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The Pianura Padana Emiliana Earthquake

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Indice

THE PIANURA PADANA EMILIANA EARTHQUAKE

Introduction

Paolo Clemente, Massimo Forni, Alessandro Martelli

On May 22nd, 2012, at 04:03 local time, an earthquake of M_L = 5.9, according to the INGV (Italian National Institute of Geophisics and Vulcanology) estimation, struck the Pianura Padana Emiliana, Italy. The hypocenter was only 6 km deep, resulting in the consequent strong effects observed on the surface. The epicenter was located at Latitude 44.89° N and Longitude 11.12° E, in a sparsely inhabited area between the towns of Mirandola, Finale Emilia, Poggio Rusco and Bondeno (Fig. 1).

The main event was preceded by a shock at 01:13 (M_L = 4.1) and followed by a number of events of magnitude > 4.0. In particular, an earthquake of M_L = 4.9 occurred just one hour after the main event, at 05:02, and another of M_L = 5.1 occurred at 15:18. The most significant events until 15:21 (Italian time) on 20/05 are listed in Table 1.

The epicenters of the various shocks stretched over an area of about 40 km in W-E direction. The strongest earthquake of the sequence was due to a phenomenon of active compression in North-South direction, related to the thrust of the northern Apennines to the North, above the Adriatic / African plate. It is a complex system of faults (Fig. 2).

In the following days, many events occurred, some of magnitude greater than 4.0 (Table 2), while an important new sequence was recorded on May 29th, when at 09:00 (Italian time) an event of M_L = 5.8 was recorded with epicenter between the towns of Medolla, Mirandola and Cavezzo. It was followed by numerous other events with a magnitude > 4.0, two of which > 5.0 (Table 3). Further events were recorded in the followings days (Table 4). It is worth reminding that another event was recorded on June 9TH with epicenter on the Venetian Prealps (Table 5). After the main event of May 20th, the number of dis-

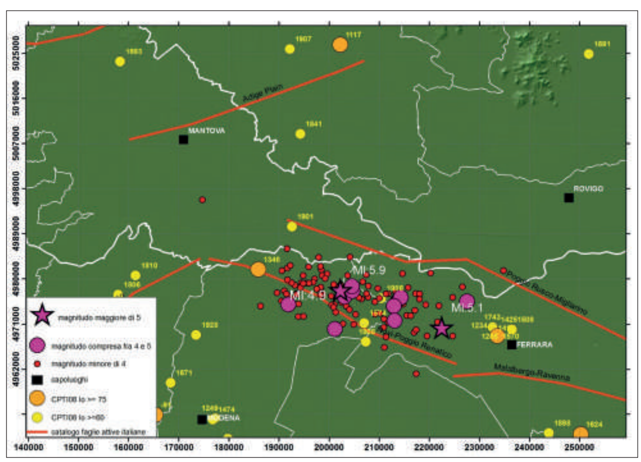

FIGURE 1 Map of the events of May 2012 and some historical seismic occurrence
Source: ENEA from INGV data

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placed persons – initially 3000 – rose gradually. The victims were 7, 4 of which were workers: one in the collapse of a factory at Bondeno, two in the collapse of three industrial buildings at Sant'Agostino, and one in the collapse of an aluminum foundry.
The final estimation of damage, after the shock of May 29th, was much heavier. In total there were 26 victims, most of them workers, and 20,000 homeless.
Immediately after the first shock, ENEA gave the national Civil Protection Service its support to perform macroseismic observations and to assess the damage to houses and industrial buildings. Moreover, ENEA

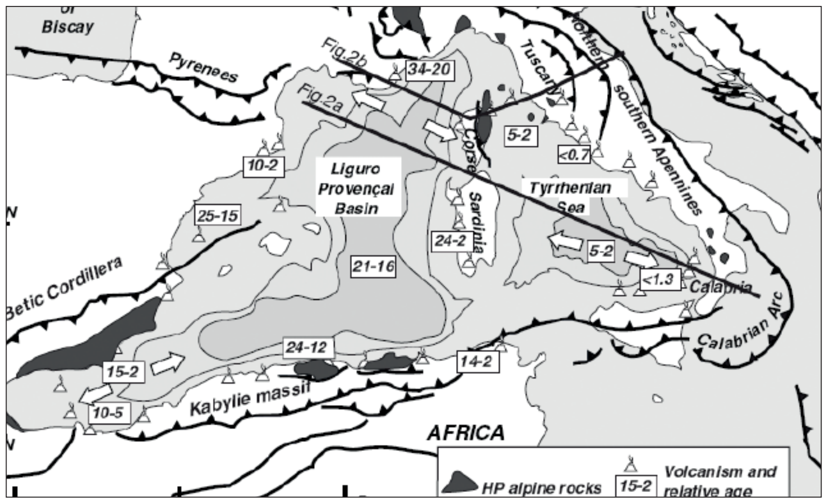

FIGURE 2
Complex system of faults
Source: courtesy by Faccenna et al.

Date	Time (UTC)	Lat	Lon	Depth (km)	M_L
2012/05/19	23:13:27	44.898	11.258	6.2	4.1
2012/05/20	02:03:52	44.89	11.23	6.3	5.9
2012/05/20	02:11:46	44.84	11.37	7.8	4.3
2012/05/20	02:12:42	44.82	11.22	20.4	4.3
2012/05/20	02:35:37	44.88	11.55	10	4.0
2012/05/20	02:39:10	44.89	11.26	5.2	4.0
2012/05/20	03:02:50	44.86	11.1	10	4.9
2012/05/20	09:13:21	44.879	11.241	3.1	4.2
2012/05/20	13:18:02	44.831	11.49	4.7	5.1
2012/05/20	13:21:06	44.882	11.383	2.4	4.1
2012/05/20	17:37:14	44.88	11.38	3.2	4.5

TABLE 1 Main events of May 20th, 2012
Source: INGV

Date	Time (UTC)	Lat	Lon	Depth (km)	M_L
2012/05/21	17:37:14	44.851	11.348	10.4	4.1
2012/05/23	21:41:18	44.868	11.251	4.8	4.3
2012/05/25	13:14:05	44.883	11.108	10	4.0
2012/05/27	18:18:45	44.882	11.158	4.7	4.0

TABLE 2 Main events between May 21st and 27th, 2012
Source: INGV

Date	Time (UTC)	Lat	Lon	Depth (km)	M_L
2012/05/29	07:00:03	44.851	11.086	10.2	5.8
2012/05/29	07:07:21	44.854	10.992	10	4.0
2012/05/29	07:09:54	44.926	11.036	10.4	4.1
2012/05/29	08:25:51	44.901	10.943	3.2	4.5
2012/05/29	08:27:23	44.854	11.106	10	4.7
2012/05/29	08:40:58	44.892	10.962	5.3	4.2
2012/05/29	09:30:21	44.892	11.053	1.2	4.2
2012/05/29	10:55:57	44.888	11.008	6.8	5.3
2012/05/29	11:00:02	44.873	10.95	11	5.1
2012/05/29	11:07:05	44.876	11.076	15	4.0

TABLE 3 Main events of May 29th, 2012
Source: INGV

Date	Time (UTC)	Lat	Lon	Depth (km)	M_L
2012/05/31	14:58:21	44.88	10.867	5.8	4.0
2012/06/03	19:20:43	44.9	10.940	9.2	5.1
2012/06/06	04:08:31	44.434	12.354	25.6	4.5
2012/06/12	01:48:36	44.88	10.888	10.8	4.3

TABLE 4 Main events after May 29th, 2012
Source: INGV

Date	Time (UTC)	Lat	Lon	Depth (km)	M_L
2012/06/09	02:04:56	46.209	12.444	7.1	4.5

TABLE 5 Characteristics of the event of June 9th, 2012
Source: *INGV*

also provided the Emilia-Romagna's General Directorate for the Promotion of Cultural Heritage with the assessment of the damage to churches and other historical buildings. The Civil Protection responded positively and assigned ENEA the task of performing safety controls on civil buildings, which was, of course, most urgent. Three teams of ENEA technicians began the on-site surveys in Cento, Bondeno, Finale Emilia on May 25th and, after the second shock of May 29th, in Novi di Modena, Carpi, Rovereto and Molinella. The activities, carried out on over 100 structures, were concluded at the beginning of July. In most cases, the activities were not limited to safety controls only: as a matter of fact, ENEA technicians participated actively in the design of the most urgent interventions to secure crumbling buildings. They also performed geological campaigns in the area affected by soil liquefaction. Finally, interventions on the cultural heritage started at the beginning of September and are still in progress; they include important structures like the very famous Ghirlandina Tower and the Cathedral in Modena.

The Pianura Padana Emiliana earthquake was characterized by the phenomenon of soil liquefaction and the heavy damage to cultural heritage structures (churches, castles, historical buildings) and to industrial buildings, pointing out the importance of seismic preservation of such structures. All these issues are discussed in the papers of this Focus, in which the main results of the activities carried out immediately after the quakes are reported. The analysis of the data are still in progress and will be presented in the next future. We thank all the authors, ENEA's researchers and others, that contributed to realize this volume in a short time.

THE PIANURA PADANA EMILIANA EARTHQUAKE

The main characteristics of May 2012 seismic sequence have been analyzed. The comparison of data from macroseismic surveys and historical information on the main events that struck the area in the past has shown that the present sequence was the most violent in the last 500 years, highlighting the possible criticality in this sector of the Italian territory seismic hazard assessment. Finally, the analysis of some accelerometric recordings has revealed that the response spectra close to the epicenter exceed technical code design provisions, while heavy damage is also present where response spectra are far lower than code provisions; some considerable damage to both civil and industrial buildings can be explained by the ground motion characteristics

The May 2012 seismic sequence in Pianura Padana Emiliana: hazard, historical seismicity and preliminary analysis of accelerometric records

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The seismic sequence started on May 20th, 2012, 02:03:52 UTC with the main shock (M_L=5.9, 44.889N 11.228E, depth 6.3 km), close to Mirandola (Figs. 1a and 1b), without any seismic activity in the area in the previous months, except three events the day before (M_L=2.5, 4.1 and 2.2, respectively). In Fig. 1a, the historical earthquake and the known active faults are also represented. The activity that followed had a major aftershock, on may 29th, 2012, at 07:00:03 UTC (M_L=5.8, 544.851N and 11.086E, depth 10.2 km). Source mechanisms are presented in Fig. 2. Note that M=M_W in this figure and the values are different from the previous ones.

Coseismic deformation has been evaluated through the satellite-based SAR (Syntetic Aperture Radar), that gives the interferometric representation of the differential motion between May 12th and June 5th, shown in Fig. 3.

By the shape of the interferogram it is possible to estimate that two almost parallel faults have been activated. Separated analyses of the two main events gave about 15 cm uplift for the first one, and 12 cm for the second one, respectively.

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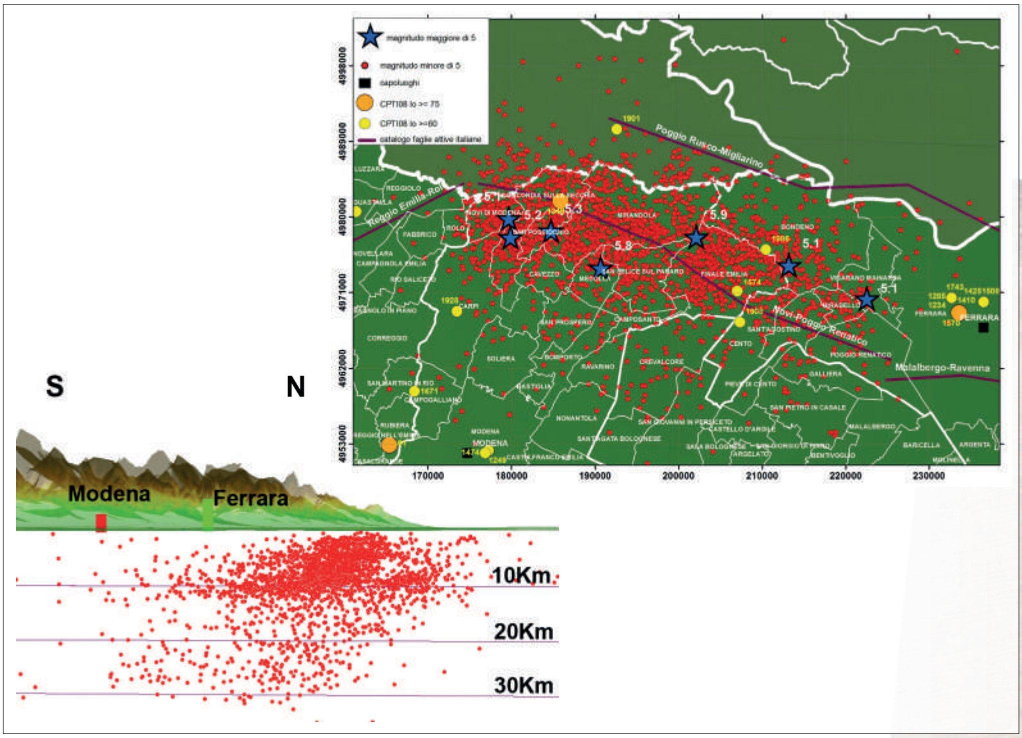

FIGURE 1 (a) The seismic sequence epicenters (up to 09/15/2012) and (b) NS section
Source: ENEA elaboration of INGV data

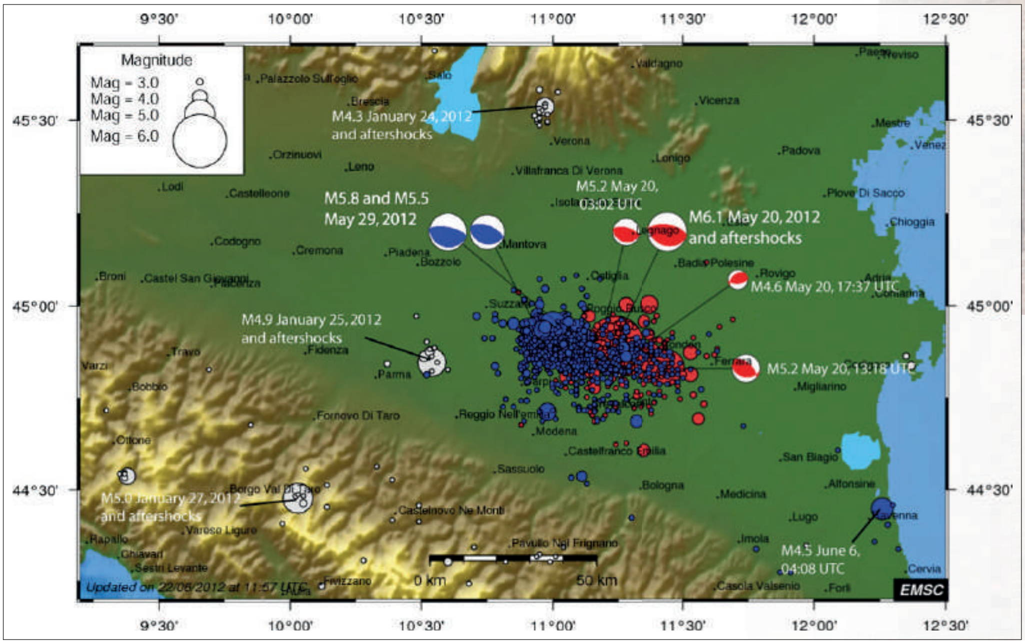

FIGURE 2 Source mechanism (blue after May 29th)
Source: ENEA elaboration of EMSC data

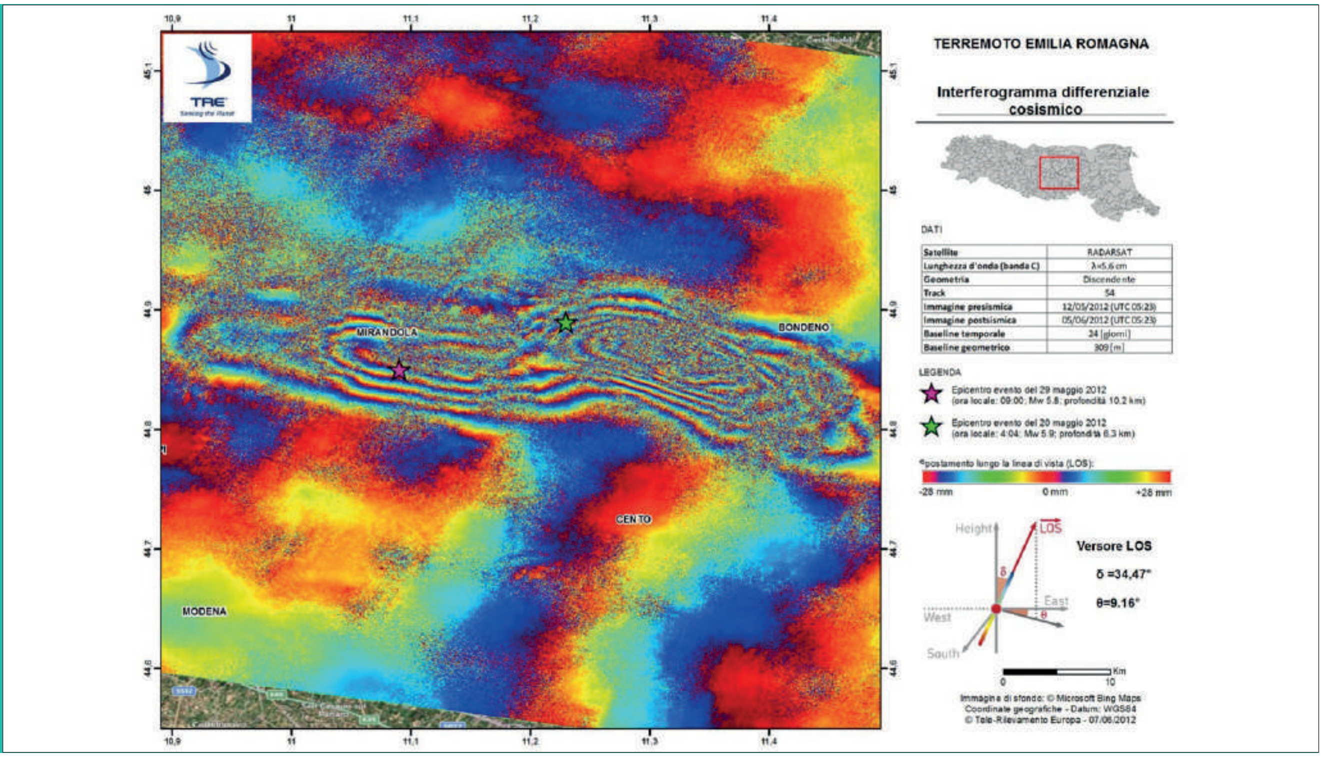

FIGURE 3 Interferogram 05/12/2012-06/05/2012
Source: GEO

Tectonic settings and earthquakes

Most seismic activity in central Mediterranean area is attributed to the Adriatic plate that is part of the African plate, as depicted in Fig. 4, moving towards N. Actually there are quite different points of view. With reference to Fig. 5 we report some of the main conclusions by Cuffaro et al. (2010): "*The northern Adriatic plate boundaries are deformed by the three belts, i.e., Apennines, Alps, and Dinarides. ... Northeast Italy is usually interpreted as an area affected by N–S compression due to the African-Adriatic indenter. However, this comes from a misleading kinematic approach, where local stress field is assumed to be an indicator of plate motion. The stress field rotates along oblique plate margins, and the WNW-ward motion of the Adriatic plate relative to Europe can generate right-lateral transpression and consequent NW–SE to N–S compres-*

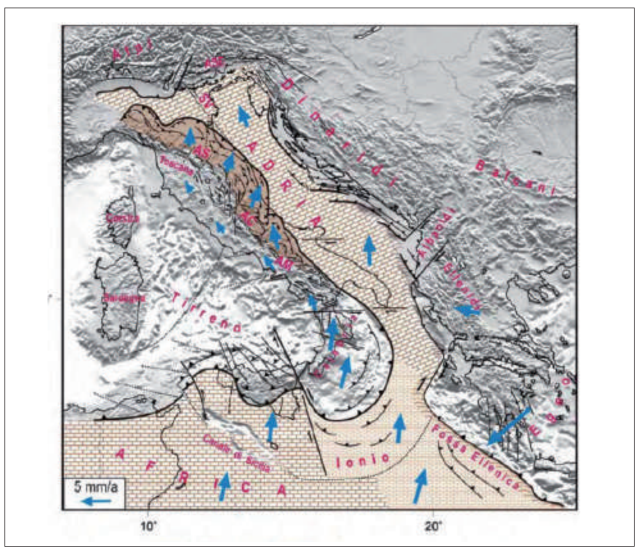

FIGURE 4 Sketch of general tectonic setting
Source: EERI

sion along the central-eastern Alps. ... Apart from local regional details, the main conclusions based on seismic reflection profiles and space geodesy data are that the three belts around the northern Adriatic plate are still converging and seismically active ...".

In the same figure, the Ferrara salient is the area of the Emilia earthquakes. In Cuffaro et al. (2010) Fig. 6 is also reported, and the following sentence expresses the possibility of earthquake in the area where they happened: "*The areas where the strain rate sharply decreases along a tectonic feature (e.g., the Ferrara salient, the Venetian foothills front) are proposed to be occupied by locked structures where stress is accumulating in the brittle layer and thus seismically prone*".

Seismic hazard

In Italy, since the beginning of '900, the seismic hazard has followed the main seismic events through a

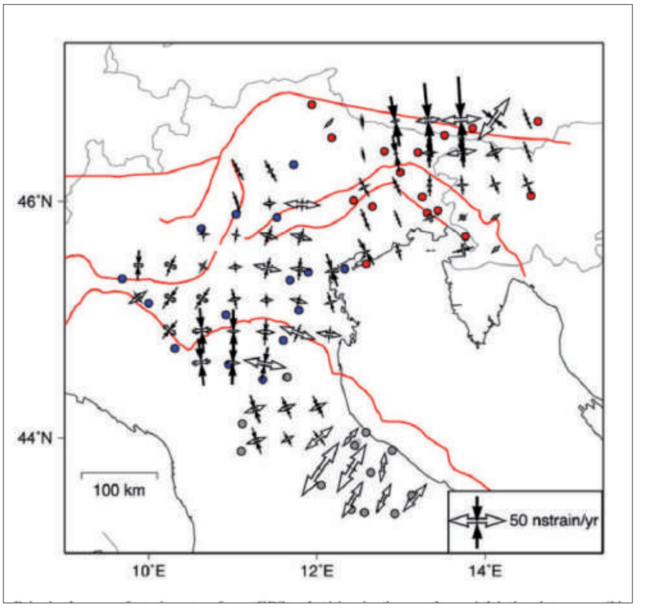

FIGURE 6 Strain rates in the northern Adriatic plate
Source: Cuffaro et al., 2010

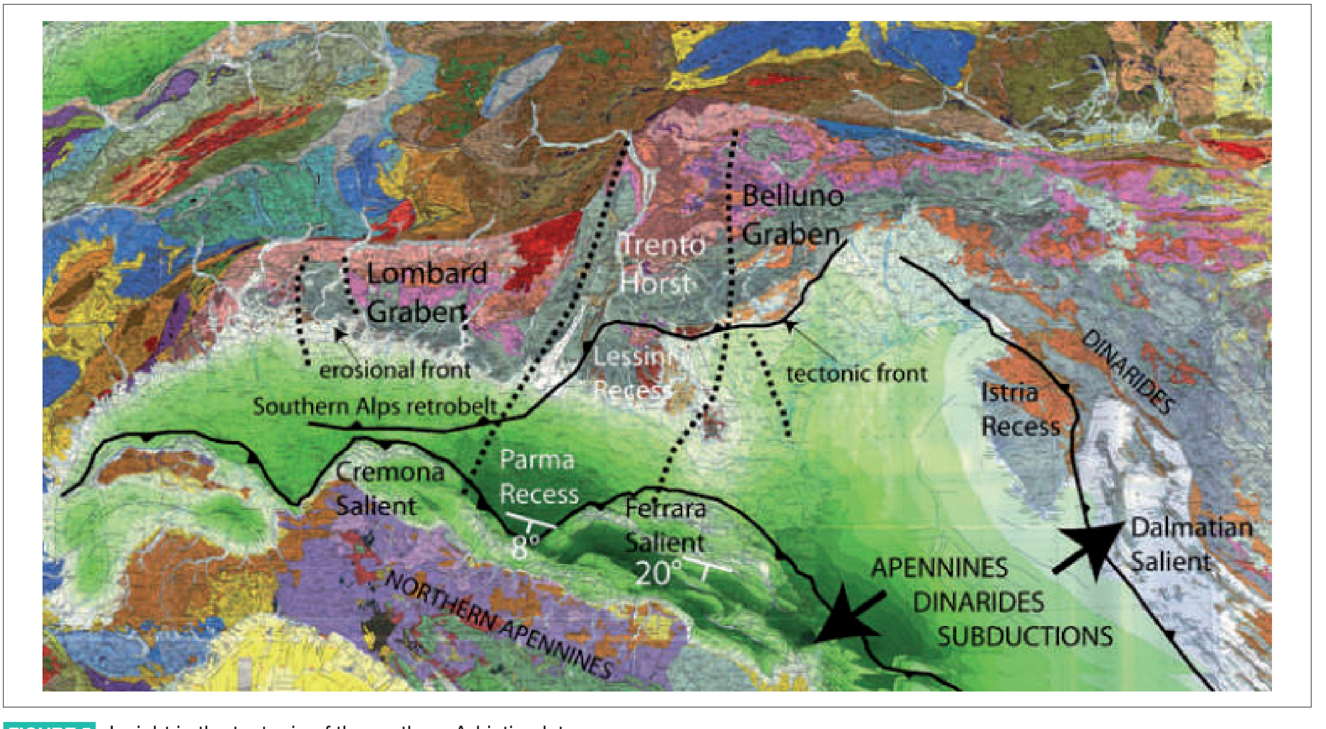

FIGURE 5 Insight in the tectonic of the northern Adriatic plate
Source: Cuffaro et al., 2010

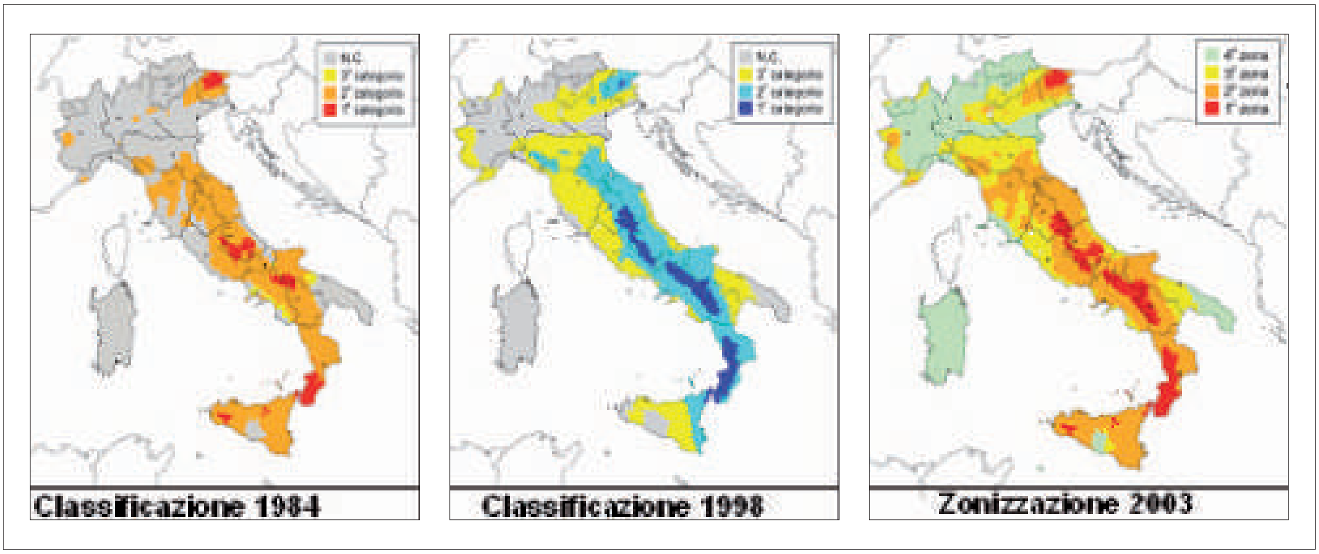

FIGURE 7 Evolution of seismic classification
Source: INGV

"classification" by seismic zones, for which the seismic codes have provided the rules for new constructions. In Fig. 7, the evolution in the last decades is summarized.
All the structures built until the end of last century appear to have no seismic provision.
After the 2003 zoning, the building code (NTC2008) has provided the basis for new buildings as a design spectrum base shape, to be scaled according to the expected PGA, the local soil condition and the structural type. The expected PGAs for the examined area are shown in Fig. 8.

