008), so coefficient  $S$  is equal to 1.5.

From Table 5, it can be seen that throughout the area the vertical component of the ground motion is quite sizeable with respect to the horizontal. Moreover, the closer the station is to the epicentre, the greater the relative vertical component. Lastly, comparison of the North-South with the East-West component seems to suggest a possible polarisation of the ground motion.

The site acceleration on the bedrock in Reggiolo has been estimated through a weighted average of the values of the anchorage accelerations  $S_{ei}$  of the response spectra of all stations referred to the bedrock. Through the signal-distance attenuation law (Sabetta and Pugliese 1987), the soil acceleration  $a_{gi}$ , can be expressed as a function of the magnitude  $M$  (5.8 for the 07:00 UTC main shock of May 29th) and the epicentral distance  $d_{ei}$  (in km). According to the expression for the Italian area, we have

$$\log(a_{g_i}) = -1.845 + 0.363 \cdot M - \log \sqrt{d_{ei}^2 + 25} + 0.195 \cdot S_{SP} \tag{10}$$

where  $S_{SP}$  is the Sabetta and Pugliese coefficient (1 for shallow soil, 0 for deep or hard soil). The soil acceleration  $S_{eR}$  in Reggiolo referred to the bedrock has been obtained as

$$S_{eR} = \sum_{i=1}^6 S_{ei} \cdot q_i, \tag{11}$$

with

$$q_i = \frac{a_{gR}}{a_{g_i}} \cdot \frac{1}{\delta_{Ri} \cdot \sum_1^6 1/\delta_{Ri}}, \tag{12}$$

**Table 5** Site data of the stations located in the surroundings of Reggio

Station code	Latitude N	Longitude E	Site	Soil class	Topography category	Epicentral dist. (km)	Local amplif. coefficient S	Distance from Reggio (km)	PGA NS (cm/s <sup>2</sup> )	PGA EW (cm/s <sup>2</sup> )	PGA UP (cm/s <sup>2</sup> )
NVL	44.843	10.732	Novel lara	C*	TI	28	1.5	10	49	54	47
MRN	44.878	11.062	Mirandola	C*	TI	2	1.5	21	290	220	900
MDN	44.646	10.889	Modena	C*	TI	28	1.5	31	51	30	35
CRP	44.782	10.870	Carpi	C*	TI	19	1.5	16	170	120	83
MOGC	44.932	10.912	Moglia temp.	C*	TI	16	1.5	9	170	240	130
MODE	44.630	10.950	Modena	C*	TI	27	1.5	34	22	44	42



where  $a_{gi}$  is the local acceleration at station  $i$  estimated via (10),  $a_{gR}$  is the local acceleration at Reggiolo, again estimated via (10), and  $\delta_{Ri}$  is the distance of each station from Reggiolo. So, the nearer the station is, the greater is its contribution to the average.

The resulting evaluation of the anchorage acceleration in Reggiolo  $S_{eR}$  referred to the bedrock is about 0.061 g for the North-South direction, 0.063 g for the East-West direction and 0.058 g for the upwards direction.

By comparing this results with those obtained from the mechanisms analysis, it can be seen that significant amplification of the local seismic signal originated at Reggiolo, probably due to the geotechnical features of the soil: the value of the local amplification coefficient in the North-South direction may have exceeded 2.7, whereas in the East-West direction this value may have been likely greater than 2.

## 6 Final remarks and conclusions

This work reports the outcomes of inspections to damaged buildings after the 2012 Emilia earthquakes. In particular, the cities of Reggiolo and Carpi located almost equidistant from each of the epicentres have been analysed.

The damage survey provided the chances to examine the peculiarity of the different form-based methods for the evaluation of the usability and the damage index and to apply the calculation method proposed by MiBAC for the costs assessment of building repair.

The general results of post-earthquake surveys in the cities of Reggiolo Carpi in terms of features and seismic behaviour of different types of building substantially confirms the observations of other authors who have inspected different areas. In particular, the assessment carried out on modern masonry or r. c. buildings has evidenced, in the great majority of the cases, an adequate seismic performance without any significant damage in structural and non-structural elements. Furthermore, regarding the old or historic buildings, it was found the high vulnerability of both the churches and those masonry buildings which were constructed with low quality materials. An example is given by vernacular buildings and by palaces and villas made up of brickwork with poor mortar. It was also observed a satisfactory seismic behaviour of the historic buildings that were built with high quality materials and proper detailing.

A comparison between the results for the cities of Reggiolo and Carpi shows a higher percentage of completely unusable structures in Reggiolo (42 % in Reggiolo vs. 34 % in Carpi) and a higher percentage of buildings in Carpi that were accessible or repairable through emergency measures (45 % in Reggiolo vs. 53 % in Carpi). Moreover, the percentage of the bad outcomes for masonry units is higher than for r. c. structures, and the ratio between the two groups is the same for both cities.

The data obtained demonstrate the better quality of the buildings in Carpi along with the greater intensity of the seismic actions at Reggiolo due to local soil amplification effects. The issue of local amplification has been further investigated and the results indicate that, although rather high levels of local amplification occurred at both sites, such effect was particularly intense around Reggiolo, a finding further supported by soil acceleration determinations based on study of the damaged buildings.

Following the experience gained during the inspections, it must be added that the high number of applications after the seismic events, along with the number of surveys for safety inspections of production facilities in both cities highlight the responsiveness of the population and public authorities.

Regarding the historic buildings, those examined in the Carpi city centre generally exhibited an adequate structural behaviour during the main shocks, as shown by the rather modest damage indices. Although no numerical modelling under the current regulations would have endorsed the earthquake resistance of these structures, many of them behaved adequately, as most were built with high-quality materials and using good construction techniques. However, it must be observed that their vulnerability stems not from structural aspects, but from their inherent historical and artistic value, as well as their functions, especially when they harbour other highly prized artistic elements, such as paintings and other heritage items.

On the contrary, historic buildings in Reggiolo, mostly built with poor quality mortar, suffered extensive damage. In this case, repairs lead some difficulties in terms of reinforcement methods, which could be invasive and may be not conforming to conservation principles: Palazzo Sartoretti is an emblematic example and, in this sense, it is an open issue facing the structural field and the conservation.

Finally, it must be recognized that the method proposed by the MiBAC for the costs assessment of building repair and seismic reinforcement offers simple formulas that are easy to be used, but strongly underestimate the amount of restoration costs for historic constructions (halved from Carpi experience). Therefore, the coefficients of the formulas should be strongly increased through a calibration procedure based on a wide set of real cases. However, the costs assessment in the restoration is an extremely delicate operation because every case is unique and the cost of an intervention is highly dependent on many different factors, including the artistic value and the need of provisional structures, whose cost may have a significant impact.

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