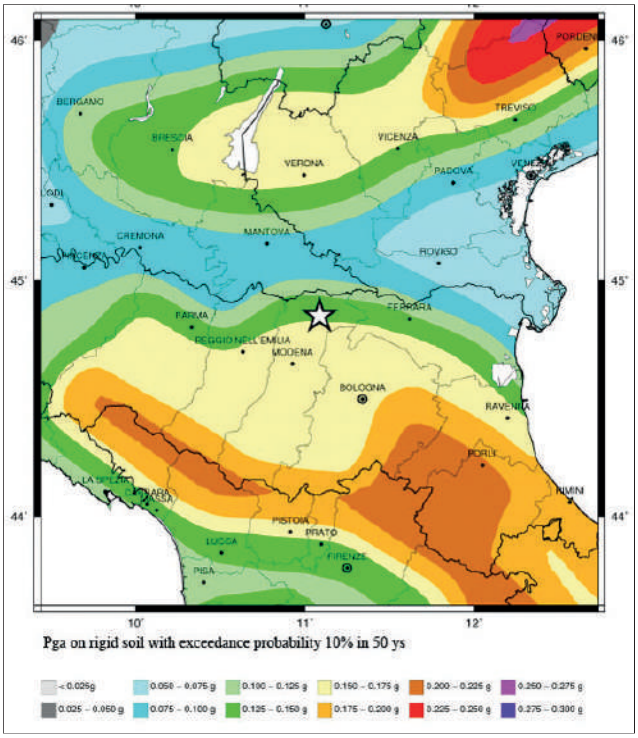

FIGURE 8 Design basis PGAs
Source: INGV

Historical vs. today's seismicity

The May 20th 2012 earthquake (5.9 M_L) struck the towns of Finale Emilia, San Felice sul Panaro and Sant'Agostino, involving a wide, adjacent area.
This event was followed by a series of significant aftershocks, such as the May 29th (5.8 M_L) event in the surroundings of Novi di Modena, which caused even more severe and extensive damage on a larger area.

The seismic sequence occurred on an area traditionally considered as characterized by low seismicity, where the population is – or rather, was – not very accustomed to earthquakes and where, unfortunately, the anti-seismic techniques were applied to a marginal portion of the housing. In fact, the area was included in the low seismic level category only in 2003 (OPCM 3274/03), but only in 2005 designing with anti-seismic techniques became mandatory.
In the past, the area between Ferrara and Novi di Modena had already been affected by seismic events. Some of these were destructive, such as the 1570 earthquake, while others, though causing less damage, aroused deep feeling in the population; in both cases the events left their traces in the chronicles of the time.
In the days immediately following the Emilia earthquake, the group Quest (Quick Earthquake Survey Team) of the National Institute of Geophysics and Volcanology (INGV) visited some of the affected areas and produced a report of damage and environmental effects caused by the earthquake (Arcoraci et al., 2012a-b). Contemporarily, the Italian Department of Civil Protection performed a macroseismic survey of the area (Galli et al., 2012).
In the present work, analysing the damage described in the Quest report, it is possible to obtain a comparison with the damage occurred during two historical earthquakes, namely November 17th, 1570, and October 22nd, 1796, in selected localities.

The 1570 earthquake

"Tutta questa notte s'è stato vegghiando ed aspettando nuovi terremoti, sì come hanno seguitato sempre, sebben più deboli e seguitano tuttavia" ("This whole night was spent watching and waiting for new earthquakes, just as they have always continued, albeit weaker and still they continue", Passeri, 1570).
All contemporary accounts agree in remembering how the day before the destructive shock was marked by a long series of shocks. The main shock, at 3 a.m., shook buildings already weakened partly.
Pirro Ligorio, who at that time lived in Ferrara as court antiquarian under duke Alfonso II d'Este, in his book *Libro di diversi terremoti* describes the early phase of the seismic sequence (Ligorio, 1570). According to him, the buildings' vulnerability was also affected by the damage caused by a previous earthquake occurred on November 24, 1561. In this regard, he stresses that several buildings, as the Castle Estense, do suffer heavy damage to those structures that had not been correctly repaired.
The greatest damage occurred mainly in Ferrara: the Castle, the Cathedral and some great palaces (e.g., Tassoni, Paradiso and Este palaces) were severely damaged as well as the monasteries. Essentially all buildings, public and private, suffered damage and needed shoring. The damaged area was in a radius of 15-20 km.
The replicas were numerous. Baratta (1901), citing sources, reported that the replicas lasted nine months and for some authors, according to others, until February 1574.
The affected area, according to historical sources was very extensive. North up to Milan, East up to Venice and South down to Pesaro. The historical sources of the same period also report the phenomenon of soil liquefaction in Ferrara and nearby towns.
Regarding the soil liquefaction, the description reported in Ligorio (1570) is very interesting. It refers to Ficarolo (RO), where the successive quake on November 24th caused 11 victims in the collapse of a building: "*…filled some wells with sand, so that putrid water came out of the ground*" and again on December 1st in Ficarolo, where "*… ruined some ploughed fields, and dried some wells by directing all water out; where stagnating water was reclaimed by man, the soil cracked and sand leaked out of it*". Be noted that the descriptions match up perfectly with the observations that the evidence gathered in this earthquake (including the smelly water leaking from the ground). Last but not least, in spite the above detailed descriptions, the seismic history of Ficarolo reported in DBMI11 (Table 1) does not include the earthquake of 1570.
A phenomenon that, as shown by the engraving in Fig. 9, has characterized the recent earthquake. Table 1 shows the places mainly affected by the earthquake of 1570.

Fc

Locality	MCS
Ferrara	VIII
Cona (FE)	VII-VIII
Gaibanella (FE)	VII-VIII
Gambulaga (FE)	VII-VIII
Castelmassa (RO)	VII-VIII
S. Maria Codifiume (FE)	VII-VIII
Bondeno (FE)	VII
Casaglia (FE)	VII
Cassana (FE)	VII
Gurzone (RO)	VII
Masi Torello (FE)	VII
Occhiobello (RO)	VII
Runco (FE)	VII
San Nicolò (FE)	VII
Aguscello (FE)	VI-VII
Baura (FE)	VI-VII
Canaro (RO)	VI-VII
Corpo Reno (FE)	VI-VII
Fiesso Umbertiano (RO)	VI-VII
Focomorto (FE)	VI-VII
Formignana (FE)	VI-VII
Fossalta (FE)	VI-VII
Melara (RO)	VI-VII
Quartiere (FE)	VI-VII
Sabbioncello San Vittore (FE)	VI-VII
Tresigallo (FE)	VI-VII
Vigarano Pieve (FE)	VI-VII
Voghenza (FE)	VI-VII
Voghiera (FE)	VI-VII
Calto (RO)	VI
Cento (FE)	VI
Finale Emilia (MO)	VI
Francolino (FE)	VI
Papozze (RO)	VI
Ravalle (FE)	VI
Viconovo (FE)	VI
San Giovanni in Persiceto (BO)	Felt
Sermide (MN)	NC

TABLE 1 Places mainly affected by the earthquake of 1570
Source: INGV

For some of these places (in particular Bondeno, Cento, Finale Emilia, San Giovanni in Persiceto and Sermide) a comparison between the damage suffered in 1570 and the present one is possible, as reported in the Report of the Quest (INGV) after the first shock of May 20th.

Bondeno needs some clarifications. The damage assessment (VII MCS) is based essentially on a letter reporting indirect information. Based on this information Bondeno and Finale Emilia were severely damaged. Finale Emilia, according to an eyewitness, suffered limited damage (see below), then it is likely that damage level in Bondeno may have been overestimated: *"The damage [Ferrara] is such that it cannot be estimated, but we fear the worst, because should another [earthquake] occur like that of last night, it would certainly cause all Ferrara to go to the ground, just as it seemingly happened in Finale [Emilia] and Bondeno*" (Passeri, 1570).

In a letter sent on November 22nd, 1570, from Finale Emilia to the Duke's Secretary, the limited damage suffered by the town is reported. "*Then Friday... while writing in my study, there occurred a great earthquake, which lasted the space of half a miserere* [few seconds], *continuous and impetuous, some chimneys were ruined, but despite the great noise it did not cause much damage, whereas in other occurrences I knew of minor earthquakes which caused much more damage, but in other places...*" (Bartolaio, 1570).

A similar situation was in Cento, with light damage: "*At eight o'clock there was an earthquake, not so great, with not any damage, and the following night at midnight another furious and noisy earthquake; on the same night at three o'clock a weaker earthquake, four chimneys fell down and no more damage ... but* [in the earthquake] *not anyone did get hurt here in Cento*" (Filippi, 1570).

For Sermide and San Giovanni in Persiceto, the quake was felt and is remembered laconically in chronicles. For the same locations the Quest reports the following damage descriptions.

Bondeno (FE) (Arcoraci L. et al 2012a)

General characteristics: it woke and scared everyone, with strong vibration and drop of small orna-

FIGURE 9 Soil liquefaction near Bondeno
Source: ENEA

FIGURE 10 Bondeno: damage of grade 2-3 (EMS98 classification)
Source: ENEA

ments; oscillation of liquids; the clock in the square at the earthquake time has stopped.
Damage to civil structures: the main damage is the breakage or falling of chimneys; sporadic minor damage (cracks spread) to buildings of type B (brick building, with possible presence of curbs, with a sufficient degree of maintenance); some crumbling brick buildings, unreinforced buildings suffered moderate damage. Damage to monuments and special buildings: moderate damage to churches, with fallen friezes and cracks in the facade; collapse of the portico of the cemetery; collapse of industrial buildings.

Cento (FE) (Arcoraci L. et al 2012a)
General characteristics felt by the whole population. Damage to civil structures: few buildings of type A (brick or stone buildings, not reinforced, pushing roof structure, wooden beams, low maintenance, no chains nor presence of curbs) and B have suffered minor damage to the plaster.
Damage to monuments and special buildings: collapse of the spire of the steeple of the church of S. Lorenzo.

Finale Emilia (FE) (Arcoraci L. et al 2012a)
General characteristics: no information. Damage to civil structures: isolated buildings of type A (brick or horizontal elements without constraints, with pushing roofs) partially or entirely collapsed.
Many evidences of type 1 and 2 damage (light lesions, many cracks, falling plaster) in buildings of Type B; large fall of chimneys and tiles. Some serious damage to buildings of type B and C (buildings with curbs and / or reinforcement, reinforced concrete floors, concrete buildings).
Minor and no structural isolated damage to concrete buildings. Damage to monuments and special buildings: serious damage to historic buildings, with collapse and destruction.

San Giovanni in Persiceto (BO) (Arcoraci L. et al 2012a)
General characteristics: felt by the whole population, who fled outdoors, sporadic falling of light objects. Damage to civil structures: most buildings are of type B masonry, very little damage of grade 1 (capillary cracks). In the surrounding area, largely composed of reinforced concrete buildings, no damage was detected. Damage to monuments and special buildings: church, fall of a statue.

Sermide (MN) (Arcoraci L. et al 2012a)
General characteristics: felt by the whole population. Damage to civil structures: rare fall of chimneys. Damage to monuments and special buildings: no evidence of damage to churches.

The 1796 earthquake

*"Alle ore poi quattro, e tre quarti dopo la mezzanotte secondo l'orologio francese si è sentita una terribile scossa di terremoto, anzi due una più forte dell'altra, che a mio giudizio dev'essere durata due o più minuti secondi, no avendo in vita mia che è di 44 anni sentito l'eguale" (*At 4.45 A.M., French time, a terrible earthquake was felt, or rather two shocks, one stronger than the other, which I believe to have lasted two or more minutes, since in my whole 44-year life I never felt any suchlike. *Lami, XVIII Century*).

The event, which took place on October 22nd, a few months after the French occupation, was preceded by a low intensity shock, but without any damage that might have put people on alert.

The quake was felt North to Brescia, South and West to Senigallia and Lucca, respectively. The area most affected by the damage was quite extensive. Ferrara, Portonovo Medicina suffered damage, but also Bologna and Vicenza did (Table 2). Minor damage in other places.

The descriptions of the damage in San Felice sul Panaro and Mirandola were very interesting.

Francesco Lami, the author mentioned above, witnessed the earthquake effects in San Felice sul Panaro. He only reported the downfall of many chimneys: "*I was shocked and panicked, in the dark noise and swaying of the house, the motion was from west to east. Many house chimneys fell*" (*Lami, XVIII Century*).

Locality	MCS
Portonovo	VII
Ferrara	VII
Medicina	VII
Bologna	VI-VII
Vicenza	VI-VII
San Felice sul Panaro	VI
Ravenna	VI
Mirandola	VI
Mantova	VI
Imola	VI
Forlì	VI
Correggio	VI

TABLE 2 Locations with levels of damage up to VI (MCS), 1796 earthquake
Source: INGV

FIGURE 11 The damaged fortress of San Felice sul Panaro
Source: ENEA

At Mirandola, we know from a contemporary chronicle that the quake was very strong but the damage was limited: "*The morning of 22nd (October, 1796) at quarter to five a strong earthquake caused the falling of 24 chimneys and damaged a little part of a face [of a statue] of the church of S. Francesco. For this misfortune after lunch a Triduum was organized.*" (*Anonymous, XIX Century*)

For San Felice sul Panaro and Mirandola, in the recent earthquake, Quest team observed the following damage.

San Felice sul Panaro (MO) (Arcoraci et al. 2012a)

General characteristics: felt by the whole scared population, fled outside. Damage to civil structures: the earthquake has heavily damaged the historic downtown, very small if compared to the extension of the country; entire and partial collapse of some old houses already in poor status; widespread damage of grade 3 (moderate structural damage or major damage in the structural parts of the building) in buildings of Type A and B, with the fall of ledges, slip tiles, large and deep

cracks; observed fall of chimneys; a dozen buildings have minor damage (grade 2, diffuse cracks); concrete buildings do not show significant findings.
Damage to monuments and special buildings: entire or partial collapses in most of the monumental buildings such as churches, the castle, the theatre, the towers; the overpass of the highway was displaced by 20 cm, approximately; several concrete industrial buildings, located on the outskirts, have suffered collapses; almost all the abandoned houses in the surrounding countryside have partially or entirely collapsed.

Mirandola (MO) (Arcoraci L. et al 2012a)
Resentment: the quake was felt by the whole population with fear; diffuse loss of objects (paintings, bottles, computers, printers, and so on); also on the lower floors and in shops. Damage to civil structures: the historic downtown is the most corrupt, many buildings are affected by light to moderate damage, ranging from cracks in large and deep capillary lesions mainly on buildings of type B; widespread loss of chimneys and cornices; occasionally there has been more severe damage such as partial collapses; these little damage outside the historic downtown, especially the fall of chimneys in buildings of Type C (both brick and concrete buildings); isolated cases of damage of grade 3 (deep lesions in the outbreak of the cladding and covering iron) in recent constructed buildings. Damage to monuments and special buildings: widespread damage and severe partial collapses to monumental buildings (cathedral, churches, towers, historical buildings); in some cases, the collapse of industrial buildings in the periphery of the city was observed; in suburbs and surrounding countryside, frequent partial collapses of buildings and entirely collapsed rural buildings (farmhouses and barns) have been observed.

Considerations

It is now possible to draw some general considerations for the above mentioned localities. As regards the towns of Cento (FE), Finale Emilia (FE), Mirandola (MO) and San Felice sul Panaro (MO), the effects of 2012 earthquakes matched or exceeded the maximum levels of damage caused by historical seismic events (Table 3).
This statement is clearer when comparing the descriptions of the recent damage on historical centers and monuments, which have (and in some cases had) structural characteristics close to those in use in 1796 or 1570, although restored and consolidated over the centuries. Regarding Bondeno, for which some remarks about the VII MCS assigned to this location due to the 1570 earthquake were previously made, the level of damage after the May 20 event is likely to

a)
b)


FIGURE 12 Mirandola. Damage in the historical downtown
Source: ENEA

be similar with its all-time maximum. In San Giovanni in Persiceto and Sermide, at least in the shock of May 20 did not exceed their maximum level of damage.

Other general considerations can be done for the industrial structures and isolated rural buildings. Both these typologies were in large numbers destroyed, entirely or in part, on the occasion of the recent earthquakes.

Although they were included in the analysis of the damage caused by the 2012 earthquakes, as stated by the authors of macroseismic surveys (Arcoraci et al, 2012a-b; Galli et al, 2012), it must be highlighted that the probable structural deficiencies in the case of industrial structures, and the poor state of maintenance for rural buildings increased their level of damage.

Moreover, it must be emphasized that a great number of residential masonry buildings, also in the case of recent constructions, suffered damage of grade 3 and 4 (in some cases up to grade 5). The class of vulnerability of such buildings should be assessed considering the degree of connection of the various structural elements (Section 2.2.2.6 EMS98 and DM 1987/11/20), so as to assign a reliable macroseismic intensity. This important aspect of seismological analysis should be enhanced by further specific studies.

Finally, the role played by the local geological features in the distribution of the level of damage must be stressed. For example, in localities like San Carlo, Sant'Agostino and Mirabello, significant effects on territory and buildings, related to liquefaction phenomena and surface fracture, have been observed (see another paper on this issue). In addition, the level of ground motion measured locally has highlighted the appearance of local seismic amplification phenomena (see below).

Some relevant aspects of the accelerograms' records

The two main events, May 20th (A, M_L=5.9) and May 29th (B, M_L=5.8), have been recorded by 139 and 145 accelerometric stations, respectively (Mirandola Earthquake Working Group (2012). In this analysis we consider two records, Mirandola and Modena; in Table 4, the epicentral distance and the soil clas-

Locality	Maximum damage level reached (1)	Earthquakes (1)	Iloc May 20, 2012	Emilia (cumulative)
Mirandola	VI MCS	Oct. 22, 1796 June 7, 1891 Oct. 27, 1914 July 15, 1971 May 2, 1987	VI-VII EMS (2) VII MCS (3)	VII-VIII EMS (2) VII MCS (3)
Finale Emilia	VII MCS	March 17, 1574	VII EMS (2) VI-VII MCS (3)	VII EMS (2) VI-VII MCS (3)
San Felice sul Panaro	VI MCS	Oct. 22, 1796 May 2, 1987 May 8, 1987	VII EMS (2) VII MCS (3)	VII EMS (2) VII MCS (3)
Bondeno	VII MCS	Nov. 17, 1570	VI EMS (2) V-VI MCS (3)	VI EMS (2) VI MCS (3)
Cento	VI MCS	Nov. 17, 1570 Jan. 13, 1909 Oct. 27, 1914	V EMS (2)	VI EMS (2) VI MCS (3)
San Giovanni in Persiceto	VI-VII MCS	Jan. 3, 1505	V EMS (2)	V EMS (2) V MCS (3)
Sermide	V-VI MCS	Jan. 13, 1909	V EMS (2)	V EMS (2) V MCS (3)

TABLE 3 *Sources: (1) = DBMI 11 (2) = Arcoraci et al, 2012b (3) = Galli et al, 2012*

Station	Epicentral Distance (km)	Soil Type (NTC2008)
Mirandola (A)	13	C
Modena(A)	38	C
Mirandola (B)	4	C
Modena (B)	27	C

TABLE 4 Selected records

sification are presented according to the Technical Code. Both sites are classified as C (deep deposits of dense or medium-dense sand, gravel or stiff clay, with thickness from several tens to many hundreds of m, Vs30=180–360 m/s), according to geological data, as regards Mirandola, and in situ measurements, as to Modena. In Fig. 13, the geological cross section for Mirandola station is shown. The geological cross section for Modena station and the experimental station VS profile are shown in Figg. 14 and 15, respectively. Time histories and FFT (Figg. 16 and 17) exhibit the following feature:

1) Higher duration for Modena, higher epicentral distance. Duration is not taken into account in the code for standard design.
2) Low frequency content, < 1 Hz, is apparent for both sites, as expected for the local soil condition. This fact, associated to high acceleration, will be discussed with the exam of the response spectra for Mirandola.
3) High frequency content, > 10 Hz, is mainly present for UP component in Mirandola, as result of the epicentral distance and of the deep soil characteristics; this fact could have played a relevant role in the damaging effects on old masonry.

A comparison of the response spectra of the Mirandola station (A) with the provisions of the technical code (NTC 2008), Fig. 18, shows that even for the SLC (Collapse prevention Limit State) the Spectral Accelerations (SA) and the Spectral Displacements (SD) of the record are higher than the code provision.
All the other records do not show the same feature; PGAs other than Mirandola are lower than .05 g for event (A) and the same happens for event (B) except for two stations at 16 km, PGA=240 cm/s^2. and at 26 km, PGA=130 cm/s^2; however, it is worth underlining that event (B) gave 900 cm/s/s at Mirandola, UP component, and 79 cm/s^2 at Sant'Agostino station, 4 km epicentral distance, where soil liquefaction phenomena occurred.

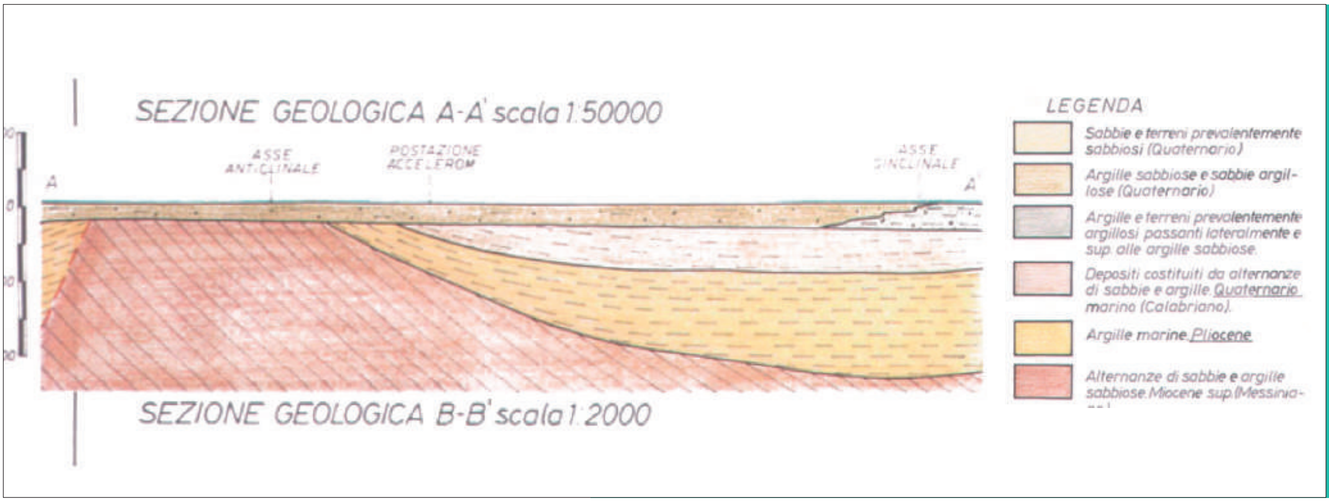

FIGURE 13 Mirandola station geological cross section
Source: INGV

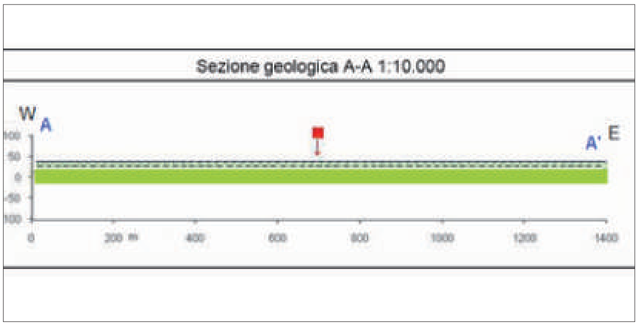

FIGURE 14 Mirandola station geological cross section
Source: INGV

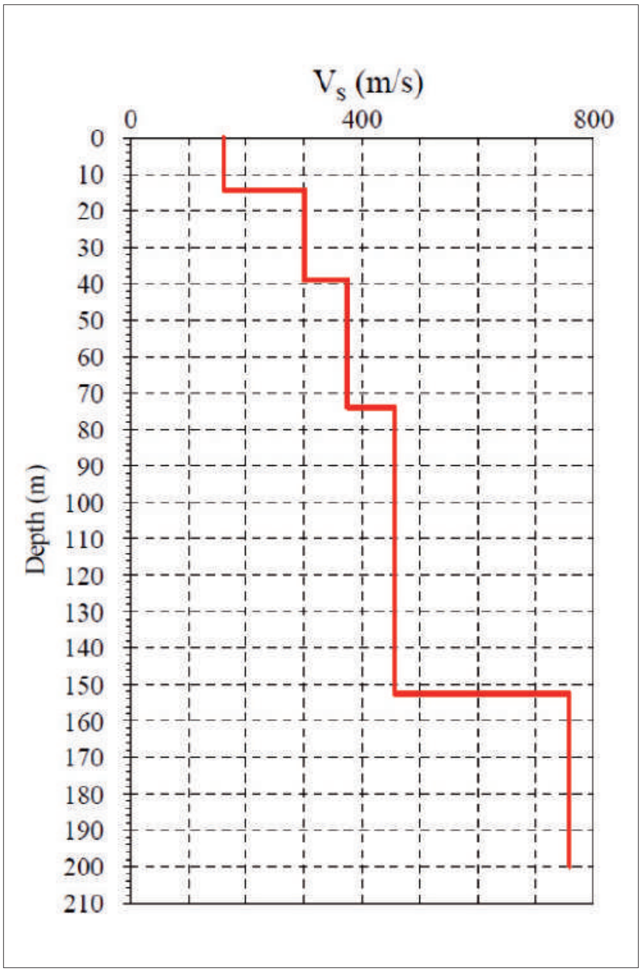

FIGURE 15 Mirandola Station VS Profile
Source: INGV

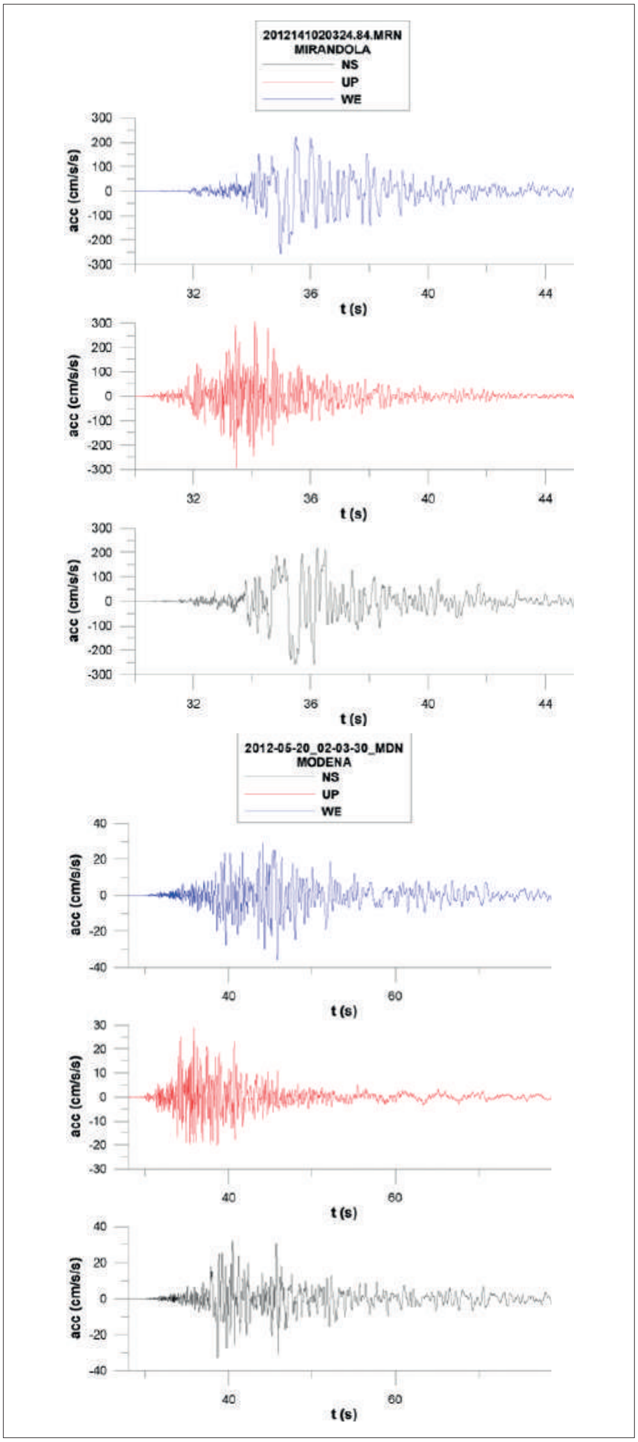

FIGURE 16 Mirandola (A) and Modena (A) uncorrected records

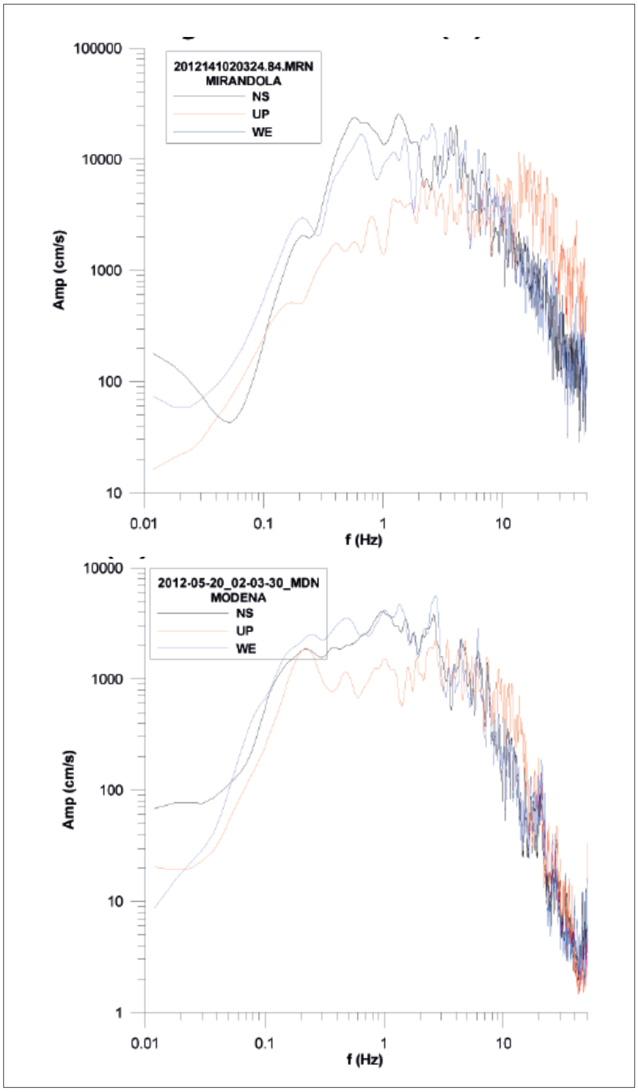

FIGURE 17 Mirandola (A) and Modena (A) Fourier spectra of uncorrected records

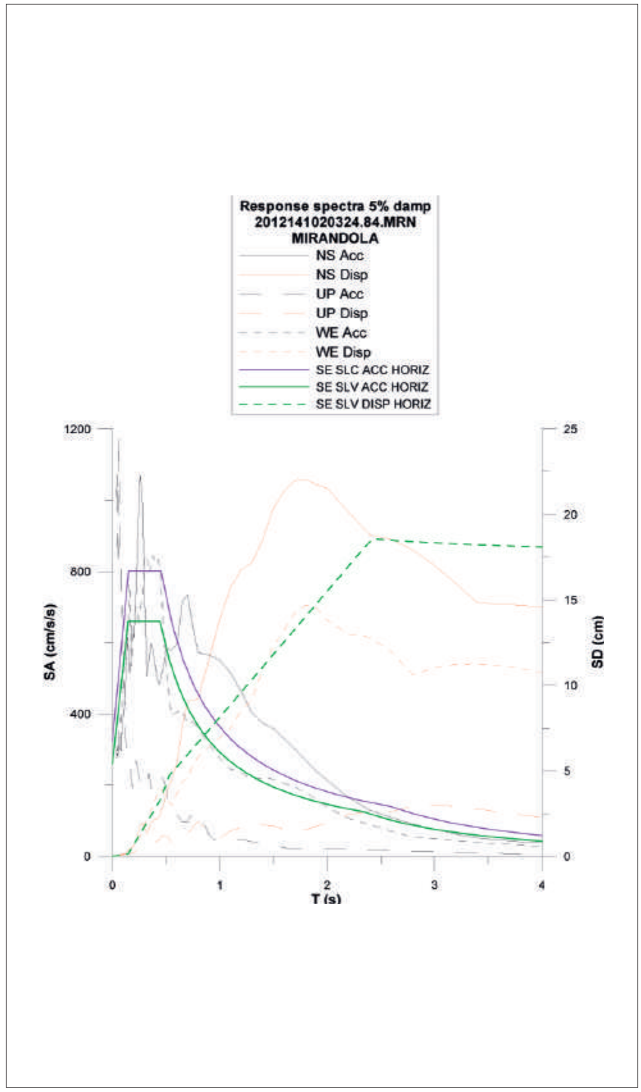

FIGURE 18 Comparison of the response spectra of the Mirandola station (A) with NTC2008

How can we explain then the considerable damage occurred both to civil and industrial buildings? One possible answer comes from the displacement time histories, shown in Figg. 19 and 20, and the soil characteristics. In the near field, the displacement has a pulse-like shape and the duration is very low.
Going far from the epicenter, surface waves are generated; these waves have low frequency and last several tens of seconds; since the propagation velocity of surface waves is a little lower than V_s (Fig. 15), when extended in plan structures it could have been subjected to differential motion. This effect could have been the reason of the collapse of several industrial buildings, with or without concurrent effects as soil liquefaction or poor structural characteristics.

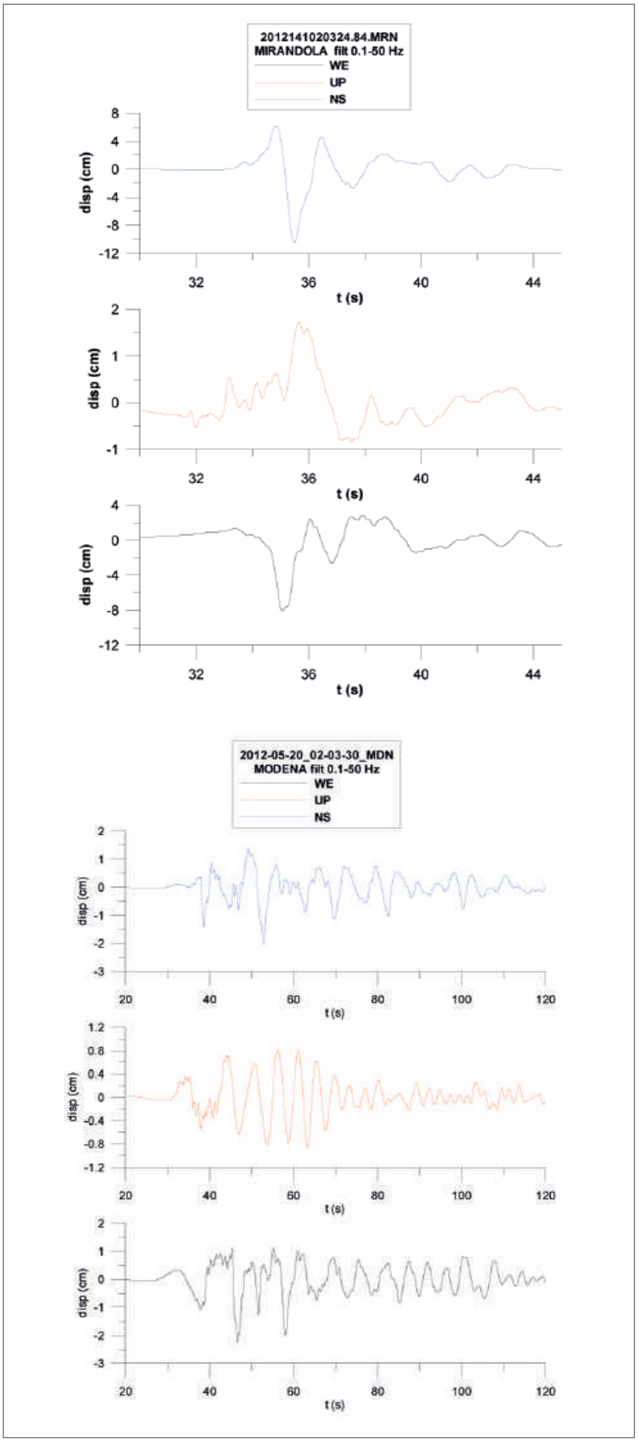

FIGURE 19 Displacement time histories: Mirandola (A) and Modena (A)

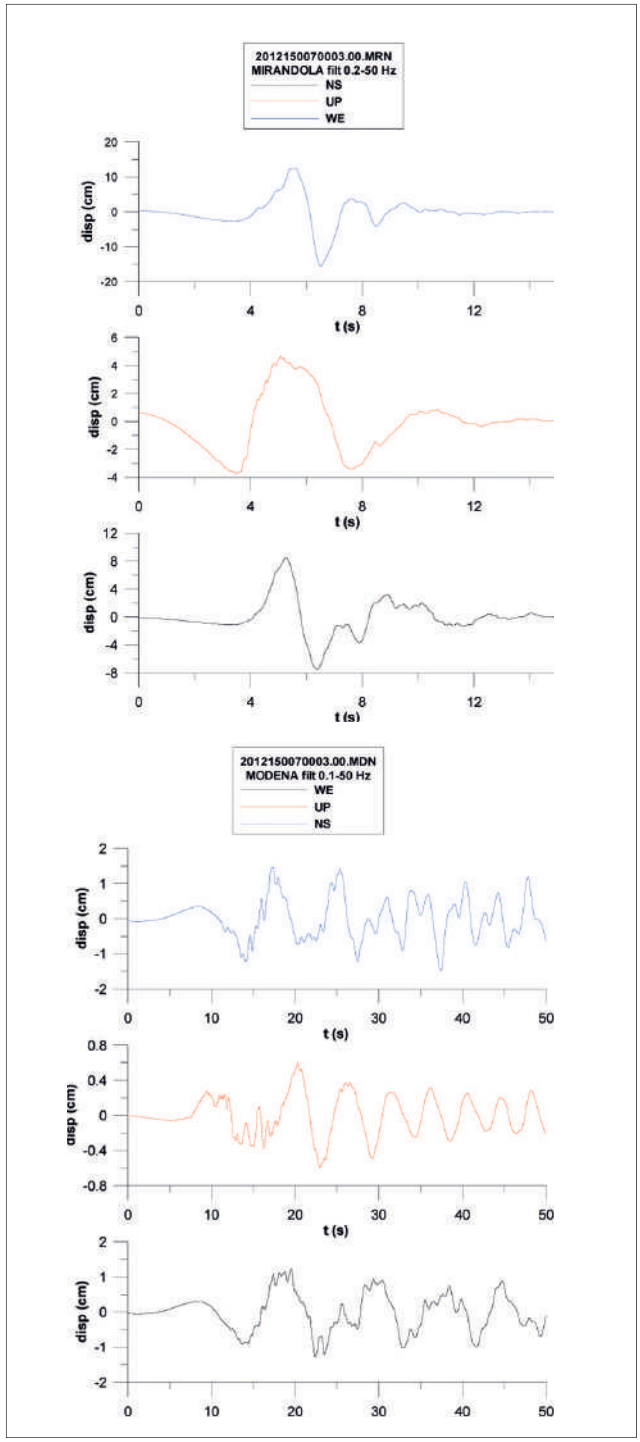

FIGURE 20 Displacement time histories: Mirandola (B) and Modena (B)

Conclusions

The seismic crisis of May-June 2012, for the localities here examined, was definitely the most violent in the last 500 years and should serve as inspiration for a critical review of seismic hazard maps, that only a few years ago assigned a rather low level of seismicity to those areas.

The first problem involves the level of magnitude which can be generated by local seismogenic sources. According to the INGV report "*Redazione della Mappa di pericolosità Sismica prevista dall'Ordinanza 3274 – Rapporto conclusivo – Aprile 2004*" (Drafting of Seismic Hazard Map provided by the Ordinance 3274 - Final Report - April 2004) the final M_w values for the areas under consideration is equal to 6.14.

On the other hand, in the "*Database of Individual Seismogenic Sources, version DISS 03 - INGV" (DISS Working Group, 2010), the existence of the seismogenic source of Mirandola is proposed* "... based on the evidence of the recent tectonic activity of the buried Ferrara Arc, highlighted by the control exerted on the evolution of the drainage network and by the geometry of syntectonic growth strata". Furthermore "*The Mirandola Source is not associated to any historical and/or instrumental earthquake, and as such it may represents a seismic gap. Given its dimension this source is able to generate earthquakes of M_w=5.9. The low slip rate suggests long recurrence interval for the potential earthquake*".

In the commentary enclosed to the DISS Database, particularly interesting are the "Open Questions" that the compilers left unanswered:

1) "Considering that the Mirandola Source is not associated with any earthquake, is it possible that the current Italian seismic catalogue missed an earthquake generated by this source?"
2) "What is the recurrence interval for the earthquakes generated by the Mirandola Source?"

These unanswered questions acquire now a dramatic importance and stress the necessity of further efforts by the scientific community in order to increase our knowledge on the earthquakes occurred in Italy in the past. Generally speaking, the historical seismology, which is based on documentary sources, is the main tool that should be deeply used and could be helpfully integrated with other methodologies, such as archaeoseismology and historical seismography, where ancient constructions are regarded as a potential source of information on past earthquakes, according to the principle that "every building is the manifest history of itself" (Pierotti and Ulivieri, 2001).

Another critical issue involved the level of seismic hazard assigned to the area by the national seismic code. On this issue, for the Municipality of Mirandola, the 0.141g value of PGA calculated for a return period of 475 years, and with local condition of hard rock outcrop and flat morphology (OPCM 3274/03), greatly underestimate the PGA value of 0.264g recorded in the "Mirandola" accelerometric station that, by the way, is located on a thick layer of soft soil which can probably produce local seismic amplification phenomena.

On the other hand, the PGA values diffused by INGV for a return period of 2475 years is 0.306g, corresponding to the 84° percentile more in line with the recorded value. An open question arising from these consideration is: which is the more reliable value of ground-motion parameters to be used for a safe design in seismic areas?

Finally, although the historical memory of the local seismicity seemed lost, the Pianura Padana-Emiliana area is prone to a not negligible seismic hazard which should be calculated with more detail. A great effort should be made for its mitigation, both with an adequate campaign for the reduction of structural vulnerability, and by in-depth studies of Seismic Microzonation and Local Seismic Response.

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THE PIANURA PADANA EMILIANA EARTHQUAKE

In May 2012, a large area of the Po river plain between the provinces of Ferrara and Modena was affected by a strong seismic event with magnitude greater than 5 (6.1 peak). This portion of the alluvial plain hosts many urban centres and industrial production activities, workshops and intensive farming.
This paper describes these phenomena and their relationship with the stability of buildings. In the urban and suburban centres as well as in rural areas, the earthquake caused the collapse of buildings and surface fracturing with sand liquefaction; this phenomenon occurs when a saturated soil devoid of cohesion passes rapidly from solid to liquid state, in conjunction with a strong earthquake. The sand bodies leaked from underground as large flows affecting the agricultural areas and urban centres located on top of old bumps that are found in ancient riverbeds. The seismic events occurred in rural areas have often used the wells and the irrigation network as a way of escape, whilst when on the inside of a building, the sand is likely to have followed escape routes created by human intervention

Sand liquefaction phenomena induced by the May 2012 Emilia Romagna Earthquake: geomorphological features and relations with the territory and building stability

■ *Elena Candigliota, Francesco Immordino, Guido Martini, Carmela Vaccaro*

The fracturing phenomena was mainly about the Ferrara area, where the ENEA *Technical Unit for Seismic Engineering* of Bologna intervened along with the Civil Protection and municipal technicians for AEDES surveys, and in the geological and geophysical surveys in collaboration with OGS Trieste and the Department of Earth Sciences of University of Ferrara.
This area of the Po Valley hosts many urban centres and industrial production activities, workshops and intensive farming, in addition to an important historical structure made up of old farm buildings and fortifications.

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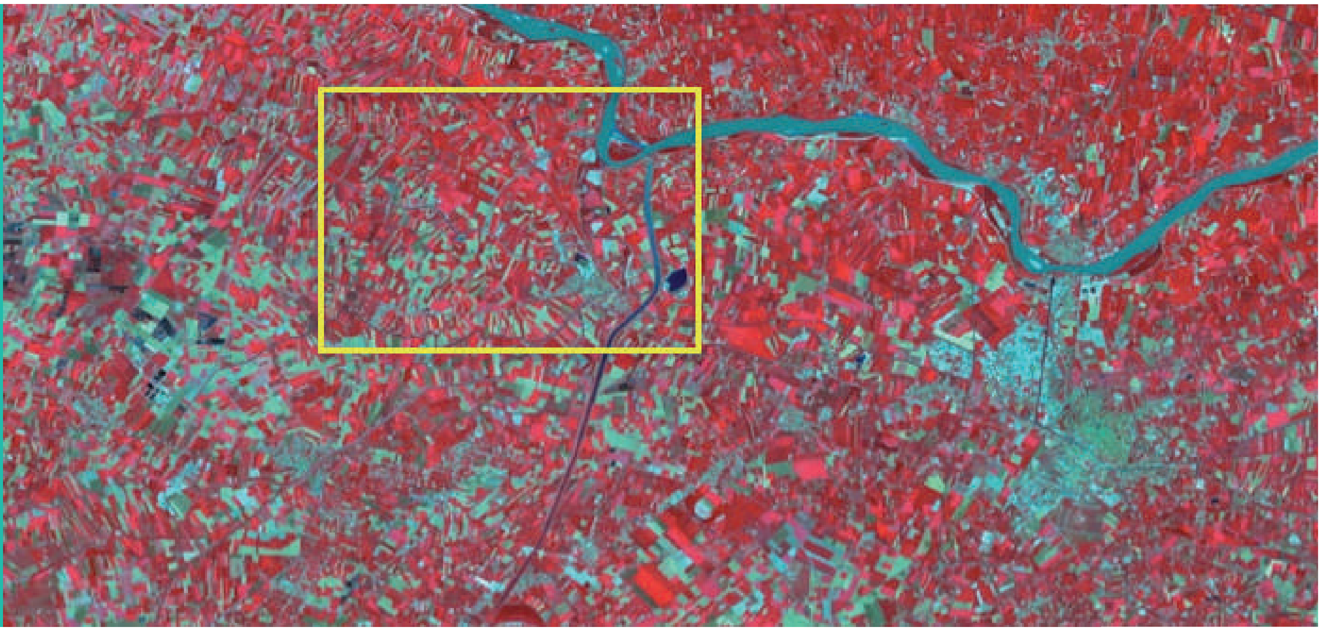

FIGURE 1 Landsat 7 ETM image, RGB 432)*: the false colour image takes up the land portion of the *alluvial plain,* there is intense agricultural activity.* In red is shown the vegetation (cultivated areas); in cyan*, bare soils and urban centres* and economic activities

The area affected by the earthquake is a portion of the river plain between the Po and Panaro rivers and is a fluvial-marsh area. The evolutionary history of this area is very complex because the presence of important structures in the subsurface tectonic compression affects the rate of subsidence, sedimentation processes and the evolution of the rivers. Despite the great contributions of sediment from the Apennines (Reno River and Panaro), in this region there were large marsh areas as tectonics is responsible for high rates of subsidence [3], which not coincidentally correspond with the areas in which we measure negative gravity anomalies. Such marsh areas are interspersed among the areas with the lowest rate of subsidence, corresponding to the high structural, collisional active fronts [4]. Humans from the earliest settlements had been coping with this problem by building riverbed guns and through reclamation of marshlands controlled by overbank (filled).

These interventions of sandy sediment deviation (step flood) into the marshes, documented in historical maps and witnessed by archaeological studies, explain why clayey sediments and peat (typical of wetlands of low energy) intercalations of coarse sands are incompatible with the environment sedimentary swamp.

These areas reclaimed into the morphology of plain fluvial-marsh, are affected by intensive human settlement and highly fragmented land.

Thanks to the reclamation of these areas to flat morphology of fluvial-marsh, they were of particular interest to an intensive human settlement of the agricultural high fragmentation. The false color Landsat 7 ETM image takes up the land part of the Bondeno and Sant'Agostino Municipalities, and shows an intense agricultural activity with strong fragmentation (Fig. 1).

Liquefaction of loose deposits due to earthquakes

Soil liquefaction is the phenomenon obtained when a saturated-unconsolidated soil passes rapidly from

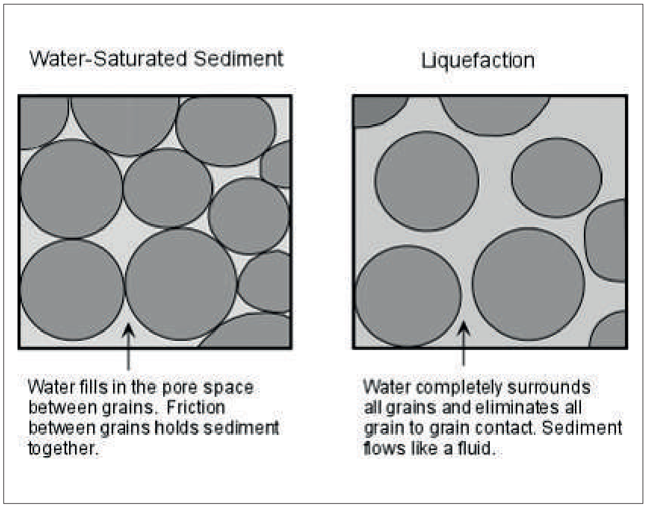

FIGURE 2 Loss of the resistance in a sediment due to liquefaction

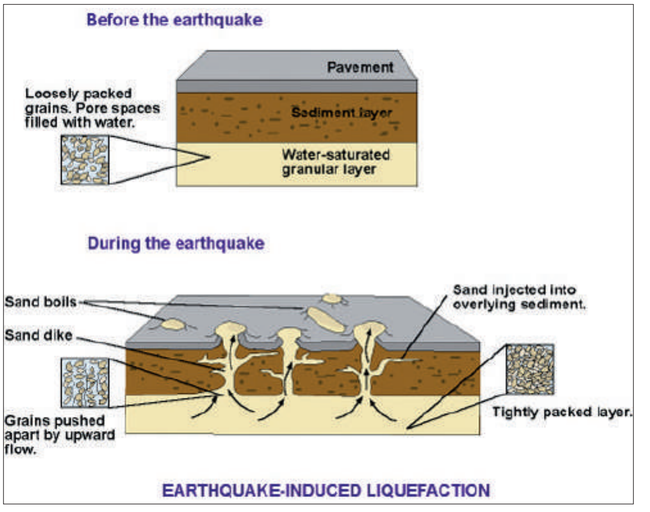

FIGURE 3 Diagram of the liquefaction phenomenon induced by earthquake

solid to liquid state; this transition is mainly due to the increase in interstitial pressure causing the loss of shear strength.

In geotechnics, the term 'liquefaction' is used to describe a loss of load-bearing capacity in water-saturated terrain under static or dynamic stress, in consequence of which the deposits reach a state of fluidity equal to that of a viscous mass.

The soils susceptible to liquefaction are those in which the deformation resistance is only due to the friction between particles (granular deposits, e.g. sand and silt).

A cyclic load applied to a saturated deposit can cause, for each cycle, an increase in pressure of water filling the pores between soil grains; if the water has not time to flow out before the next cycle, the hydraulic pressure can rapidly increase up to exceed the contact stress between grains (Fig. 2) with the consequent loss of shear strength. In this case, a soil layer can be unable to bear any weight and may be observed to flow like a liquid.

The most important phenomena that accompany liquefaction are therefore:

1) changes in pressure systems within the soil, with simultaneous effects of enhancement, redistribution and dissipation of the pore pressure;
2) changes in structure and relative position of soil layers during and after the phenomenon (Fig. 3).

The appearance of seismo-induced liquefaction in an area depends both on local geotechnical and hydrogeological characteristics of deposits (inducing conditions) and on the dimension of earthquake loadings (setting-off condition).

Between the inducing conditions it is worth mentioning: deep and thickness of potentially liquefiable deposits (less than 15-20 m from the ground surface); deep of water table (less than 5 m); relative density, average diameter and contents in fine fraction of fill material.

The setting-off conditions depend on the characteristics of the seismic action, which can be summarised in: magnitude (generally greater than 5.5); peak ground acceleration (PGA greater than 0.15g); duration of dynamic loading (more than 15-20 s). All these conditions are strictly related to the magnitude of inducing earthquake and to the distance from the epicentre.

In Italy, the distribution of magnitude vs epicentral distance values of earthquakes causing soil liquefaction (Fig. 4) shows that the level of magnitude reached by the May 2012 Emilia Romagna earthquake sequence can induce liquefaction phenom-

ena up to 40 km from the epicenter. Indeed, geological surveys found that the May 20th event (Mw 5.9) produced liquefaction phenomena up to about 25 km from the epicenter.
The phenomenon of liquefaction in the seismic areas of the event sequence being considered involved mainly the levels of sandy riverbed (Mirabello, St. Agostino, San Carlo), but also the marsh areas where fill interventions have made significant thicknesses of sandy sediments interbedded with clays.
In some cases the sand rose through the wells that are fed from the first confined aquifer, for which we cannot exclude contributions from this deeper body of water.
Generally in the phenomena of liquefaction the gases present in the subsurface are not involved, but in this case the abundance of peat levels within the sediments favors the formation of layers rich in methane and CO_2 present in solution in the water, which can increase the thrust upwards of the sands and therefore favor the triggering of liquefaction phenomena.
In support of this possibility occurred evident residues of peat in the sediments erupted in the liquefaction features, along with the emanation of malodorous gases from some of the fractures. It should be noted that they were already known phenomena of type "sinkhole" in the territory of Finale Emilia [7,8].
Considerable evidence indicates that liquefaction events were preceded by elevations of the piezometric level in the aquifer "pitched rid" of the seismic areas [7] and increase the enactment of gas from the ground, on which some blame the fish kill in the irrigation canals of the area; for this reason, in the future it would be important to build a network for monitoring these important precursors.

Geomorphological features

The phenomenon of liquefaction of the ground is quite common in the area affected by the earthquake (lower alluvial plain of Modena and Ferrara provinces), where there are deposits of silty-sandy riverbeds of the rivers Po, Panaro and Reno.
The first confrontations between the geomorphologic characteristics of the area and the location of the effects observed have shown a clear correlation with the presence, in the subsoil, of the riverbeds of the Secchia, Panaro and Reno rivers.

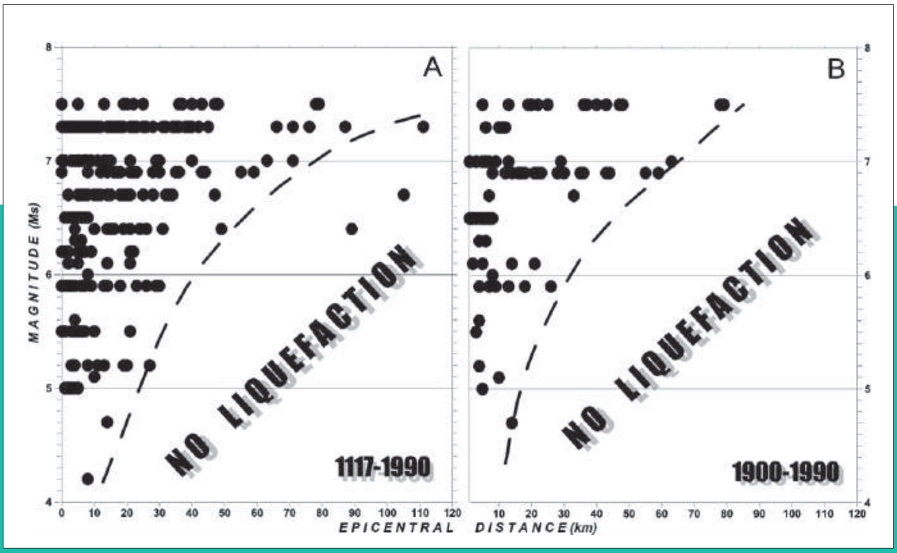

FIGURE 4
Relation between magnitude and epicentral distance for liquefaction effects in Italy
Source: Galli, 2000

FIGURE 5 Sand liquefaction phenomena within an agricultural area

FIGURE 6 Morphological structures of casting sand

FIGURE 7 The structures are characterized by large sandy plateau

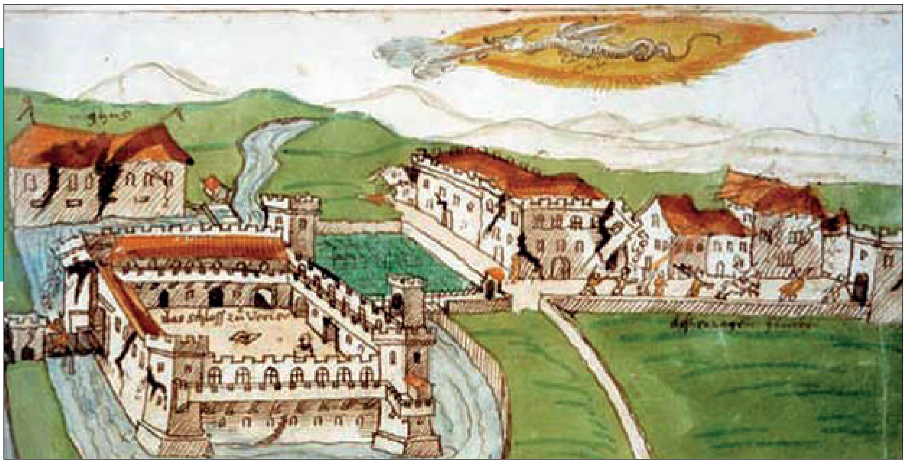

FIGURE 8
Ferrara destroyed by the earthquake of 1570
Source: H. J. Helden, Zurich, University Library

The phenomenon of sand release has manifested a series of en echelon iso-oriented fractures, that despite the modest extension (usually around meters) are expression of local environmental geo-tectonics. From the geomorphology point of view, the structures are characterized by large sandy plateau with a central ridge along the fracture line and with very light slopes to the outside (Figs. 5-6-7).
The sand release has manifested as casting sand and often has taken on the typical morphology of sand volcanoes. In many cases, the activity was polyphasic with changes of the grain size in the sediment issued. Often, at the base we have a strong presence of sand and silt fraction on top. The sand leakage from these large fractures (Figs. 6-7), that opened up the land after the big quake, is very fine and with well classed grain size, because it represents a large part of the layer of alluvial sediments in the subsurface, which deposited during the historic floods that have affected the area in the past centuries.

Liquefaction phenomena and buildings stability

Soil liquefaction cases in Italy

The phenomenon of soil liquefaction is not unknown to Italian geologists and seismologists, who over the years have developed complex risk studies involving the stability of buildings in the affected area.

The liquefaction phenomena usually occur in conjunction with a strong earthquake that causes drastic impact in the underground and on the stability of buildings; this event has accompanied the greatest earthquakes in the last century that have characterized the history of Italy: Calabria and Messina with the disastrous earthquake of 28 December 1908 up to the strong shocks in recent years that have affected the Apennine area. Indeed, during the great earthquake of Calabria in 1783, the phenomenon, as described in the chronicles of the time, forever changed the morphology of the territory, between the Serre and the Aspromonte massif. The destruction of Tedalto Castle and the San Paolo Church is attributed to liquefaction phenomena occurred during the Ferrara earthquake of 1570 (Fig. 8) and described by Pirro Ligorio [11].
In the case of the recent earthquake in Emilia Romagna, the sand liquefaction covered the land portion and buildings located on top of old bumps that are found in the ancient riverbeds.

Effects on building structures in the affected area: preliminary considerations

The release of the sands occurred in agricultural areas is often used as a way of escape for irrigation wells, in the cases occurred on the inside of buildings, the sand probably formed escape routes followed by human intervention. Figure 9 shows the effects of the sand liquefaction phenomena on the

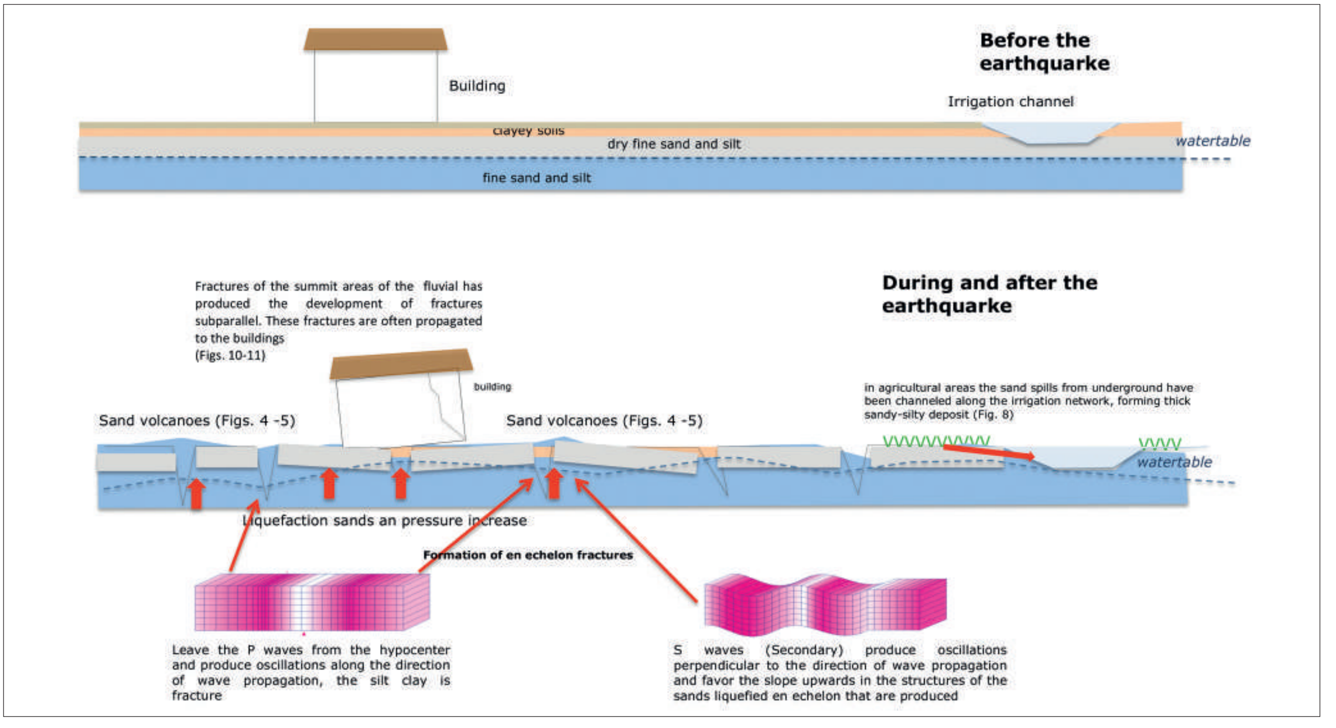

FIGURE 9 Soil liquefaction and effects on the stability of man-made structures: up) before the earthquarke; low) during and after the earthquake
Souce modified from: Institution of Professional Engineers of New Zealand) [10]

stability of man-made structures built before, during and after an earthquake.
The phenomenon is most evident in Sant'Agostino, particularly in the urban area of San Carlo (Fig. 10), the most damaged by the May 20th earthquake, where a great fracture has affected the city centre. During the main shock, the underground aquifer has raised sharply upwards to embrace the thick layer of sandy sediments present in the subsoil; the viscous sandy bodies then created have pressed strongly upwards until they escaped to the surface, through the fractures open in the ground. In agricultural areas the sand spills from un-

FIGURE 10 Sant'Agostino Municipality: one of the most damaged town by the earthquake of May 20th

FIGURE 11 Bondeno Municipality: sand spill that affected the irrigation channels in rural areas

FIGURE 12 Sant'Agostino Municipality: cracks with sand spill that affected the buildings and the road surface, and the sports field of San Felice

derground have been channelled along the irrigation network, forming thick sandy-silty deposits (Fig. 11).
Once the sandy mud was lying on the ground below the earth's surface without the previous sedimentation transferred, this process has greatly changed the structure of the subsoil, endangering the stability of buildings. Some other consequences of the soil liquefaction are:

- Loss of support to building foundations (Figs. 11-13);
- Fracturing of the summit areas of the banks of the old river, that has produced the development of fractures subparallel to its trend. These fractures are often propagated to the buildings and in the cemetery of San Agostino, in buildings of San Carlo and Mirabello and in the sports field of San Felice sul Panaro (Fig. 12);
- Near streams and rivers, the dry surface soil layers

FIGURE 13 San Carlo, Sant'Agostino Municipality: damage in residential buildings

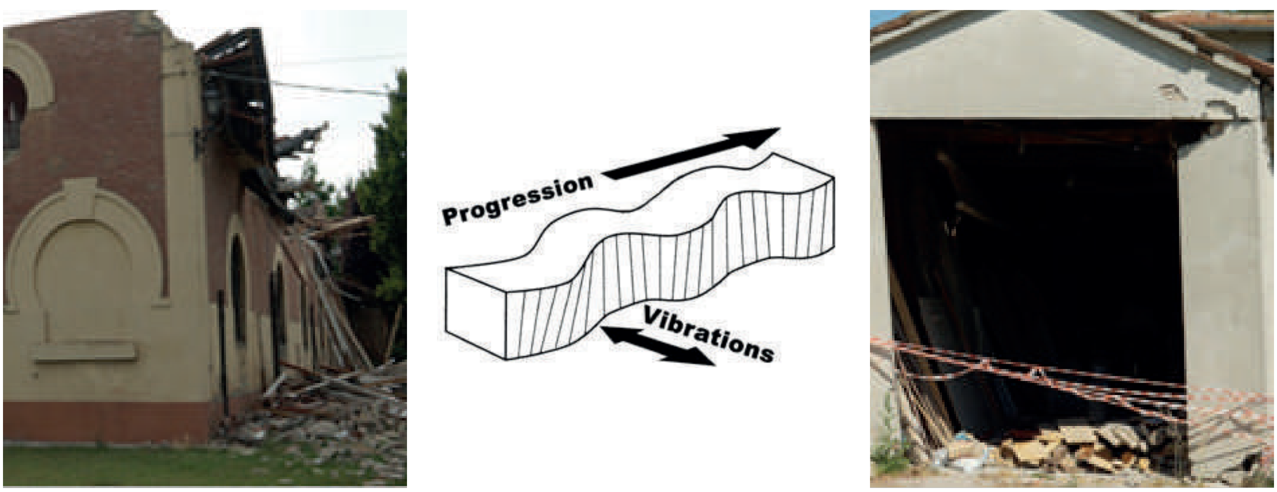

FIGURE 14 Deformation by P waves due to L wave: rural buildings damaged in the Sant'Agostino area

can slide sideways on the liquefied soil towards the streams; this is called lateral spreading (Fig. 9); this could be the cause of the damage to several rural settlements and can severely damage a building. It typically results in long fractures and cracks occurring in the soil surface and they resemble a classic fault line. Not every foundations of a building can be affected by liquefaction, as the affected area may shrink or be pulled sideways by lateral spreading and can seriously damage the building.

Conclusion

The seismic sequence that affected large areas of the alluvial plain of the Po river, on the border between the provinces of Ferrara, Modena, Mantova and Rovigo, has revealed the fragility of the area due to amplification phenomena and site effects that can be assessed by identifying morphological elements, and especially with a detailed reconstruction of the ex-

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treme variability of the subsurface lithology. In this work, demonstration activities in areas of significant tests have revealed the relationship between building structure, geomorphology and seismic phenomena (Fig. 9).

The damage observed (Fig. 14) may be mainly due to the amplification of S waves and L waves in alluvial sediments and their proximity to urban areas present in the earthquake hypocenter.

Moreover, important and visible structural damage reported by buildings due to the sands liquefaction phenomena may be a secondary sand erosion phenomena affecting the construction materials of foundations.

Acknowledgements

We thank VVF of Bondeno, Marco Negri, Violetta Fabbri and Rossella Setti, technicians of Bondeno Municipality, the Bondeno Administration Municipality and Monia Benini for the pictures of buildings in the Sant'Agostino area.

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THE PIANURA PADANA EMILIANA EARTHQUAKE

The Istituto Nazionale di Oceanografia e di Geofisica Sperimentale "OGS" in Trieste, the University of Ferrara – Department of Earth Sciences, Edilgeo and Eurekos Srl, with the supervision of the Emilia-Romagna Region and the Civil Protection Department (CPD), have carried out a geophysical exploration at two test sites located in the villages of Bondeno and Mirabello, both situated in the western and south-western part of the province of Ferrara respectively. The geophysical survey was accomplished by using the Ground Penetrating Radar (GPR) and the seismic reflection techniques. Scope of the survey was to set insights on the uppermost part of the subsoil interested by the co-seismic effects of the May 20, 2012 earthquake (M_L 5.9, hypocenter depth: 6.3 km, INGV) and manifested by the formation of surface ruptures and the ejection of sand due to the liquefaction of sand layers present in the shallow subsurface. The attained preliminary, geophysical results have allowed for the geometrical mapping of these site effects also in depth. Despite the 2D nature of our results, this work has pointed out the ability of the GPR technique, if proper frequencies are employed, to map the shallow subsurface extent of both fractures and, under certain conditions, the liquefied sand bodies too. The possibility to trace back these fractures at greater depths was accomplished thanks to the employment of high resolution seismic reflection profiling. The preliminary results achieved in this work can help geologists get proper characterization of the subsurface below the damaged buildings, which would aid engineers and decision makers in formulating appropriate site-specific solutions. The 3D extension of these results would, surely, provide a better vision of the 3D nature of these fractures at minor costs

Geophysical methods for the assessment of the surface structures in the Mirabello area

Luca Baradello, Flavio Accaino, Alessandro Affatato, Daniel Nieto Yàbar, Francesco Fanzutti, Carmela Vaccaro, Nasser Abu Zeid, Mauro Piccolo, Guglielmo Soncin

Following the main shock of M_L 5.9 that hit the area whose hypocenter was located at 6.3 km some 20 km NW of Mirabello, sand liquefaction effects have been observed along the entire paleo-river bed of the Reno river between Sant'Agostino and Vigarano Mainarda. In particular, these effects have interested both the urban and industrial warehouse zones of Mirabello village, among others, such as Sant'Agostino and San Carlo (Fig. 1). From the tectonic point of view, the observed seismic activities are related to the buried active front of the Romagna and Ferrara thrust belt. In this area, this folded belt represents the advanced northern rim of the Apennines mountains,

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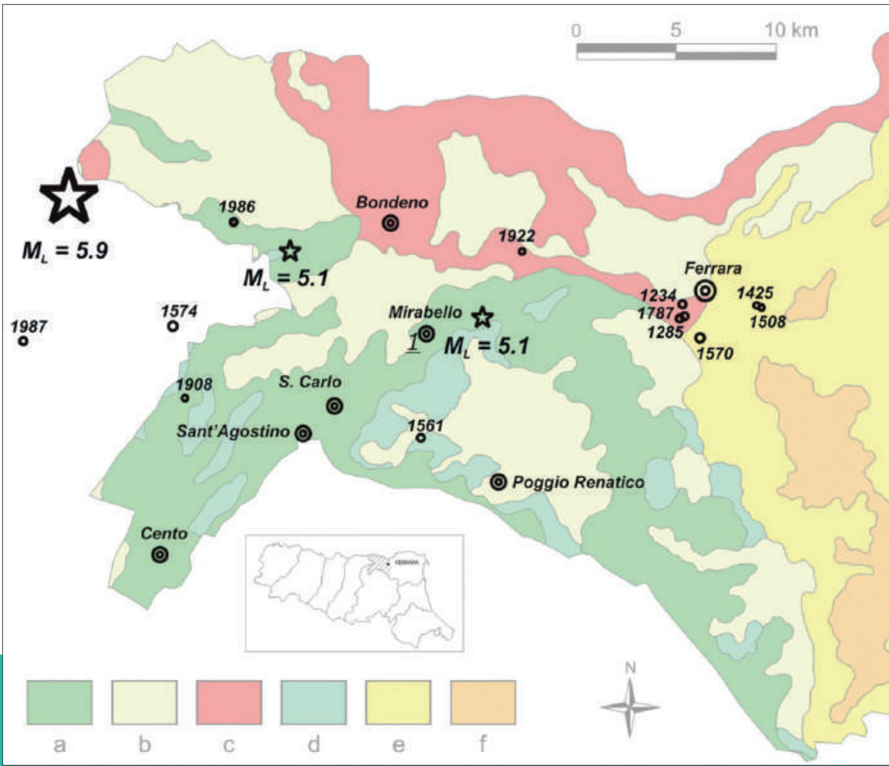
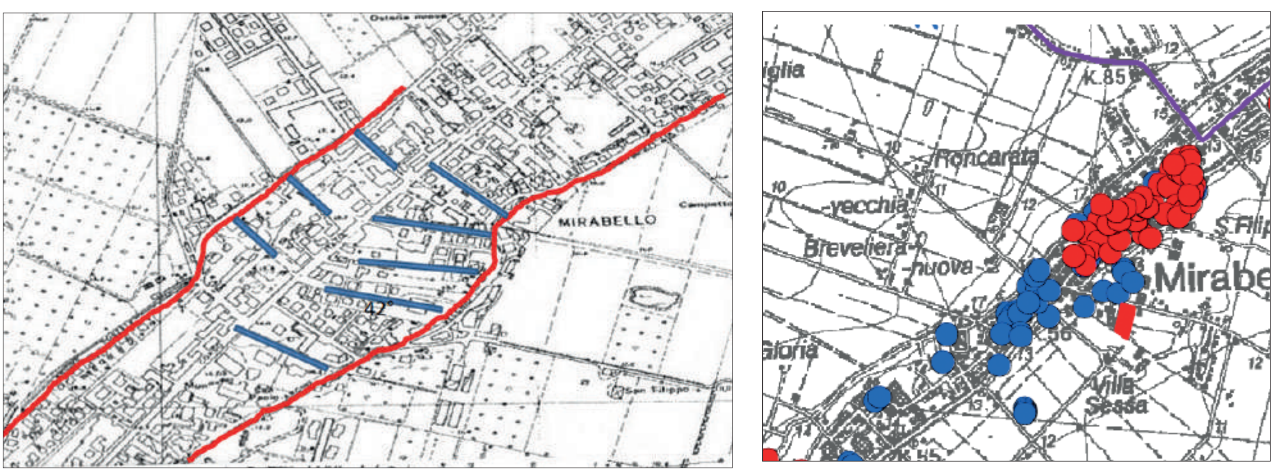


FIGURE 1 Simplified geological map of the western portion of the Province of Ferrara. The map shows the location of the main earthquakes of May 20th, 2012 (stars) and the location of the test site discussed in this paper (1). The main lithological units, of Holocene age, are: (a) medium to fine sand (channel and proximal levee deposits); (b) silty clay (distal levee deposits); (c) sandy silt, fine sand and silty clay (distal levee deposits); (d) medium to coarse grained sand (alluvial plain and meander deposits); (e) medium to fine grained sand (distribution channel and levee deposits); (f) silt, clayey silt (swamp deposits). (Modified after Data Base of the Emilia-Romagna Region (URL: geo.regione.emilia-romagna.it/geocatalogo/).
This sector, according to historical documentation –the profiles of Cardinal Aldovrandi's projects– and to toponomastic, is still characterized by the presence of two levees in good state of conservation



(a) (b)

FIGURE 2 Relationship between the urban texture of the central part of Mirabello village and man-made hydraulic protection structures (left). These structures created the conditions for the deposition of sand sediments that underwent liquefaction following the main shock of May 20, 2012 (right), where the distribution of liquefaction manifestations is shown in red and blue solid circles (STB Reno River, STB Tributaries of the PO River, "Geo-Pro-Civ" non-profit Association). Modified after the Emilia-Romagna Region Geological Survey, 2012 which is overlain by a thick sequence of Pliocene and Quaternary sediments forming a wedge-like shape of sediments beneath the Po plain. The superficial geology of the area, including the test site, is mainly composed of alluvial deposits that have been deposited in different environments comprising: channel and proximal and distal levee, inter-fluvial, meander and swamp. These sediments also form the main hydrogeological units overlying the bedrock, which can be found at depths ranging between several hundreds to few kilometres. The heterogeneity of damage distribution is, therefore, controlled firstly by the geological and geomorphological characteristics of the territory, and secondarily by the building's vulnerability.

The distribution of sand boil manifestations, and the fracture's distribution and orientation in relation to the observed damage severity have pointed out the existence of a possible relationship not only to the litho-stratigraphic settings but also to the diffused artificial man-made hydraulic structures and reclamation activities carried out in different historical periods.

As an example, in Fig. 2 we show the reconstruction of the past hydraulic structures with the twofold aim to decrease sediment transport and to help in low land reclamation. It is interesting to observe that these reclaimed areas were heavily affected by liquefaction effects (sand boils and fractures).

The analysis and interpretation of a series of georadar (GPR) and seismic reflection profiles supported by geomorphologic and geologic interpretations are presented and discussed in this paper.

The geophysical survey

The test site (1 in Fig. 1), represented by a residential building that was affected by surface ruptures (Fig. 3), is situated in Via Argine Postale, 57 (southwestern part of the village centre). In this site we accomplished several 2D GPR and seismic reflection profiles. Details regarding the employed techniques can be found in specific literature[1]. Concerning the GPR application for the investigation of seismically-induced fractures, we came across

FIGURE 3 Side view of the investigated building with structural damage. The residential building is situated in Via Argine Postale, 57, Mirabello village (Italy). Near the fence, the seismic cables with geophones can be seen

few and sporadic examples in the literature[2]. A brief summary of the main finding shall be presented and discussed hereafter.

GPR Survey

The GPR profiles were carried out along the building sides in a direction perpendicular to the surface ruptures.

GPR data acquisition was accomplished using the GSSI SIR 2000 Georadar, equipped with 100 MHz, 200 MHz and 400 MHz antennas. As it is widely known, resolution is function of the antenna frequency: higher frequences provide higher detail, while low frequences result in greater penetration with less resolution[3,4]. The penetration depth of the radar signal (electromagnetic wave) is also function of materials' resistivity. In fact, all the recorded profiles using the higher frequency antennas were affected by low penetration and ringing, most probably caused by the presence of conductive material in the uppermost part of the section. As an example, we show a GPR section recorded by a 200 MHz antenna (Fig. 4), where ringing problems are evident apart of the high attenuation of the E.M. signal, which has reduced the depth of exploration. This profile was recorded over the left embankment going towards the lowland area.

The interpretation of processed sections shows the presence of reflectors characterized by several horizontal unconformities and phase changes that could be associated to fractures or infiltration of sand (red lines). Reflectors associated to clay/sand interfaces are in general not parallel to the surface but show undulated geometries, probably associated to alternances of paleo erosion and sedimentation surfaces. It could also refer to the sediments used in the contruction of the embankments. For the transformation of time sections to detph, a velocity of 8 cm/ns – typical of this type of soil (relative dielectrical permitivity “$\square_r$”: 14-15) –, has been applied.

It is worth mentioning that, upon request of the National Civil Protection Department and the Geological Survey of the Emilia Romana Region, pre-earthquake GPR sections have been compared[5]. Both radar images were similar, with the only difference that vertical unconformities are present in our data. These features are characterized by phase changes associated to seismically-induced fractures such as those reported in Fig.5.

Seismic investigation

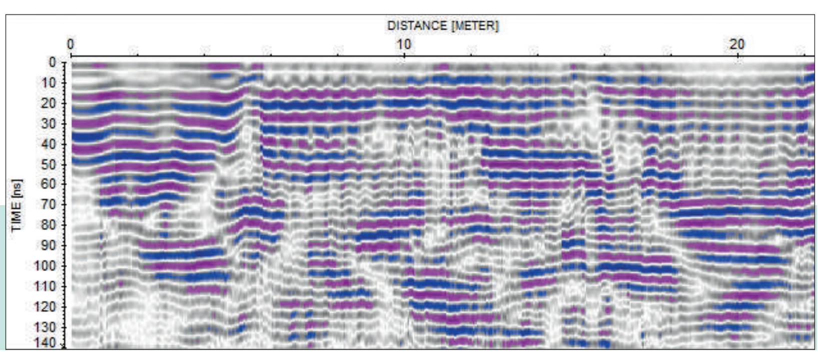
A seismic line has been recorded from the alluvial plain (west) perpendicular to the paleo-river bed (east) (Fig. 1, insert in Fig. 5). The characteristics of this profile were:

- length of the line 75 m;
- geophone spacing 2 m;
- geophones' natural frequency: 100 Hz;
- shooting interval: 2 m;
- energy source: hammer;
- sampling: 0.5 ms.

Seismic data processing was based on: definition of the geometry of acquisition; calculation of static corrections, to obtain a horizontal reference plain for both energization and recording points; application of NMO (Normal Move Out) corrections for Common Depth Points (CDP) and further Stacking. Data was filtered in the FX domain allowing for a better visualization of the reflections. In Figure (6b), we show the final stacked section (the horizontal scale represents CDP, whereas the vertical time scale represents the TWT (Two Way Time). This section shows the presence of two reflectors: the first one is well delineated (0.06-0.075 s) along the whole section, whilst the second one is less continuous, located at 0.15 seconds towards west and increasing to 0.2 sec towards east (embankment). The most interesting feature regards the presence of seismic attributes associated to interruptions of the reflection surface(s). These interruptions signal the location of the seismically-induced subsurface ruptures. The visual comparison with the GPR profile, that superimposes part of the seismic reflection profile (Fig. 6), shows a good correlation at least for the common depth section investigated by both methodologies. Further analysis of the seismic section suggests the presence of deep fractures that may not be correlated with the seismic event of May 20th, but may provide a clue about the occurrence of past seismic events that had produced seismically-induced fractures. However, more analyses are required

FIGURE 4

GPR profile acquired with a 200 MHz antenna. Structures are masked by ringing effect



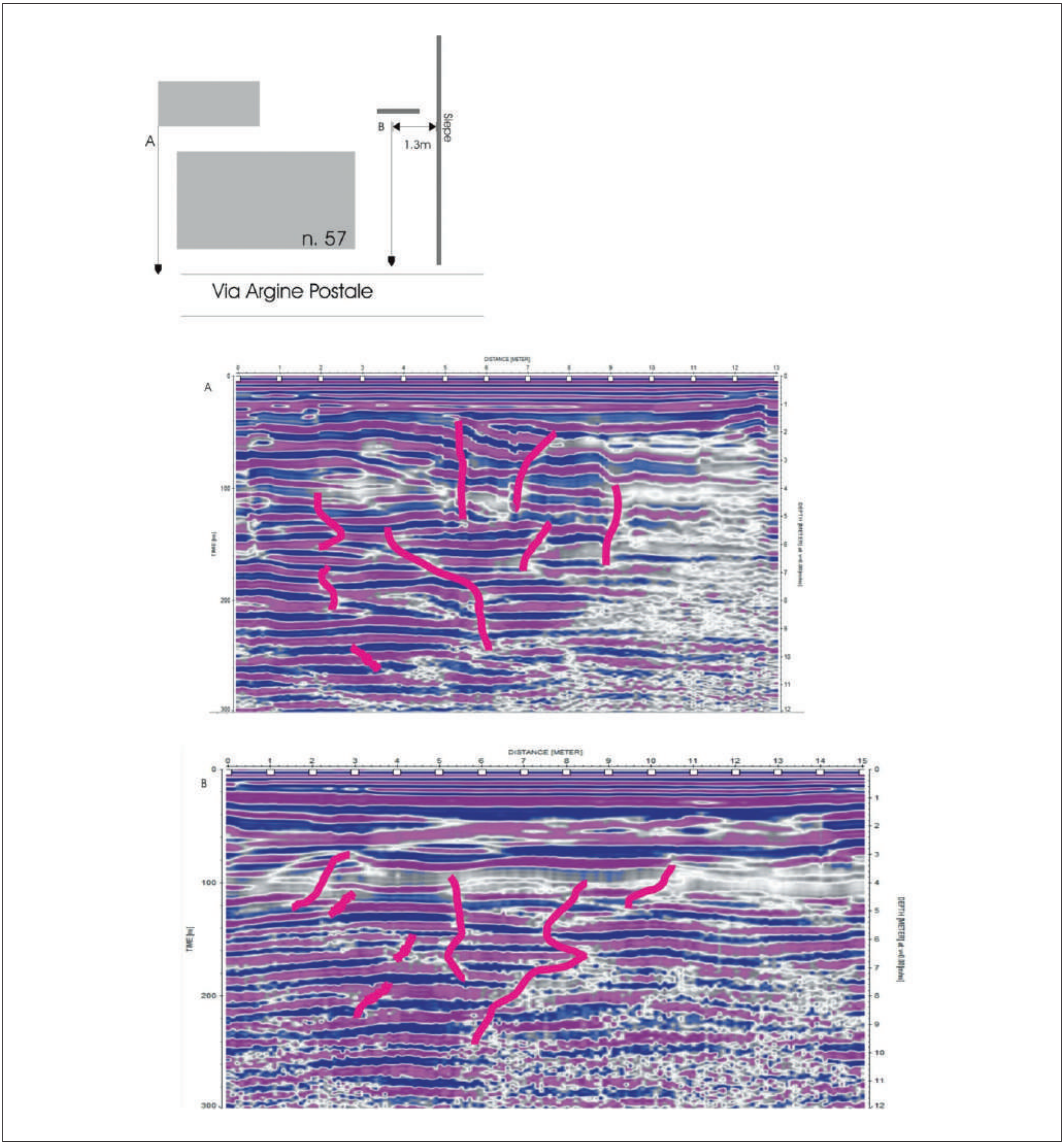


FIGURE 5 Example of GPR sections, 100 MHZ, recorded on the side of building in via Argine Postale 57 at Mirabello. Possible fractures and/or sand intrusions are highlighted in red. The upper left insert shows the position of the GPR and seismic profiles with respect to the building. A and B: GPR sections. Thick vertical line: seismic reflection profile

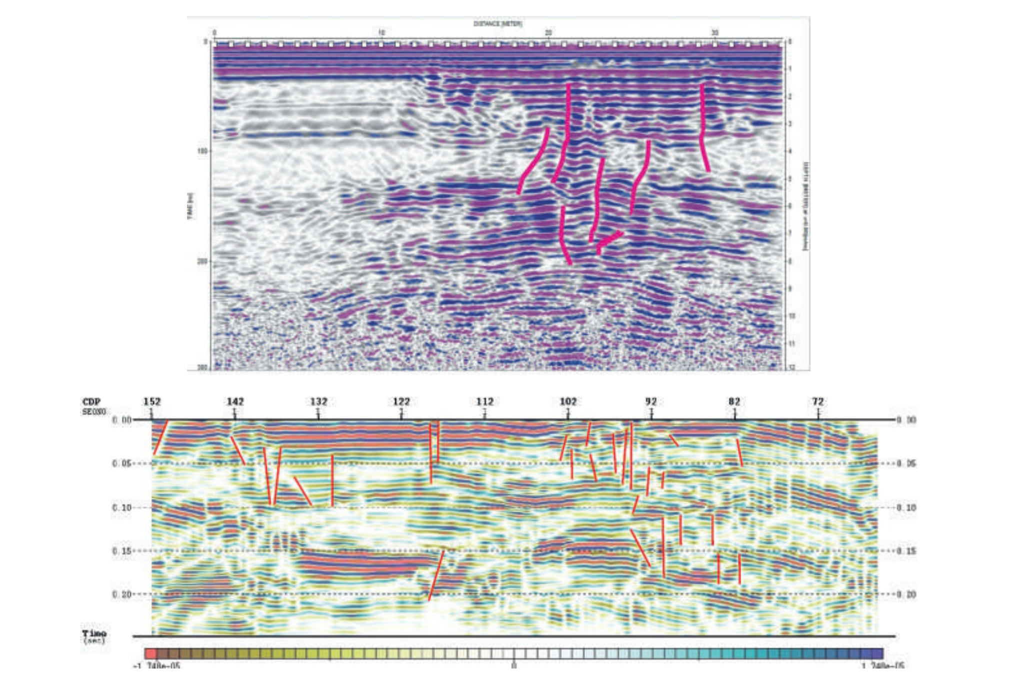


FIGURE 6
a) GPR (100 MHZ) and b) seismic reflection section. Fractures and sand intrusions are highlighted in red colour

Discussion and conclusions

The territory of Mirabello can be subdivided into four areas characterized by different levels and types of damage due to different geo-lithological conditions and anthropogenic interventions.

The application of GPR and seismic reflection geophysical techniques for the study of shallow structures has permitted to precisely define the areas where hidden fractures could be a factor of risk. The combined use of both methods proved to be very useful as it permitted to map the presence of deep structures, not reachable by the electromagnetic signals, down to a depth of about 100 m, maintaining a comparable high resolution from the surface to the bottom. The combination of the two methods pointed out the presence of deep dislocations that need to be further investigated in order to identify both probable causes and formation time period. The latter is very important for the paleo-seismic characterization of this area.

The results achieved, albeit in two dimensions, can help geologists and engineers construct more accurate geological models upon which technical solutions, for the stabilization and mitigation of the seismic risk, can be based. Finally, the extension of these techniques from 2D to 3D is feasible, especially as to the characterization of the subsurface beneath residential and industrial buildings. The integration with the 3D Electrical Resistivity Tomography is also feasible as these methods are sensitive to sediment texture variation.

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THE PIANURA PADANA EMILIANA EARTHQUAKE

The industrial warehouse area of Mirabello – located 12 km west-southwest of Ferrara, in northern Italy – suffered dissimilar intensities of damage during the earthquake sequence started on May 20th, 2012. The observed site effects were mainly concentrated along the course of the paleo-river bed of the Rhine River, where other villages are situated: Sant'Agostino, San Carlo, Mirabello and Vigarano Mainarda. The extent of the damage has highlighted the need to improve seismic resistance countermeasures of residential and industrial buildings as well as to identify appropriate measures to address the risk of liquefaction and surface rupturing. Our study tries to consider the effect that geomorphology had on the observed damage at Mirabello. The analysis is based on both newly collected geological and geophysical data and the revision of historical data related to the geomorphological evolution of the area. The main outcome of this work regards the importance of detailed mapping of the local structure of the paleo-river bed and its spatial variation. The opportunity to use the non-invasive and indirect methods, such as the Electrical Resistivity Tomography and Induced Polarization (ERT/IP), in mapping subsurface fractures and, possibly, the spatial continuity of the liquefied sand layer(s), has proved its efficiency. Such methods could be promoted to become an integral part to support other subsurface methods routinely employed for the reconstruction of the geological and hydrogeological models. Finally, the possibility to repeat the geoelectric measurements at low costs may also promote it as a tool for short-/long-term consolidation monitoring

Geological and geophysical investigations of "site effects" due to liquefaction in Mirabello following the May 20th, 2012 Emilia earthquake

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On May 20th, 2012 at 04:03:53 an earthquake (ML: 5.9, hypocenter depth: 6,3 km, INGV) hit the area near to Finale Emilia. The co-seismic effects associated with this event were observed in the nearby towns located within 20/25 km from the epicenter and belonging to four provinces (i.e., Ferrara, Modena, Mantova and Rovigo).

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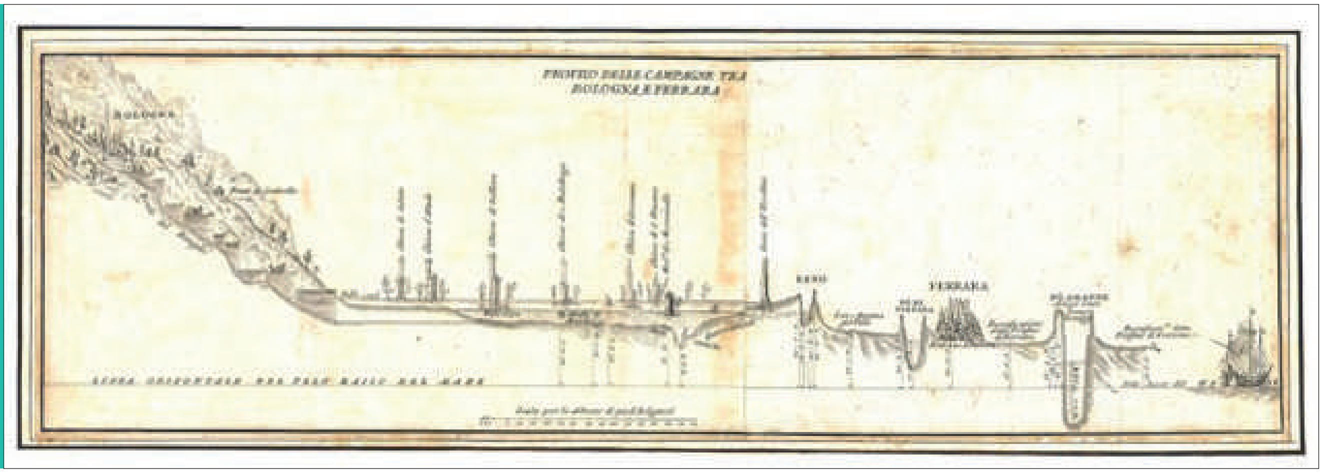

FIGURE 1 Sketch summarizing the details of Reno River deviation, started in 1604, as was proposed by Giovanni Domenico Cassini. The profile extends from Bologna (left) to Ferrara (right)
Source: Museum of Rural Life of Mirabello, Ferrara[3]

The observed heterogeneous near-field damage distribution indicated that the geologic and geomorphologic characteristics of these territories had an important role in causing, and sometimes augmenting, the observed site effects1. The most important effects are related to the occurrence of liquefaction and subsequent formation of tension cracks. These effects were observed, mainly, along the levees of the paleo-river bed of the Reno River, where the towns of San Carlo, Sant'Agostino and Mirabello are situated. The site effects, at Mirabello, had heavily encroached the factories where fractures have crossed them, leading in many cases to their demolition and consequent reconstruction for safety reasons2.
This work concerns the presentation and discussion of the peculiar geological and geomorphological characteristics of this area which, according to the observed damage distribution, could aid in clarifying the reason(s) of these co-seismic site effects. Moreover, modern geophysical techniques (ERT/IP) were employed in this work to retrieve rapid subsurface information about the depth extent of these fractures.
To start with, we show an historic map depicting the hydrometric profile in the year 1760, where it reports a summary of the hydrologic regime of the Paleo-Reno River with respect to ground elevation of the surrounding territories of Bologna and Ferrara. The profile evidences that during large flood events, water had submerged churches and towers whilst, in low level periods, the water level was much higher than in Sanmartina Valley, located further to the northeast of Mirabello. This confirms the artificial and hanging river typology of the Reno palaeo-river channels (Fig. 1).

Geology and geomorphology

The subsurface geology of the Reno River, in the study area, can be better understood through a brief reconstruction of the historical evolution of the Padana Alluvial Plain. Briefly, we can say that the general structure of the paleo-river bed is the result of many anthropogenic interventions following, most probably, major climatic changes and seismic events that likely led to deviating and rectifying the Reno's natural course.
Documented information related to the earliest works can be traced back to the Roman Age (i.e., second century A.D.)[4,5,6,7,]. In that period, the Sant'Agostino territories were subjected to intense rain periods. This indirectly supports the acceleration of works concluded in that period in order to mitigate the flood risk 8,9. A summary of the main climatic periods is reported in Table 1.

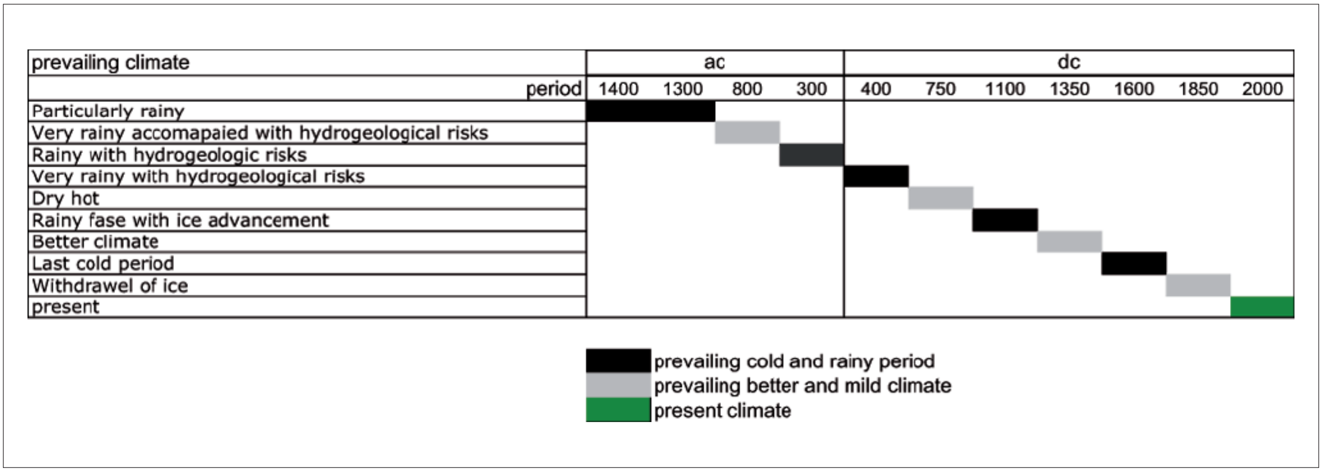

TABLE 1 Climate evolution of the Sant'Agostino village and the nearby territories [8,9]

The Reno River has been affected by numerous movements of its bed and floods probably caused by climatic changes in addition to a series of past earthquakes that may have produced damage to its banks. The most important earthquakes that occurred in the Emilia Plain, during the eleventh century after Christ, include the two large events that destroyed Verona City on 29th March, 1001 and 1st March, 1117. These events also resulted in the destruction of many cities in Emilia[10]. In Ferrara we remember the earthquakes occurred on 24th June, 1119. The low urbanization and lack of historical documentation makes it difficult to reconstruct the paleo-rivers routes[11,12]. This period of arid climatic conditions has been very important in the structuring of the territory of the municipality of Mirabello, due to the reduced flow of the Reno River, which in the year 1152 was no longer navigable. During this draught period, the city of Bologna financed several projects for the construction of dams along the following rivers: Santerno, Lamone, Senio, Sillaro, Quaderna, Gaiana and Savena in order to increase the flow and ensure navigability. The water drainage and the fortification of the levees did prevent the sediment transport from the Apennine, which augmented the subsidence phenomenon in the Emilia territories. This resulted in the formation of vast marshes. Although the Reno River was not concerned at this stage of the reorganization of its bed, its basin has been affected by the phenomena of subsidence, probably due to the reduction of sediment transport during the long dry period of the optimum medieval. The manifested hydraulic vulnerability of the territory following the two historical earthquakes, occurred in 1165 and 1222, created the conditions for further hydraulic problems that ended in 1240 with the change of the course of the Reno River, that was drifted to Finale Emilia to end in the Panaro River near Bondeno (Ferrara).

The significant alteration of the Reno River was related to routes of 6th February, 1455, when an earthquake of VIII grade intensity (Mercalli) struck the middle valley of the Reno, resulting in damaging the river banks. Such morphological changes did produce a fragile hydraulic system and the overflowing of the Reno River. The significant share variations observed with the recent earthquake of 2012[2] provide guidance on the impact that an earthquake has on the hydrological regime. Furthermore, the events of liquefaction support the hypothesis that similar effects have affected the stability of the banks and associated floods of the Reno River, that affected the area where the most disastrous event occurred in 1459. Since 1497, the Reno abandoned the Panaro changing its course and passing between Cento and Pieve villages.

In the northern part of Sant'Agostino Municipality, the river then free of protective banks had distributed sediments in the swamp waters until it reached the Po River after crossing the marsh areas. In 1522, the extreme climate that evolved towards the cold periods of the little ice age, in addition to the absence of canalization of the river-bed, had favored a disastrous flood of the Reno, with major effects on Mirabello's settlements and agricultural activity. These conditions led the government of Este to accept the intervention of canalization of the river, that resulted in the structuring of the river-bed. The same river-bed was affected by liquefaction after the recent earthquake of 20th May, 2012.

During the late medieval cold climate, the high rainfall and sediment transport created the conditions for structuring the paleo-river bed of the Reno, which was channeled with an almost straight bank from Sant'Agostino to Porotto (8 km NE of Mirabello).

The unfavorable weather conditions of heavy rain and high levels of sediment transport made it hard for the Reno water to enter the Po, causing its rapid silting. This fact is well documented by a letter sent, in 1598, by Gian Battista Aleotti of Argenta to Pope Clement VIII asking for support for the diversion of the Reno River. The diversion of the Reno River towards Sanmartina Valley took place in 1604.

In this period numerous solutions were adopted to reduce the sediment transport in the Reno River and transfer it to overcome subsidence in marshes. A particular intervention aimed at reducing sediment transport during floods is evidenced by the morphological feature of the central-northern part of the Mirabello Municipal area, where the paleo-river bed becomes wide, and in the urban organization traces of panels crossing the river are evident, whose function was to facilitate the sedimentation of soil transported by the flood waters (Fig. 2).

A representative example of these hydraulic works is the Reno Chiavica (II in Fig. 3), constructed in 1723 by Cardinal Aldrovandi, that served to mitigate the burial risk of the Po river once converged to the Reno. This solution proved unfortunate as it favored the occurrence of a number of disastrous routes (e.g., Bisacca, III in Fig. 3), after which it was necessary

FIGURE 2
Reconstruction of the principal anthropogenic structures along the Reno River based on the consultation of the available historical maps
Source: Museum of Rural Life of Mirabello, Ferrara

to divert its course leading to the formation of the present structure of the abundant river-bed. Further to the south of Sant'Agostino, the southwestern portion of the Reno was diverted towards Argenta (SW of Mirabello) with a tight angle. Consequent major interventions took place following the 1949 and 1951 floods, that lead to the construction of the presently known "*Cavo Napoleonico*". In relation to its construction, most of the materials that once were part of the left embankment of the Reno River were excavated and used in the construction of the "*Cavo Napoleonico*" embankments.

Detailed reconstruction of the Reno paleo-river at Mirabello

The co-seismic site effects urge for a systematic microzonation of all the affected areas including Mirabello. In this village, the analysis of these effects has resulted in the subdivision of the territory into five homogenous classes. The observed differences between the different classes are mainly related to both different subsurface lithologies and past anthropogenic activities. These classes are summarized in detail as follows (Fig. 3):

1a) Southern sector: In this area we have identified only the right embankment. The embankment is structured in a waterproofing system mainly composed of terraced clay.
The resistivity model (Fig. 4a) identified two resistivity levels denoted as a1 and a2. The former is characterized by resistivity values greater than 25 Ohm.m, while the latter (a2) shows low resistivity values although few heterogeneities are present laterally. These can be associated with clay and silt sediments, while the present heterogeneities (with resistivity values between 20 and 40 Ohm.m) are to be associated with the enrichment of silt and fine sand sediments. This interpretation is in accord with the subsurface lithology obtained from nearby boreholes, where a sandy silt layer has been encountered with its base located at 10.5-11 m b.g.l. It is believed that this layer has undergone liquefaction although very modest quantities of sand have reached the surface.

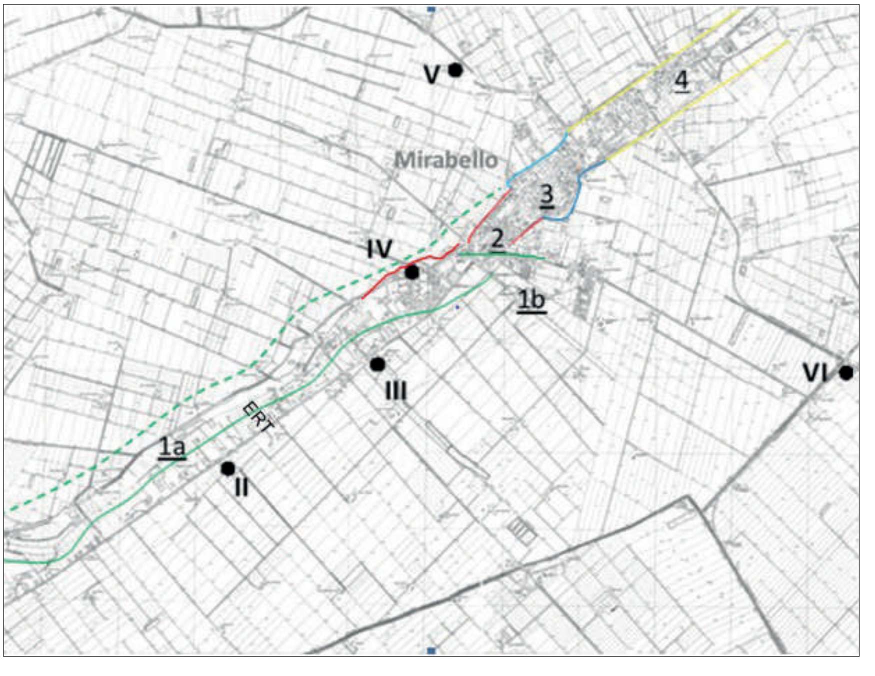

FIGURE 3
Micro seismic zoning of the Mirabello territory. The different colors indicate areas with different geomorphological and lithostratigraphic features. I-VI: principal anthropogenic structures along the Reno River (shown in Figure 2), 1-4: areas with similar site effects

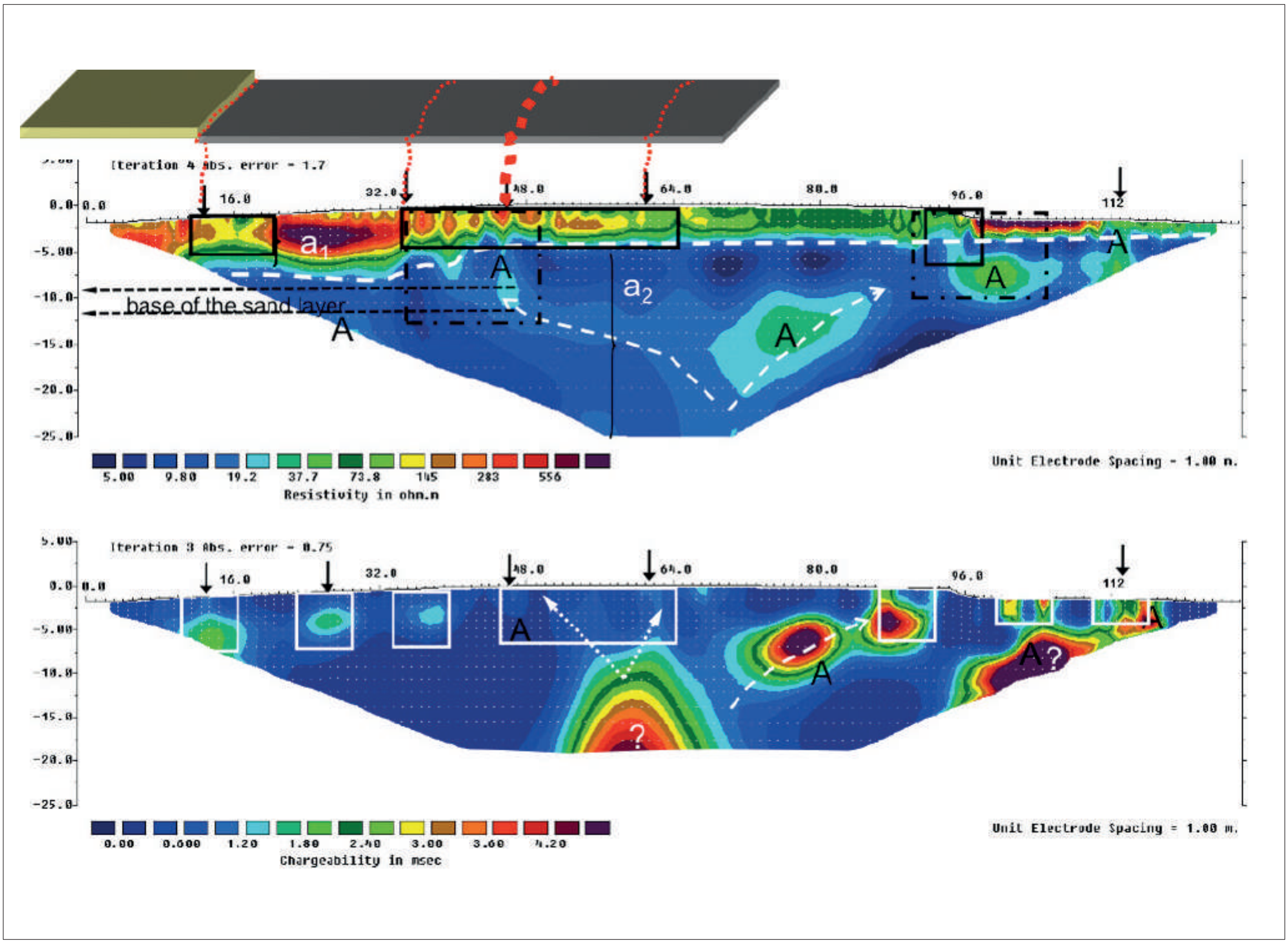

FIGURE 4 2D inverted resistivity (upper) and chargeability (lower) models. a1: resistive horizon and a2: conductive horizon. A: resistivity anomaly due to lithologic variation (silt and fine sand). Dashed white line: possible paleo-soil surface representing the old right embankment of the Reno River. The two shaded areas indicate the extension of the industrial warehouse with respect to the profile. The left one is related to the extreme western portion of the building that was severely damaged and subsequently demolished. ?: further analyses are needed to reveal the nature of these IP anomalies

As regards the first level, the resistivity model suggests the presence of lateral heterogeneities at the following chainages: 12 m, 35-65 m, and around 96 m. These are believed to be associated with subsurface fractures whose traces were visible on the surface at the moment of data acquisition.
One of these main fractures (chainage: 35 meters) has caused major damage to the industrial nearby building located some 25 meters off the resistivity profile towards NE. Moreover, the resistivity anomaly located at chainage 48 was associated with the expelling of modest quantity of fine sand that reached the surface. It is interesting to note the pathway followed by the sand following the liquefaction of the sand layer.
The corresponding chargeability model (Fig. 4b) evidences the presence of chargeability anomalies, indicated by rectangles, which are caused by variations in the sediment texture (i.e., presence of silt and fine

sand). The location of these anomalies is very near to the fractures, where some of them indicate the presence of "dykes" that may have been associated with the seismic event. The most significant is located between chainages: 45–64 m, where the trace of the nearly vertical fractures can be inferred. Similar features indicating possible upward movements of sediments can be seen at 7 m depth between chainages 75 and 90 m.
Finally, the integration of both geoelectric models and available subsurface lithology indicates that the area beneath the geoelectric profile belongs to the right embankment, which was constructed following the splay of the Reno River occurred in 1526;

1b) The eastern part of the ancient Reno River: This sector is mainly composed of clay sediments alternated with sand only in the superficial levels of the swamps.
These superficial sand sediments are related to the artificial filling operations during the lock construction and opening of a masonry drainage canal in the Reno River embankment for the distribution of sediments in the nearby plains. This hydraulic structure functioned also as a water mill in dry periods, while during the floods it was used to disperse sediments in the nearby marshes;

2) Town sector of Mirabello: In this area, portions of the two embankments are still preserved. The northern limit of this sector lays on the ancient paleo-river bed of "*Spron Mavezzi*", that marked the limits between the territories of Bologna and Ferrara during the Este Duchy; the urbanization of Mirabello occurred in this area on the border of the Reno River, and when the river was abandoned, the expansion of the urban area favored the preservation of the fluvial morphology. In the paleo-left embankment there is a strong morphological jump towards the alluvial flood plain.
Conversely, the right embankment evolves gradually towards the plain morphology due to the presence of sand sediments accumulated after flooding episodes. These differences could have contributed to the observed site effects differences caused by liquefaction;

3) The central-northern area of Mirabello: This sector represents the area of recent urbanization. It is characterized by a greater width of the paleo-river bed which served for the protection of the embankments. This has led to the accumulation of sand sediments that being saturated underwent liquefaction. Further to the north, there is a narrowing in the width of the paleo-river bed where liquefaction events are rarer;

4) The north portion of the urbanized area of Mirabello. In this sector, the paleo-river bed is of minor width and height, most probably due to the reduced supply of sediments that were blocked by the hydraulic structures belonging to sector 3.

Conclusion

The depressed morphology of the territories nearby the paleo Reno River course urged for the construction of artificial embankments against flooding. However, the suspended bed has favored, on the one side, the repeated occurrence of disastrous floods, while on the other it helped in the reclamation of the diffused marshes in the nearby territories. The paleo-river portions of the Reno treated in this study were reconstructed thanks to the availability of historical archives and geomorphological maps.
The paleo-river bed in the seismic zone 1a, belonging to the industrial warehouse area of Mirabello, shows the presence of only the right embankment while the left one has been destroyed. Towards east, its main flexure was identified by the "*Corso Italia*" street connecting Mirabello to Sant'Agostino towards south. This road separates the paleo-river embankment from the eastern, most depressed lands, where past anthropogenic activities had resulted in progressive altitude increase. This plain should be studied in order to identify the texture distribution of these sediments.
The use of the indirect and non-invasive ERT/IP technique, employed in the subsurface lithologic characterization of the industrial warehouse area (ERT in Fig. 3), evidenced the presence of 10 meters of sediments characterised by lateral lithologic variations.

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These variations are related to the transition from the river bed sands to loamy soils of the right embankment. These overlay clay sediments rich in peat, that extend and interdigitate with the nearby sediments of the lowland areas. Within these, clay intercalating sand sediments are present. The combined use of resistivity and induced polarization methods allowed, also, for tracing the surface ruptures down to a depth of 10 to 12 meters.

However, the IP section (Fig. 4b) provided indications about the probable presence of deep zones (chainage: 60m, depth: 20 m), which may be related to the presence of silty sand sediments that may underwent liquefaction.

This interpretation is supported by the observed surface ruptures at chainage 92-94 m (Fig. 4a,b). East of these ruptures, the ERT/IP models suggested that liquefaction has also interested the former swamp lands. In this case, liquefaction is due to the accumulation of sand deposited after the repeated floods.

This constitutes an important element for the vulnerability of historic buildings and should be considered in any study dealing with the microzonation of these territories.

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THE PIANURA PADANA EMILIANA EARTHQUAKE

During the seismic event of May 2012 in the Emilia-Romagna Region (Italy), several industrial structures collapsed or were severely damaged. They had been built following non-seismic old Italian codes, making use of precast concrete structures. In addition, in many cases internal steel shelves exhibited instability. This paper gives a brief description of the collapse observed, based on the construction criteria and the analysis of the seismic event

Behaviour of industrial buildings in the Pianura Padana Emiliana Earthquake

Fernando Saitta, Giovanni Bongiovanni, Giacomo Buffarini, Paolo Clemente, Alessandro Martelli, Anna Marzo, Giuseppe Marghella, Maurizio Indirli, Alessandro Poggianti

The seismic event which struck the Pianura Padana Emiliana at 04:03 (Local time) of May 20th, 2012 had magnitudes M_L = 5.9 (INGV estimation). The hypocenter of the event was only 6 km under the ground surface, and the epicenter was localized at 44.89° North and 11.12° East, between the towns of Mirandola, Finale Emilia, Poggio Rusco and Bondeno. Before and after the main event, several shocks of minor intensity occurred [1].
Almost all the municipalities hit by the 2012 earthquake were not classified as seismic areas before 2003. As a result, most of the existing structures had been designed without accounting for the seismic actions.
The Emilia plain is one of the most industrialized areas in Europe, with several factory and warehouse sheds, built in the last decades. They were often built up with a precast system, in which structural elements were made of precast reinforced concrete (r.c.), in simple or multi-storey buildings. The vertical structures consisted of squared pillars fixed at the base by grouted pocket foundations, with various connection systems for the beam location, but mainly forks at the top or corbels. For the single-storey configuration, the horizontal structures were composed of one or two-segment symmetrically sloped beams, plain covering. For the multi-storey configuration, the horizontal intermediate floor is generally realised with alveolar panels or tiles completed with r.c. cast. The upper covering system is realised with tiles of different shape, also made with pre-stressed r.c.. Beam-tile and beam-pillar connections are simply friction contacts. Another common typology of factory structure, surveyed during the post-seismic investigation, is made of mixed materials, made of pre-stressed concrete pillars, located in the central part of the building, and masonry walls along the perimeter.

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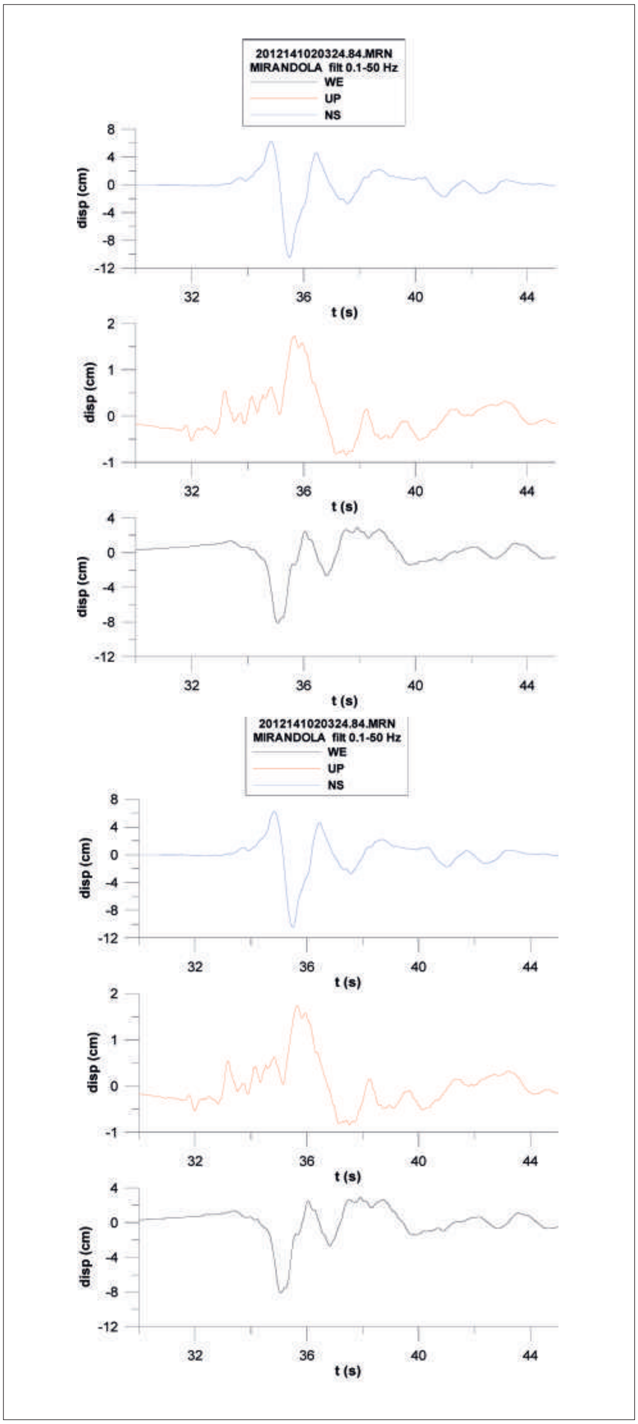

FIGURE 1 Displacement time-histories recorded at Mirandola (A) and Modena (B)
Source: ENEA elaboration of INGV data

The latter are made of solid bricks in regular configuration. The most common damage mechanisms are shown in this paper and discussed in the light of codes existing at the construction age.

Some relevant aspect of the seismic signals for industrial buildings

The analysis of some accelerograms recorded in Modena and Mirandola shows that low-frequency content (<1 Hz) is apparent for both the sites, compatible with the local soil conditions. The comparison of the response spectra of records obtained at the Mirandola station, with the provisions of the current Italian code [2], shows that the characteristics of the recorded time-histories are related to events with a

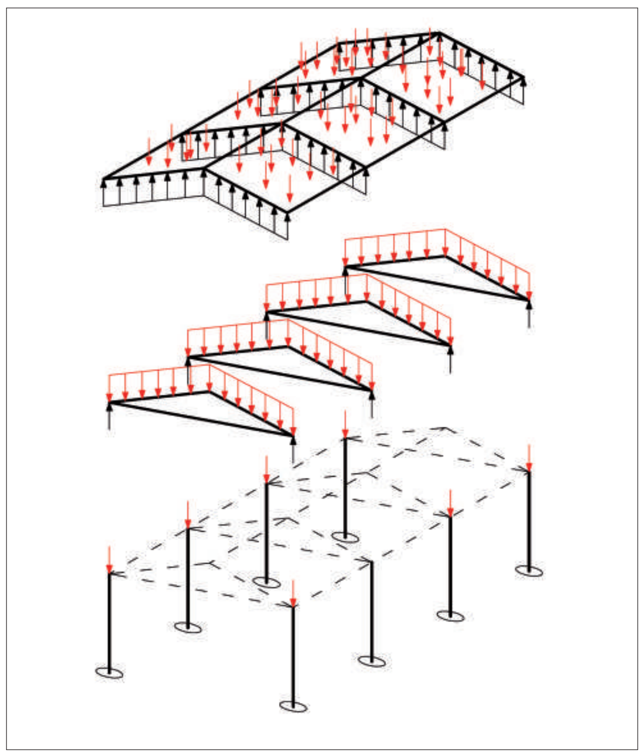

FIGURE 2 Structural conception of the industrial buildings
Source: ENEA

large return period, both in terms of spectral accelerations and displacements.

The displacement time-histories (Fig. 1) show that, in near field, the displacement had a pulse-like shape with a very low duration. Going far from the epicenter, surface waves were generated with low-frequency content, lasting several tens of seconds. Since the propagation velocities of surface waves are a little lower than those of shear waves [3], structures with significant dimensions in plan could have been subjected to differential motion. Therefore, this effect could have played an important role in the collapse of several industrial buildings, in addition to other concurrent effects.

Structural conception and damage

A scheme of a typical one-story industrial building is outlined in Fig. 2, where the vertical load path from roof to foundation is clearly depicted. The critical points of the considered structures were the joints between the different elements, beams and columns, so much as the connections between the roof panels and the beams. Before showing some failure cases, structural peculiarities of precast buildings are summarised.

The main difference with in-situ cast concrete structures is given by the absence of continuity at nodes. Thus, different elements must be joined together to obtain the whole assemblage.

With reference to Fig. 3, in which a column-beam interface is represented schematically, various effects, such us shrinkage, thermal or external loads, can induce strains. The interface friction, at the mating surface, prevents movements, generating the friction force μR, where R is obviously the normal force to the surface, i.e., the vertical reaction.

The bending rotation of the beam creates a stress concentration at the top of the pillar, with possible spalling of the concrete (Fig. 4a). This suggests the interposition of a bearing pad (Fig. 4b). If a horizontal force overcomes the friction force, the beam can lose its bearing. A steel dowel or a reinforcing bar can prevent this kind of collapse (Fig. 5).

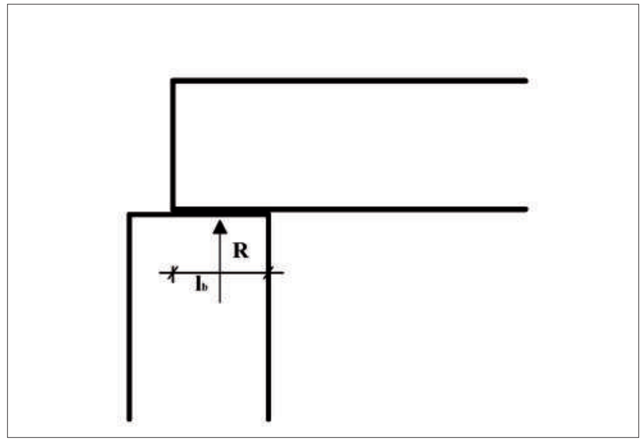

FIGURE 3 Schematic representation of the column-beam interface
Source: ENEA

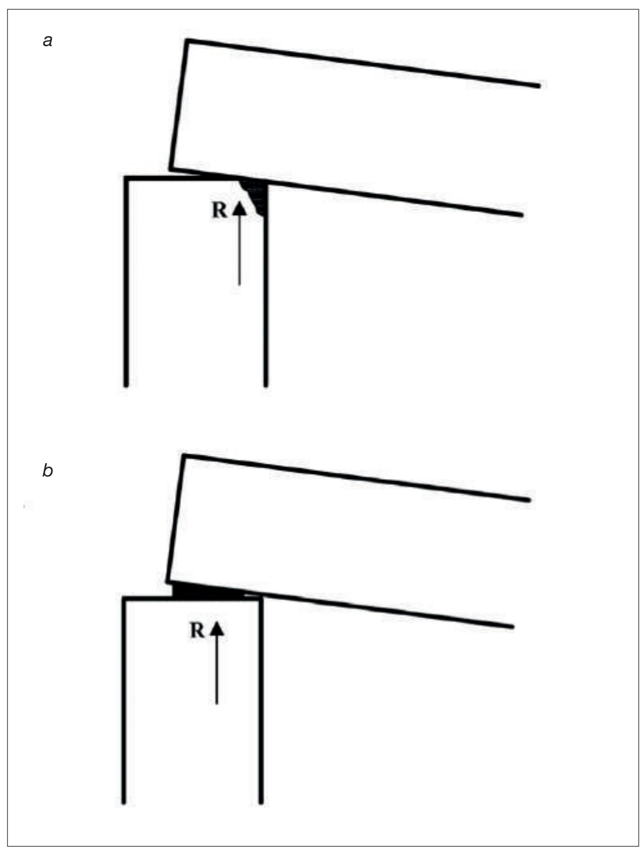

FIGURE 4 Bending stresses and concrete spalling on the column, avoided by means of the interposition of bearing pads
Source: ENEA

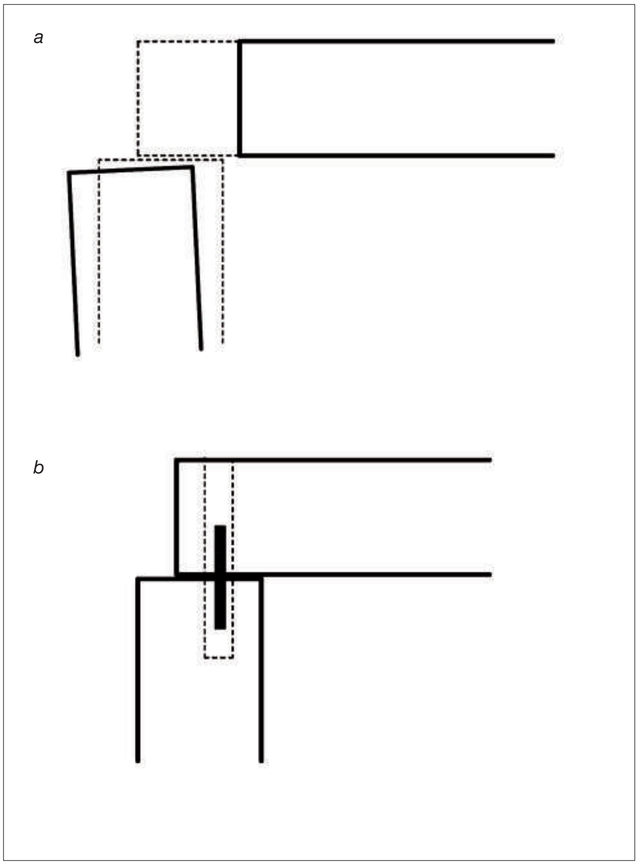

FIGURE 5 Possible relative displacement induced by external forces and insertion of a steel dowel to increase the shear resistance
Source: ENEA

FIGURE 6 Longitudinal toppling of beams for displacement limit
Source: ENEA

The observed damage in industrial buildings was mainly due to the following reasons: loss of bearing, pillar damage, collapse of external cladding panels, instability of steel shelves. Figs. 6 and 7 show some examples of loss of bearing. In many cases, the length of the bearing was too short to allow the beam-support relative motion under the seismic action. Each portal, from a structural point of view, can be depicted schematically as in Fig. 8, where the static equilibrium exists only if the horizontal forces acting on the beam do not overcome the friction forces.

Some general considerations can be made for the in-plane behaviour of the roof. To guarantee a good transfer of the horizontal actions to the vertical elements, an effective structural design requires the presence of horizontal linking elements, in order to obtain a diaphragm behaviour with effective connections to the beams. It is worth noting that horizontal actions, albeit with minor intensity, are always present on a structure. These could be related to wind [4], lack of verticality of the structures – which can be assumed equal to 1.5% of vertical permanent loads – and temperature or shrinkage effects. The loss of bearing is indeed possible if a relative motion of the top of the pillars occurs.

A surprising case of undamaged factory is sketched in Fig. 9. It shows a similar construction system, but a significant difference in the constraint details, due to the shape

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FIGURE 7 Longitudinal slipping of the roof beams
Source: ENEA

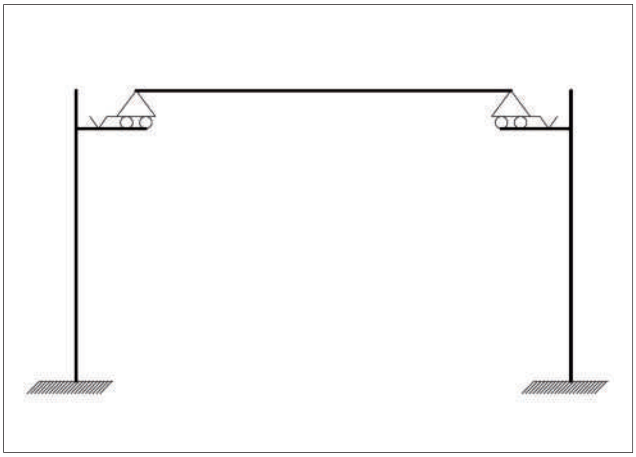


FIGURE 8 Scheme of the simply supported beams with friction
Source: ENEA

Focus

FIGURE 9 Undamaged structure: a) covering structure to beam connection; b) corner configuration
Source: ENEA

FIGURE 10 Lateral toppling of the beam
Source: ENEA

of the covering tiles, realising a tile/beam connection, effective in the seismic direction as a tying system.
In some cases the beam toppled down laterally, as shown in Fig. 10, after the failure of the lateral restraint present at the top of the columns, unable to resist to horizontal actions. Clearly, the failure mechanism depended also on the prevalent direction of the seismic motion. Different types of damage to columns are shown in Fig. 11.
Several collapses were related with non structural elements. In particular, shelves were often present in warehouse sheds, constructed by an assemblage of steel elements; they carried huge gravity loads.
Under horizontal actions, such as those due to seismic excitations, these inadequately braced structures exhibited instability (Fig. 12a). When the shelves were part of the structure (Fig. 12b), the evaluation of second order effects in the design phase is certainly significant.
Another situation observed in many cases is related to the detachment of precast external walls, due to the absence of effective connections with the main structure (Fig. 13).
In particular, the claddings were often constituted by precast panels, attached to the façade and not contained by the main structural elements, i.e., beams and columns. The mechanical connections were based on the cohesion between concrete and steel, and/or on the shear resistance of the steel element. Depending on the mass of the panels and their

FIGURE 11 Damage to columns
Source: ENEA

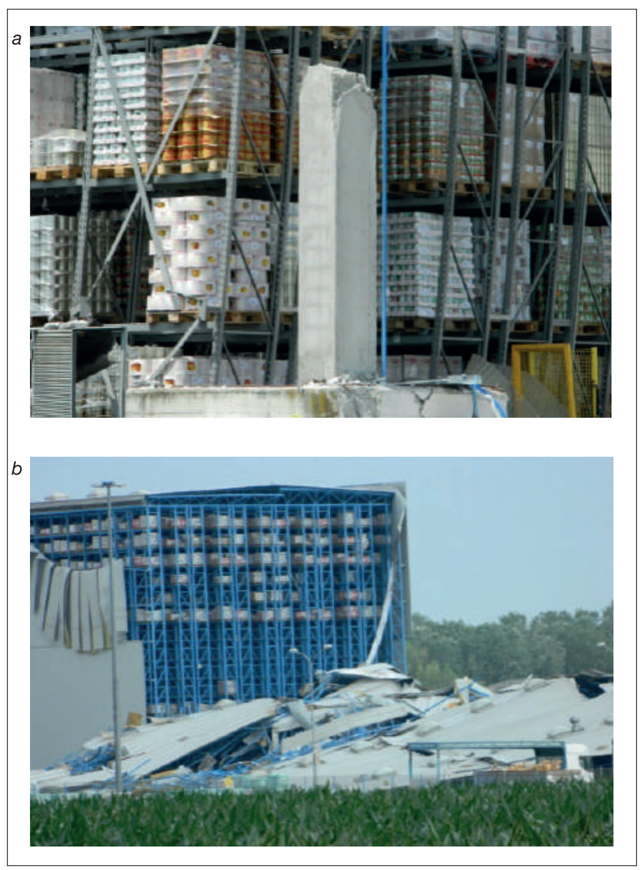


FIGURE 12 Instability of shelves
Source: ENEA

consequent inertial loads, they were unable to support stresses.
Therefore, the connections failed in many cases, leading to the detachment of the walls. Cladding made of solid brick was observed in more recent one-storey structures. In this case, the cladding suffered vast damage such as cracks (due to in-plane mechanism) or overturning (due to out-of-plane effect, Fig. 14).

Italian codes at the construction age

Historical catalogues of the events in the area did not indicate relevant seismic phenomena in a radius of 30 km away from the epicentre. The most important earthquakes are resumed as follows:
- November 17th, 1570, with epicentre near Ferrara (30 km East from the recent shock), estimated magnitude M=5.5, macro-seismic intensity I_0=VIII;
- July 11th, 1987, between Bologna and Ferrara (20 km South), magnitude M=5.4,
- July 17th, 2011, in the Reggio Emilia District (20 km North-East), magnitude M=4.7.

More important seismic events, with magnitude M≤6, occurred South of this area, in the Northern Apennines. Recently, in January 2012, two events occurred, related to the movements of the same tectonic Adriatic plate, with magnitude M=4.9 (depth 30 km) and M=5.4 (depth 60 km), respectively.
With reference to the recent Italian seismic code, the area is classified as low seismic intensity (expected peak ground acceleration PGA on rigid soil a_g<0.15g, for a return period T_R = 475 years). However, the maximum PGA values, recorded during the recent main event, were compatible with an earthquake with a higher return period.
The Italian Technical Code for Prefabricated Structures [5] indicated a minimum value of 5 cm for the support length for floor elements, in case of non-seismic areas, whereas the value 8+L/300 (cm) was given for beams, L being the span beam length. A minimum horizontal force equal to 2% of the total vertical load had to be considered in the limit state to prevent instabilities, without any combination with seismic or wind loads. The code gave also some indications about the possible insertion

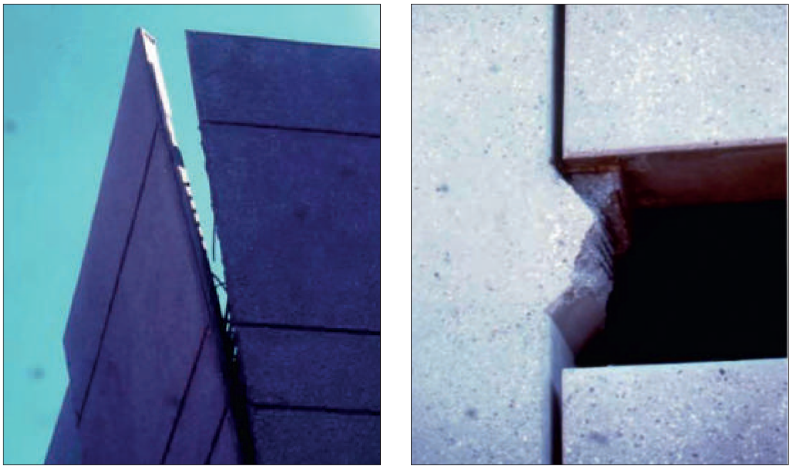
FIGURE 13 Detachment of the external wall
Source: ENEA

FIGURE 14 Solid brick cladding damage
Source: ENEA

of bracing frames to resist horizontal loads and advices against chain collapse of the elements.
Besides, it was clearly written that horizontal two-dimensional structures had to guarantee a diaphragm behavior.

Some examples of damage to industrial buildings after previous major earthquakes

Since several decades, precast/pre-stressed reinforced concrete (p/p. r.c.) structures represent a widely used typology for industrial facilities and other kinds of commercial destination all over the world. Although most of them (if well-designed and well-detailed) gave a good performance in case of major earthquakes, they showed a very sensible response when lacks in seismic codes or construction features were evident. Therefore, a short summary of cases with insufficient behaviour is set out hereafter.
For example, after the January 17th, 1994 Northridge earthquake (California, USA, M_w=6.7), several parking lots suffered widespread damage or collapse [6]. Among others, a typical example was the Cigna Garage, a multi-storey assemblage of precast and cast in-situ elements (Fig. 15), located at a distance of approximately 5.5 km from the epicentre (the closest recording station measured peak values of 0.47g, horizontal, and 0.30g, vertical). The building connections failed, due to loss of bearing of supporting elements [7].
The Northridge earthquake clearly demonstrated the deficiencies in pre-1971 (i.e., the watershed date of the M_w=6.6 San Fernando seismic event, which struck California in the same year) designed r.c. (including p/p.) structures. A large-scale revision of the code standards was carried out for various types of buildings in 1973, 1975, and later.
The January 17th, 1995, Great Hanshin-Awaji earthquake (Japan, M_w=6.9) represented another impressive lesson for seismic engineers [8].
Due to strong ground motion amplification on soft soils, extensive ground failures (caused by settlement and liquefaction), and fire after earthquake, the damage to industry resulted very heavy. In the framework of this scenario, p/p. r.c. structures, located in the most affected area, performed "remarkably well" [9]. In fact, they were newer, high quality, regular shaped construction, designed according to the 1981 Japanese revision (large for r.c. buildings, more limited for steel ones) of the code requirements since 1924 (date of the Great Kanto seismic event). On the other



(a) (b)

FIGURE 15
Cigna Garage damaged by the 1994 Northridge earthquake [7]

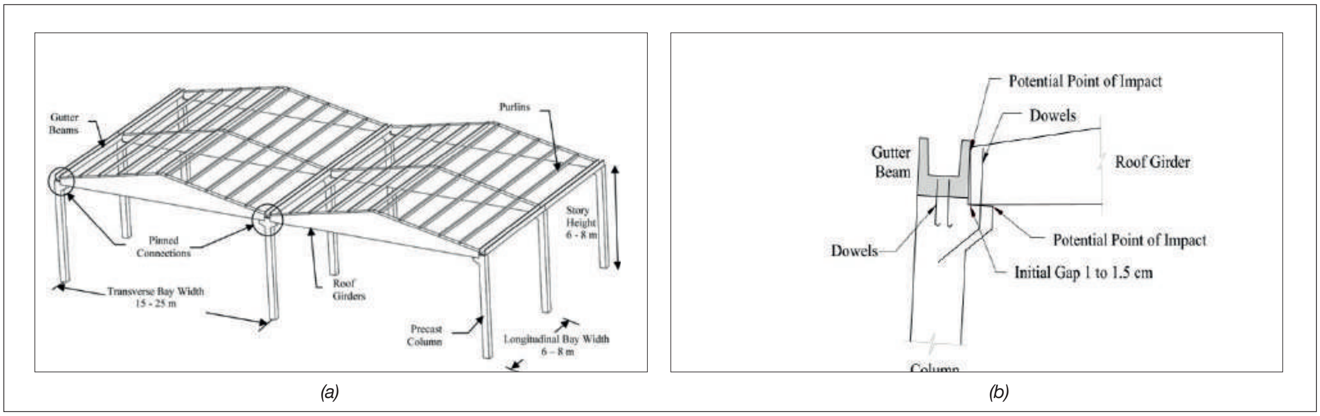


FIGURE 16 A Turkish typical configuration of one storey precast construction near Kocaeli and details [11-14]

FIGURE 17 P/p. r.c structures, with different stages of construction and seismic behaviour, located in the epicenter area of the Kocaeli earthquake, and details of the connections [11-14]

hand, collapse and extensive damage was concentrated in pre-1981 r.c. and steel stock.
Some typical one-storey industrial pre-cast structures (Fig. 16), located in the epicentre area of the August 17^{th}, 1999, Kokaeli earthquake (Turkey, M_w=7.4), didn't show good results, while others remained undamaged (Fig. 17) [10].

The collapse was mainly due to poor design, detailing, and construction, leading to the lack of diaphragm action caused by the inadequate connections (pinned or dowel, simple to realize by the prefabricators) between columns and beams. In addition, buildings under construction were susceptible to collapse when the roof girders rotated off their supports.

FIGURE 18 Damage and partial collapse of the Xiting Package Ltd. Factory complex in Mianzhu City, Wenchuan, China [15]

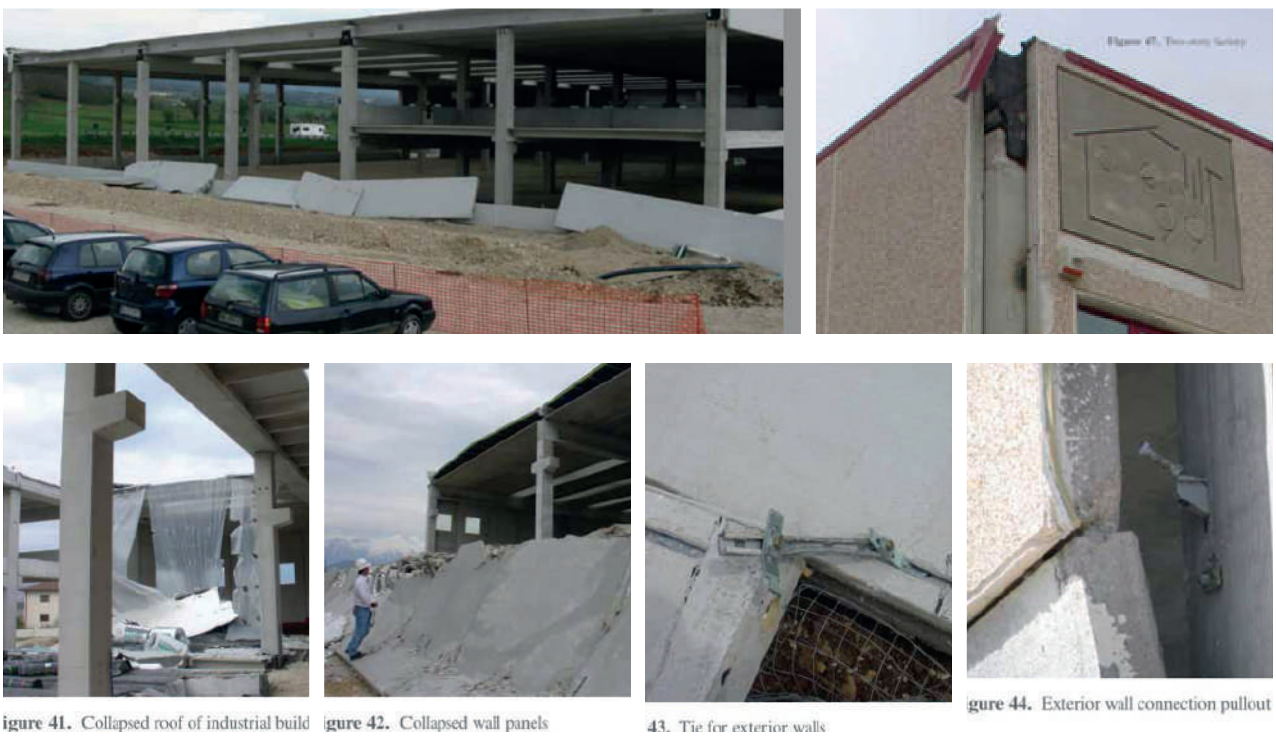


FIGURE 19 Collapse due to lack of adequate anchoring in p/p. r.c. structures in L'Aquila [17]

Also after the May 12nd, 2008, Wenchuan earthquake (China, M_w=7.9), industrial buildings and facilities in the area near the fault rupture were severely affected, as shown in Fig. 18 [15].

The April 6th, 2009, Abruzzo earthquake (Italy, M_w=6.3) again seriously affected some p/p. r.c. buildings, generally unanchored or inadequately braced [16, 17]; taking into account the relatively new vintage and the existing seismic classification of the area before the event, the level of damage was surprising (Fig. 19).

Conclusions

From the observation of the damaged buildings, as described in the previous paragraphs, some general considerations can be made. Obviously, each case has to be considered in detail and collapse causes investigated deeply. In some cases, more than prescription codes, a good knowledge of structural engineering can be sufficient to avoid failures. Indeed, the three-dimensional solidity of the entire structural system could be better guaranteed. As a concurrent cause of the damage which affected industrial buildings, the work also evidences the aspects related with soil characteristics and low-frequency content of the seismic signals.

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THE PIANURA PADANA EMILIANA EARTHQUAKE

The paper reports the most common mechanisms of damage in churches, oratories and steeples as a result of the damage survey carried out by ENEA researchers in the areas of Emilia-Romagna region affected by the earthquake of May 2012, with particular reference to the historical centres. The surveys, mainly carried out immediately after the event, concerned the mere observation of the damage from the outside. Considering the great extent of the area affected, from the province of Ferrara to those of Bologna and Modena, and the large number of churches in any Italian town, it is easy to imagine the amount of damage caused by this earthquake to religious, architectural and artistic heritage. The earthquake showed the high vulnerability of the religious heritage of Emilia-Romagna and, more generally, of the Italian heritage, mostly located in areas of high seismicity, too often subject only to unsystematic interventions of repair, consolidation, renovation

Damage to religious buildings due to the Pianura Padana Emiliana earthquake

Elena Candigliota, Bruno Carpani, Francesco Immordino, Alessandro Poggianti

An ENEA scientific team, composed by architects, conservators, engineers and geologists visited several towns damaged by the Emilia-Romagna earthquake during the period between the quakes of May 20th and 29th,and in the post-May 29th event. The mission, which is currently ongoing, has been focused on AEDES surveys of housing and commercial building at first, then several surveys were made to realize the level of damage to historic centres. Of the 2000 events occurred in the first month after the first main event, 7 had magnitudes greater or equal to 5.0 and 27 magnitude values ranging between 4.0 and 5.0 [1]. Over time, these continuous shocks worsened the historic monuments' condition, so that a certain number of structures which had been standing up after the first events eventually collapsed. Although this work shows many buildings suffering serious damage to the exterior, many others churches and bell towers without evident outside damage were declared unsafe.The present paper reports on a preliminary qualitative survey exclusively made on the outside damage of the buildings affected.

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Territorial context

Damage to the historical heritage covers a wide area (Fig. 1) from the province of Ferrara to the east to the province of Modena to the west, affecting some towns in Bologna territory too. In Italy, each city has several religious buildings, country churches, parish churches and cathedrals, towers and historical buildings, hence thinking about the extension of the area affected it is easy to imagine the extent of damage to historical heritage. Furthermore, many of these

FIGURE 1 Localization of the epicentres of the main events, of the city visited and images of their monuments become the symbol of this earthquake (on image by Google Earth)

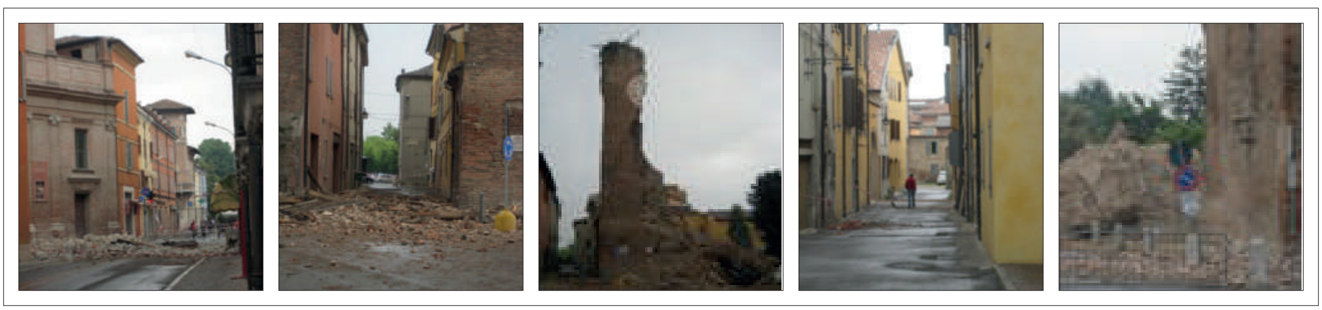

FIGURE 2 Historic centre of Finale Emilia on the morning of May 20th
Source: G. Idone

FIGURE 3 Historic centres of San Felice sul Panaro (photo 1) and Mirandola (photos 2 & 3)

ancient buildings served as symbol places for people. Some of these are now completely destroyed, while others, albeit without evident damage, were declared unsafe due to inside structural damage.
Many historical buildings are located in high-risk areas; there are whole towns of particular architectural value with churches and palaces worth preserving. Unfortunately, the Emilia-Romagna earthquake revealed, once again, the vulnerability of the historical Italian heritage. In Figure 1, the earthquakes epicentres are marked in red, and the towns and places (in yellow and green, respectively) most affected are shown, each with the image of the building become symbol of this earthquake. The historic centres have lost their symbols, the places that characterized the city – often meeting places of the community – are now inaccessible and towns show ghostly landscapes with piles of rubble and impassable fences (Figs. 2 & 3). Figure 2 shows the historic centre of Finale Emilia a few hours after the quake of May 20th. The first photo of Figure 3 shows a view of the square in front of the cathedral of San Felice sul Panaro, with the church damaged by repeated shocks; photos 2 and 3 of the same figure show two views of the historic centre of Mirandola, the first close to the cathedral whereas the second offers a view of what remains of the church of San Francesco.

The churches: centuries of history destroyed

The earthquake damaged a very large number of churches, maybe some hundreds, several of which with major collapse, others with severe structural damage and many still unusable; some of them were in poor condition, also many of those which had survived over the centuries through specific maintenance interventions, often in roofing. Examples considered relevant to the type of damage are shown below.

FIGURE 4 Church of Natività, Rivara, San Felice sul Panaro (drawing by [2])

FIGURE 5 Church of Annunziata in Finale Emilia (photos 1&2); Church of S. Possidonio, San Possidonio (photos 3&4)

Mechanisms of the top of the façade

One of the most common failure mechanisms in cases of severe damage was the out-of-plane collapse of the tympanum. In some cases the damage displays a horizontal crack and the collapse of the entire macroelement (Figs. 4 & 5).

In other cases, the collapse occurred with a V shaped crack and the crumbling of the masonry, as in the badly damaged church of S. Luca in Camurana (photos 1 & 2 in Fig. 6). Another case of V shaped crack is shown in the church of S. Francesco d'Assisi in Finale Emilia (photo 3 in Fig. 6).

There have been cases of overturning of the tympanum and disaggregation of the underlying part of masonry in such a way as not to make the collapse mechanism clear (photos 1 & 2 in Fig. 7), or cases of horizontal cracks in a position lower than the base of the tympanum (photos 3 & 4 in Fig. 7).

Overturning of the façade and mechanisms in the plan

Another mechanism observed in many damaged churches is the detachment with consequent overturning of the façade as in the church in Vigarano Mainarda (Fig. 8). The beginning of the mechanism in the top part is quite widespread, and required many interventions for safety with provisional tie rods (photo 3 in Fig. 12).

FIGURE 6 Church of S. Luca, Camurana, Medolla (photos 1&2), Church of San Francesco d'Assisi, Finale Emilia (photo 3) (drawing by [2])

FIGURE 7 Church of SS Filippo e Giacomo, Cathedral, Finale Emilia (photos 1&2), Church of Santi Senesio e Teopompo Martiri, Medolla (photos 3&4)

FIGURE 8 Church of Natività della Beata Vergine Maria, Vigarano Mainarda (drawing by [2])

FIGURE 9 Church in Finale Emilia (photo 1); Church of Madonnina, Mirandola (photo 2); Church of SS. Rocco e Sebastiano (photo 3), Pieve di Cento; Church of S. Giovanni, Bondeno (photo 4)

FIGURE 10 Church of the Madonnina, Mirandola (drawing by [2])

In plane, the damage mechanism of the façade – often with vertical cracks from the tympanum to the architrave of the entrance portal through the rose windows of the churches – has been observed too. Figure 9 shows the various severity levels of this type of damage.

Damage of domes, drums and tiburium

The figures below show some cases of this typology of damage. The drum of the Church of Madonnina in Mirandola was seriously damaged, from the outside it is not possible to see any damage to the dome because of the covering.

The *tiburium* of the cathedral of Carpi shows clearly visible cracks in the front facing the square (Fig. 11), whereas the dome of the church of S. Maria Maggiore in Pieve di Cento has completely collapsed and its drum is now bounded with provisional tie rods (Fig. 12).

Damage in the lateral chapels

Significant shear cracks are present in the lateral chapels of several churches. The detachment of the outer walls of the chapels from the walls of the church and shear cracks in the walls of chapels and side aisles are often observed (Fig. 13).

Structural collapses

The figures below show some important collapses of structural parts. The church of S. Egidio Abate in Cavezzo was particularly damaged with the collapse of roof and vault. The first photo of Fig. 15 shows the church of S. Francesco, already severely damaged by the earthquake of May 20th, almost completely collapsed after the event of May 29th.

Already damaged by the earthquake of May 20th, also the cathedral of Mirandola, with the event of May 29th, saw the partial collapse of the façade and the roof. The roof

FIGURE 11 Cathedral of S. Maria Assunta, Carpi (MO)

FIGURE 12 Church of S. Maria Maggiore, Pieve di Cento (BO)

FIGURE 13 Church of S. Silvestro, Crevalcore (BO); Church of San Michele Arcangelo, Poggio Renatico (FE); Church of San Possidonio, San Possidonio (MO); (drawing by [2])

FIGURE 14 Church of Sant'Egidio Abate, Cavezzo (MO)

FIGURE 15 Church of S. Francesco (photo 1) and Cathedral (photo 2) in Mirandola; Church of Santa Caterina d'Alessandria, Rovereto di Novi (photo 3, by courtesy of P. Clemente)

FIGURE 16 Church of S. Martino, Buonacompra, Cento (FE)

FIGURE 17 Oratorio Ghisilieri, San Carlo, Sant'Agostino (FE)

collapse in the badly damaged church of Santa Caterina d'Alessandria in Rovereto di Novi, in Novi di Modena town, has become infamous for causing the death of the priest. Little is left – except for the perimeter walls and piles of rubble to recover – of the church of S. Martino in Buonacompra, and of the Oratorio Ghisilieri in San Carlo, in Sant'Agostino town.

Bell towers damaged, collapsed or demolished

In addition to the churches, in many cities affected by the earthquake there are steeples damaged and declared unsafe, in some cases collapsed or demolished, with belfries destroyed or removed by fire-fighters due to the high risk of collapse. At the end of June, there were already reports of 147 church steeples in need of safety interventions and measures [3]. This type of construction, particularly affected by this earthquake, constitutes an important set of cultural heritage in Italy. Its seismic behaviour is dependent on many factors, such as the slenderness of the structure, the degree of gripping of the walls, the presence of adjacent lowest structures able to provide a horizontal constraint, the presence of tie rods, the presence in the top part of slender architectural elements (spiers, bell cells, etc.), or other vulnerable ones (belfries) [4].
In some cases the vulnerability is influenced by pre-existing damage, for example due to problems in the founda-

tion (frequent cases in the area where inclined steeples are found) and to masonry in bad state of conservation. The bell cells, with large openings, show serious shear cracks in the little columns, with sliding in the most severe cases (Fig. 18). Some of them are disaggregated under the action of the earthquake, others have been removed from firefighters, others made safe. When the steeple is placed in contact with other structures of lower height, this can cause local damage; an example is the bell tower of church in Cavezzo (Fig. 19).
In the pictures in Fig. 20, two cases of severe damage are reported; the first two photos show the bell tower

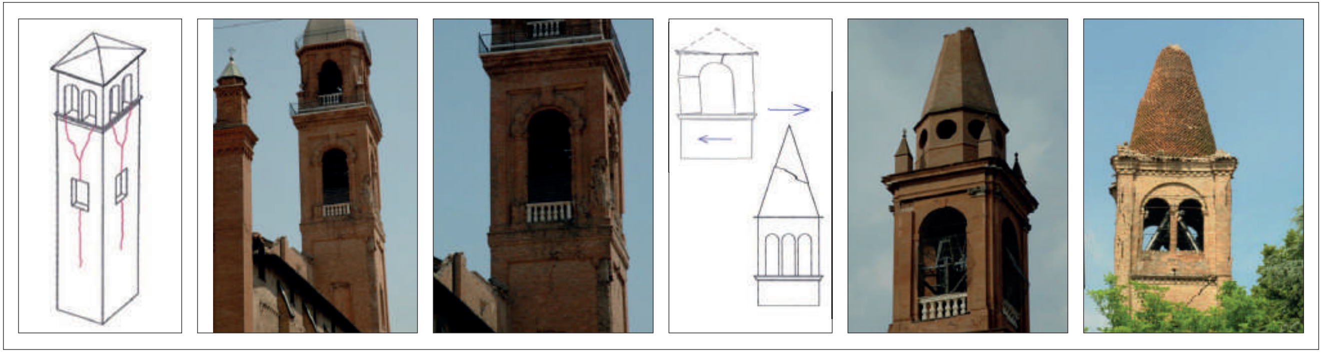

FIGURE 18 Steeples of: Cathedral, Mirandola (photos 1 & 2); Church of Sant'Egidio Abate, Cavezzo (photo 3); Church of Santa Caterina d'Alessandria, Rovereto di Novi, (photo 4, by courtesy of P. Clemente), (drawings by [2])

FIGURE 19 Steeple of Sant'Egidio Abate Church, Cavezzo (drawing by [2], photo 1 by Google maps)

FIGURE 20 Steeples of: Church of S. Martino, Buonacompra, Cento (FE), Church of S. Michele Arcangelo, Poggio Renatico (FE)

of the Church in Buonacompra during the demolition. Photo 2 shows the severe shear two-level damage, due to torsional stress, that led to the decision to demolish the tower. The last two pictures in Fig. 20 show the church of S. Michele in Poggio Renatico deprived of its bell tower, blown up as a threat to public safety due to its serious structural problems.

Hazard caused by non-structural elements

Firefighters intervened many times on the top of the church façades and bell towers to remove slender elements, such as statues and spears, with vulnerability due to their low vertical load and weight, which provides a limited stabilizing effect in regard to the turnover. Spiers, crucifixes, statues that fall from the church roofs, often with metal anchors

FIGURE 21 Church Matildica and Church of the Sante Grazie in Bondeno; Church of San Bartolomeo, Finale Emilia

FIGURE 22 Church of Santa Croce, Crevalcore (BO), (drawing by [2])

weak or too short, represent a danger often underestimated.

Many interventions have been made to put the bell cells in safety and, in some cases, disassemble them. In other cases, overhang host bells have reported shear cracks with displacements due to sliding along the shear cracks, as in the church of Santa Croce in Crevalcore (Fig. 22).

Conclusions

The Emilia-Romagna earthquake has destroyed a significant part of the cultural heritage and the identity of the people living in this region.

Many churches and bell towers were seriously damaged or collapsed, and too many of them are still unusable. In the churches damage was frequently caused by the out-of-plane failure of the church façade and by the collapse of vaults and roof. Some of them are in bad state of general conservation, with poor masonry or wood roofs deteriorated, but there are also damaged churches that have received regular interventions of repair or consolidation. Some churches were apparently well preserved, as the cathedrals, which, in spite of the various maintenance interventions, have been damaged too. As regards the steeples, the most widespread damage occurred to bell cells that show serious shear cracks in the little columns. A type of damage, often underestimated, concerned the fall of decorative elements from the roof of churches and steeples.

The earthquake showed the high vulnerability of the religious heritage of Emilia-Romagna and, more generally, of the Italian cultural heritage, mostly located in high-risk areas, too often subject to unsystematic interventions of repair, consolidation, renovation, or to local interventions carried out without analyzing the global seismic behaviour of the structures.

Acknowledgements

The authors thank the government of the visited municipalities for permission to access the confined areas, and the firefighters of Bondeno, Salerno, Rimini, Bologna, Parma for their presence during the visits, making sure that everything was done safely. A nice thank to Giuseppina Idone from Finale Emilia for the photos taken immediately after the event of May 20th.

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THE PIANURA PADANA EMILIANA EARTHQUAKE

During the seismic event of May 2012 in the Emilia-Romagna Region (Italy), several cultural heritage structures (in particular churches and bell towers) collapsed or were severely damaged. This paper gives a description of the damage/collapse mechanisms observed on some buildings, subject of the investigation of the ENEA expert teams, supporting the Italian Civil Protection Department and the Regional Directorate for Cultural Heritage and Landscape in Emilia-Romagna

Damage and collapse mechanisms in churches during the Pianura Padana Emiliana earthquake

■ *Maurizio Indirli, Giuseppe Marghella, Anna Marzo*

The seismic sequence, which hit the Emilia-Romagna Region and surroundings (May 20th, time 04:03, principal event Mw 6.0, focal depth about 6 km, epicentre near Finale Emilia; May 29th, time 9:00, principal event Mw 5.8, two strong aftershocks Mw 5.3, time 12:55, Mw 5.2, time 13:00, epicentre near Cavezzo-Medolla-Mirandola; June 3rd, time 21:20, Mw 4.9, epicentre near Concordia sulla Secchia-Novi di Modena), caused 27 deaths, some hundreds of injured people, thousands of homeless, heavy damage to and some collapses of strategic and residential buildings, factories and infrastructures, cultural heritage. This earthquake evidenced that the Po Valley is also prone to seismic risk, although the area has been included in the Italian seismic zonation only after 2003. Immediately after the first event, which struck the Districts of Ferrara, Modena, Reggio Emilia, Bologna (Emilia-Romagna Region), Mantova (Lombardia Region) and Rovigo (Veneto Region), an ENEA team of experts (Maurizio Indirli, Bruno Carpani, Elena Candigliota, Alessandra Gugliandolo, Francesco Immordino, Giuseppe Marghella, Anna Marzo, Giuseppe Nigliaccio, Alessandro Poggianti, Maria-Anna Segreto) supported the Italian Civil Protection Department, in order to perform prompt investigations regarding the safety evaluation of different typologies of structures (bridges, industrial factories, residential houses, etc.), made of various kinds of materials (masonry, reinforced concrete, precast/pre-stressed reinforced concrete, mixed). In addition, from September 4th, 2012, ENEA experts (Bruno Carpani, Elena Candigliota, Maurizio Indirli, Giuseppe Marghella, Anna Marzo, Alessandro Poggianti) joined *ad hoc* teams, arranged by the Regional Directorate for Cultural Her-

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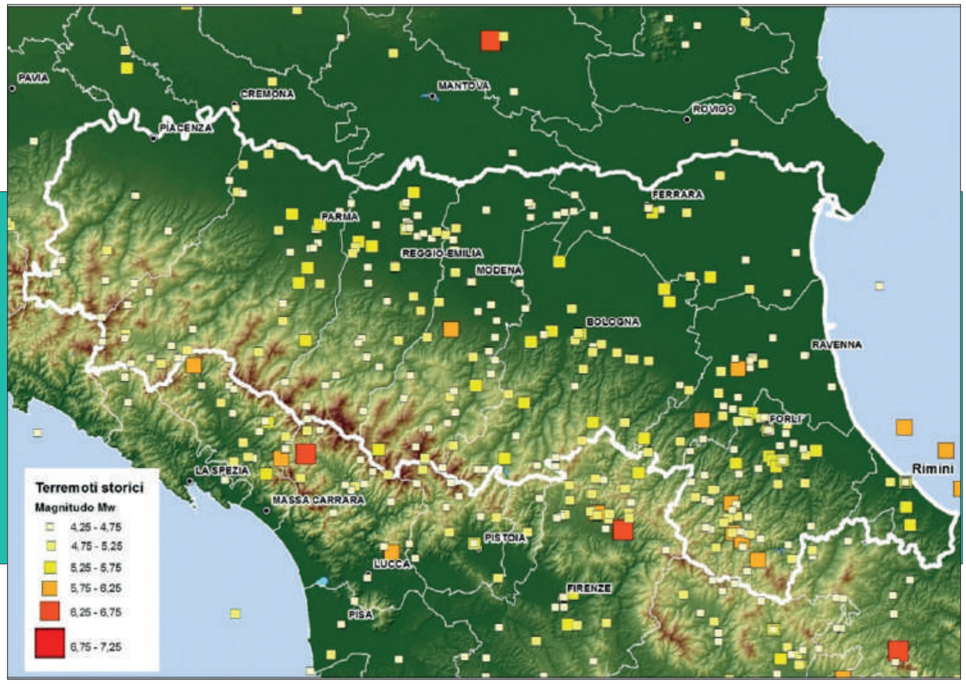
FIGURE 1
Map of historic seismicity in Emilia-Romagna and surroundings
Source: INGV



itage and Landscape in Emilia-Romagna, devoted to investigations on this category of assets.
In particular, this article focuses on the behaviour analysis of churches and bell-towers, mainly masonry construction, widely affected by the May-June 2012 seismic events.

Historic seismicity: brief information about damage due to past eartquakes

The Padana Plain was hit by earthquakes since the antiquity, including cities and villages of Emilia-Romagna (Fig. 1). In the Roman period, Gaius Plinius Secundus ("Plinius the Older") wrote in his *Naturalis Historiae* (Book Third) that the place "Campi Macri", near Modena, was abandoned by the residents after the shake occurred in 91 b. C..
The most important event, cited in several old European documents, occurred in 1117, epicentre near Verona, IX MCS (Mercalli-Cancani Sieberg) Intensity, causing maybe 30000 victims in all the large affected zone; in the city of Verona, the second circle of the Roman amphitheatre (Arena) collapsed (except the still standing small portion currently named "the Wing"), and most of the medieval architecture ruined *("terremotus maximus fuit, in quo etiam magna pars Arene cecidit"*, from the *Annales Veronenses antiqui* [1-2]); widespread failures in churches and abbeys (for example, the famous Benedictine complex of Nonantola, near Modena) were registered, but the famous Romanesque cathedral (San Geminiano) and the Tower (Ghirlandina) in Modena, starting to be built a few years before and reaching an intermediate height, showed no damage, and this fact was felt as a miracle by the inhabitants; furthermore, natural overturning affected the River Po, which changed its bed.
Other seismic events (with Intensities from VI to IX) took place in the following centuries between Bologna, Modena and Reggio Emilia (1249, 1365, 1399, 1455, 1465, 1501, 1504-1505, 1547), with different levels of damage (from moderate to strong) to churches, towers, castles and other important buildings.
The 1501 earthquake (Maximum Intensity IX) struck

FIGURE 2 Detail of “Torre Mozza” before its demolition (on the left from the Ghirlandina Tower), from a painting located in the Modena Municipality Palace

FIGURE 3 Argenta earthquake (1624) in a painting of Camillo Ricci (Picture Gallery of Argenta)

the belt among the flat and the Apennines between Bologna and Reggio Emilia, with the strongest effects in Castelvetro, Maranello and Sassuolo; the Italian personality Jacopino de' Bianchi de' Lancillotti (living in Modena from 1440 to 1502) was the reporter of the partial demolition of the Modena Municipality Palace tower (now known as "Torre Mozza", se e Fig. 2); other damage interested several churches (the Cathedral, San Francesco, Sant'Agostino, San Biagio); Jacopino de' Bianchi describes the Ghirlandina Tower under the earthquake "as a poplar shaken by the wind"

.The 1671 event (Intensity VII) hit again Modena and surroundings (until Carpi, Correggio and Nonantola), with some damage and the partial failure of the Clock Tower of the Modena Municipality Palace.

Bologna supported heavy earthquake effects in 1365 (Intensity VII-VIII), with some victims and widespread damage to important constructions (palaces, churches, towers); the people joined themselves into religious processions and pilgrimages to the Sanctuary of Santiago di Compostela; in Bologna, in 1504 (Intensity VI) and 1505 (Intensity VII), the seismic crisis was responsible of some casualties and similar damage as 1365; in all the cited events, failure of old towers occurred, and some of them were demolished or lowered.

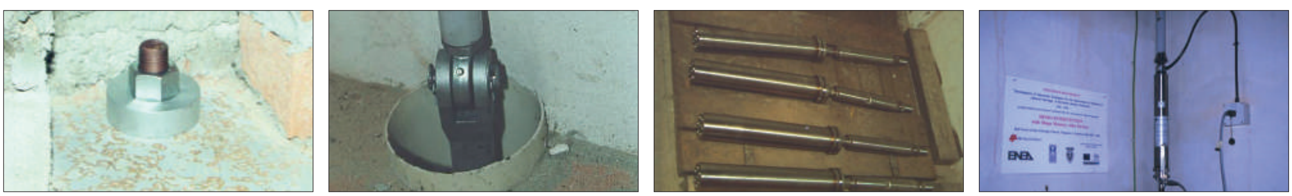
In the city of Ferrara, the 1346 earthquake (Intensity VII-VIII) caused widespread damage, but the 1570 event was the worst (Intensity VIII, series of aftershocks until 1574), with about 70 deaths, heavy failures and collapses in the medieval portion of the city (40% of high structures and houses ruined), with the escape of about 11000 inhabitants out of 32000, in an atmosphere of collective panic and prostration.

Subsequently, in Argenta (a town close to Ferrara) during the 1624 event (Intensity VIII-IX), the casualties were about 50, and the destructive effects of the earthquake were amplified by sandy soil and shallow aquifers, with the presence of cracks in the ground and outputs of black mud, causing foundation failures and subsequent structural collapses of about 25% of the houses (Fig. 3).

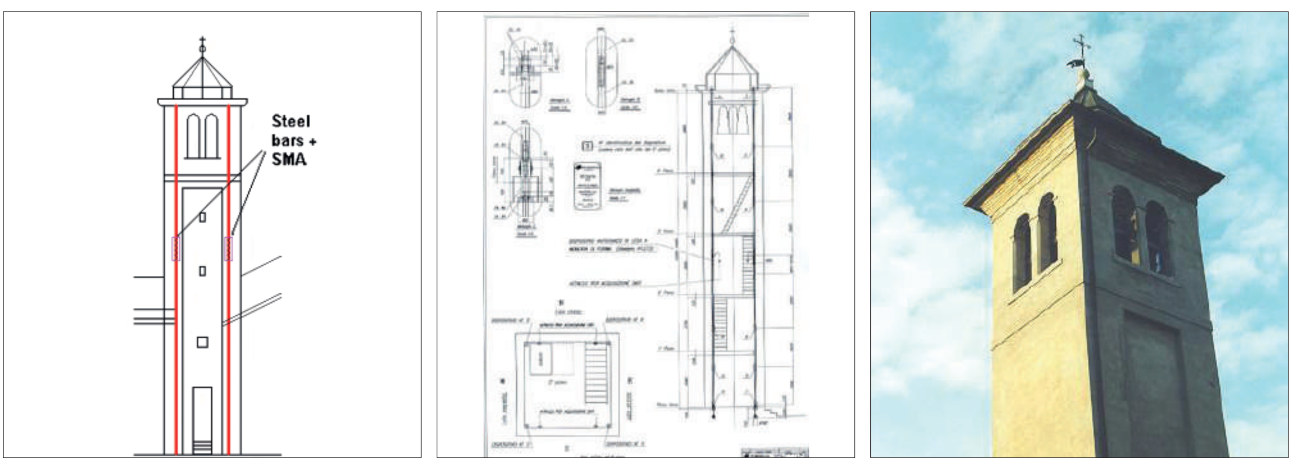
The San Giorgio Church and its Bell-Tower (Trignano, San Martino in Rio, Reggio Emilia, Italy)

(a) (b) (c) (d)

Cracks on the Bell-Tower (a, b) and rotation of the upper structure (c, d)



(e) (f) (g) (h)



(i) (j) (k)

Application of 4 steel tie bars including SMADs: intervention scheme (i); anchorages at he building top (e) and at the foundation (f); SMADs before (g) and after (h) assembling; intervention details (j); bell-tower after restoring (k)

FIGURE 4 The Bell-Tower restoration at the San Giorgio in Trignano Church (San Martino in Rio, Reggio Emilia)

More recently, an earthquake struck the Districts of Reggio Emilia and Modena on October 15th, 1996 (Mw 4.8 and VII MCS). A significant number of damaged structures was observed, especially concentrated in the historical heritage. Also in this case, immediately after the seismic event, ENEA placed some personnel to investigate the performance of the structures, operating in some towns, but principally in the Municipality of San Martino in Rio (Reggio Emilia, Italy), located inside the more affected area [3-4]. During the reconstruction phase, ENEA carried out some studies for improving seismic protection of cultural heritage, in the framework of the ISTECH Project ("Development of Innovative Techniques for the Improvement of Stability of Cultural Heritage in Particular Seismic Protection", funded by the European Commission), leading to the rehabilitation intervention of the San Giorgio in Trignano Church Bell-Tower (San Martino in Rio).
It concerned the experimental dynamic characterization of the church plus bell-tower complex, and its post-earthquake restoration, including the insertion of 4 vertical steel ties in series with Shape Memory Alloy Devices (SMADs), an innovative technique conceived in the framework of the aforesaid ISTECH project [5-6]. Damage, restoration and intervention schemes are reported in Fig. 4. A subsequent seismic event, with about the same epicentre, occurred at 9:42 on June 18th, 2000 (Mw 4.5, MCS Intensity VI-VII). Immediately after the main shock, the bell-tower was again investigated with great accuracy by the ENEA personnel, but it showed no damage of any type. The 2000 seismic event had been the best verification of the retrofit.

The May-June 2012 events and their effects on churches and bell-towers

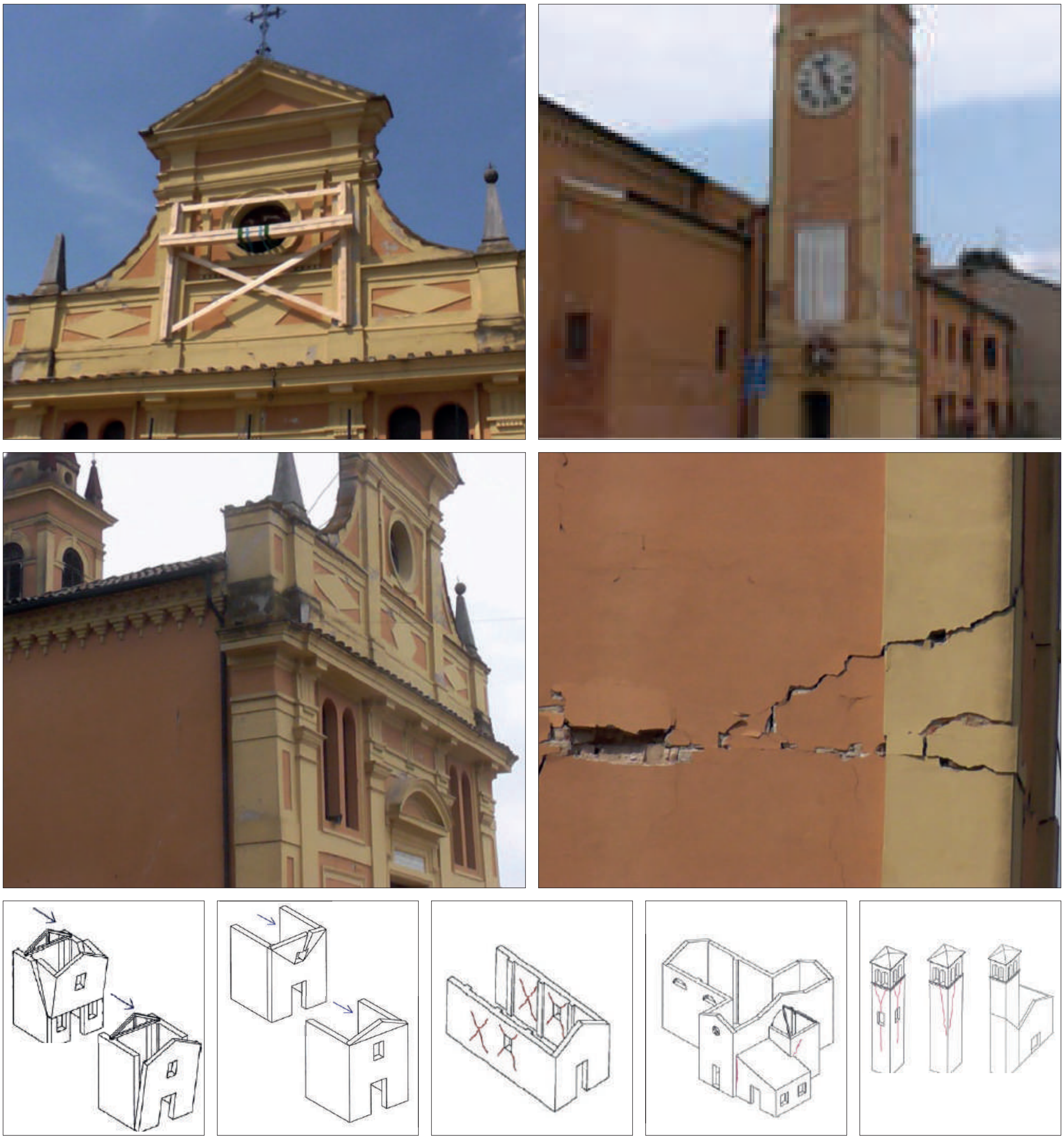
General view during the phase devoted to safety investigations, in support to the Civil Protection team

During the investigations done supporting the Italian Civil Protection Department (May-June 2012), moving inside the affected area, it was possible to carry out a quick general view on some cultural heritage assets damaged by the earthquake, although targeted technical surveys were not possible.

In this first period, an ENEA team (Maurizio Indirli, Giuseppe Marghella, Anna Marzo), operating in the vast territory of the town of Cento (Ferrara), had the opportunity to see directly some cases of damage/collapse of churches and bell-towers. The most impressive general collapse, due to the first shock (maximum May 20th peak ground acceleration, PGA: Mirandola recording station, 0.30g; Medicina recording station, 0.04g) and aggravated by the following ones (maximum May 29th PGA: Cento recording station, 0.30g), occurred in the church of San Martino di Tours (Fig. 5), located in Buonacompra (Cento, Ferrara). The construction probably started in 1399, but it was strongly modified during the XVIII-XIX centuries. A controlled demolition of the bell-tower, cut in at least three portions by the earthquake, was underway at the time of the visit, removing the masonry bricks line by line (Fig. 6).
The church of San Lorenzo at Casumaro (Cento, Ferrara) was founded in 1449 by the Bishop of Modena, but many changes were done (together with the bell-tower) during the XVIII-XIX centuries. Immediately after the first shock (the maximum PGA values are the same as the previous case), the church showed a clear out-of-plane detachment in the façade, together with shear cracks in its masonry panels and tympanum overturning; the bell-tower was close to collapse, due to deep cracks originated by bending and torsion movements during the earthquake (Fig. 7).
About a similar incipient collapse occurred to the bell-tower of the Sant'Anna church (built in 1772 and subsequently modified in the XIX century) in Reno Centese (Cento, Ferrara, PGAs as before), which has been divided into two portions by the seismic event since the first shake (Fig. 8); after a long discussion between the experts about its possible demolition, the structure has been put in safety through an innovative intervention, spraying jets of mortar and structural fibres in the cracks [7].
Also the church of San Sebastiano (XV century, modified in the XVIII) in Renazzo (Cento, Ferrara, PGAs as before) was damaged (Fig. 9). Several works of art were removed by the firemen, including a famous painting of Guercino (the miracle of San Carlo Borromeo), put in a temporary safe place.

FIGURE 5 Damage in the San Martino di Tours church and bell-tower in Buonacompra (Cento, Ferrara) and main collapse mechanisms

FIGURE 6 Controlled demolition in the San Martino di Tours church bell-tower in Buonacompra (Cento, Ferrara)



M1: façade overturning

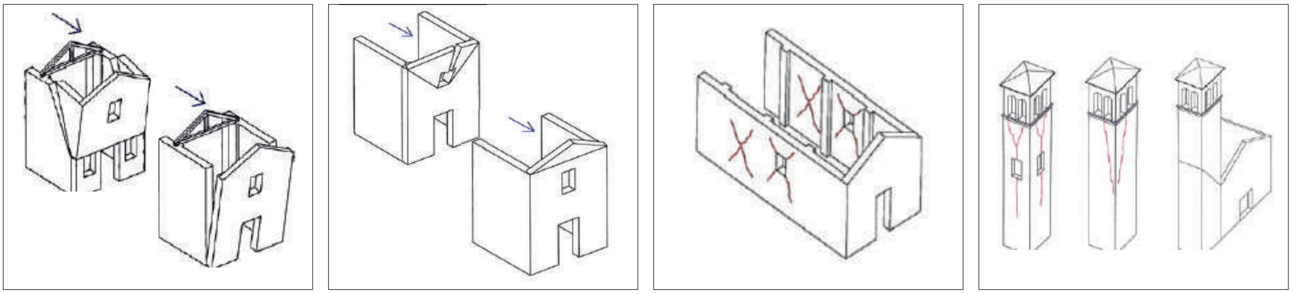
M2: mechanisms in top of façade

M6: shear in lateral walls (longitudinal response)

M25: interaction near plano-altimetric irregularities

M27: bell-tower

FIGURE 7 Damage to the San Lorenzo church in Casumaro (Cento, Ferrara) and main collapse mechanisms


M1: façade overturning

M2: mechanisms in top of façade

M6: shear in lateral walls (longitudinal response)

M27: bell-tower

FIGURE 8 Damage to the Sant'Anna church in Reno Centese (Cento, Ferrara) and main collapse mechanisms

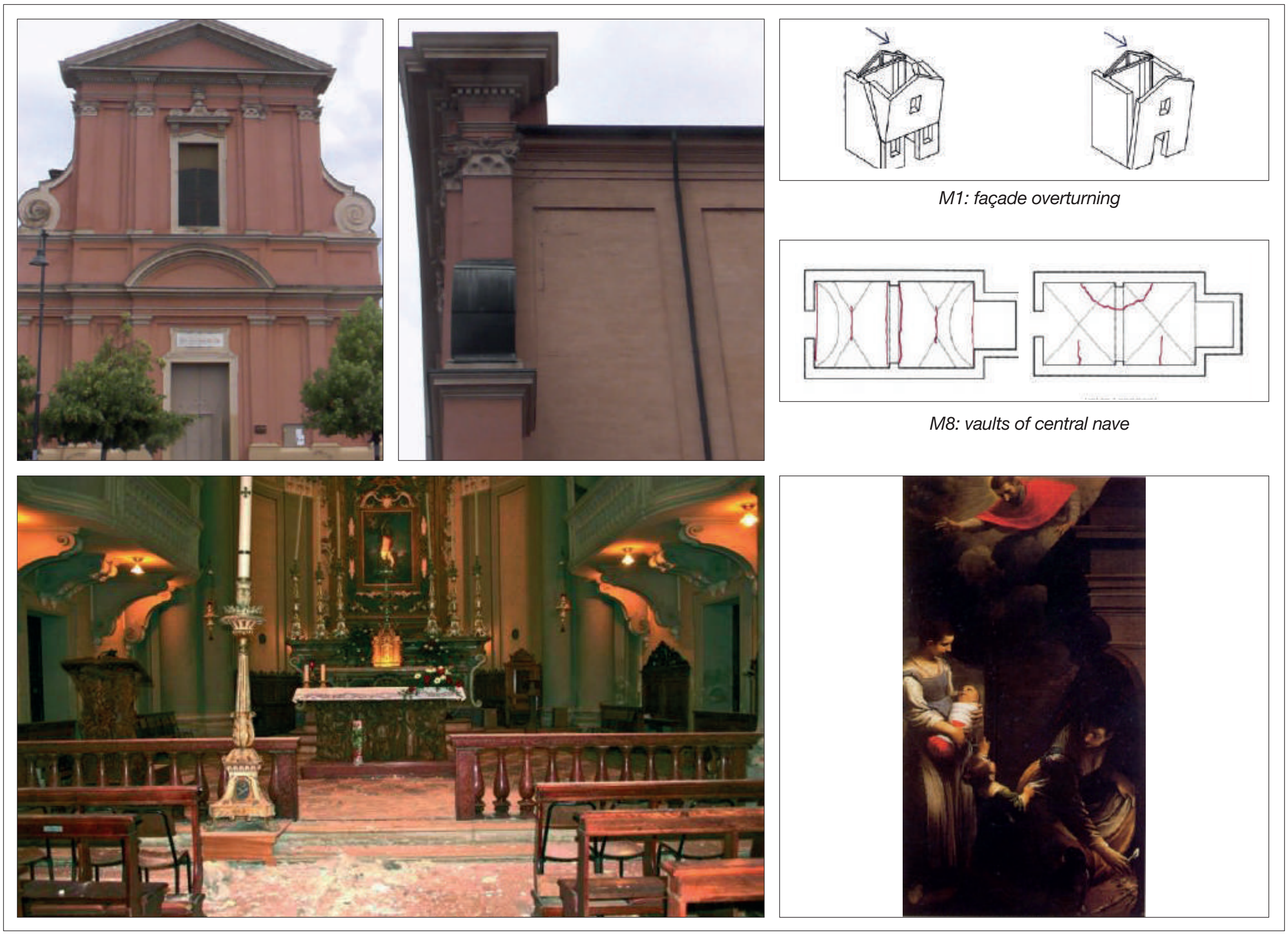


FIGURE 9 Damage to the Church of San Sebastiano in Renazzo (Cento, Ferrara) and main collapse mechanisms

FIGURE 10 Cento (Ferrara) historic centre: the church of San Filippo Neri and main collapse mechanisms

M2: mechanisms in top of façade

FIGURE 11 Cento (Ferrara) historic centre: the Church of San Sebastiano and San Rocco (Convent of Friars Capuchins) and main collapse mechanisms

M28: belfry

FIGURE 12 Cento (Ferrara) historic centre: the Church of San Biagio and main collapse mechanisms

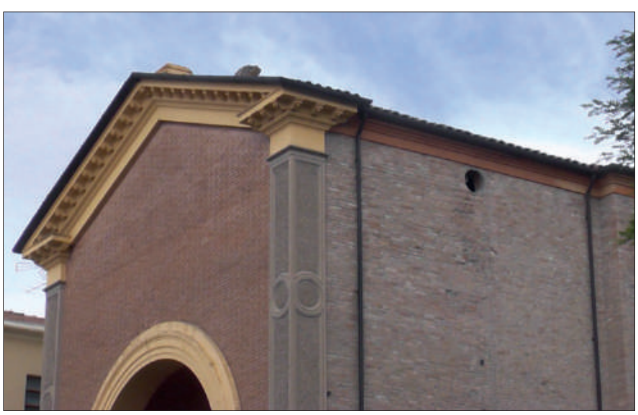
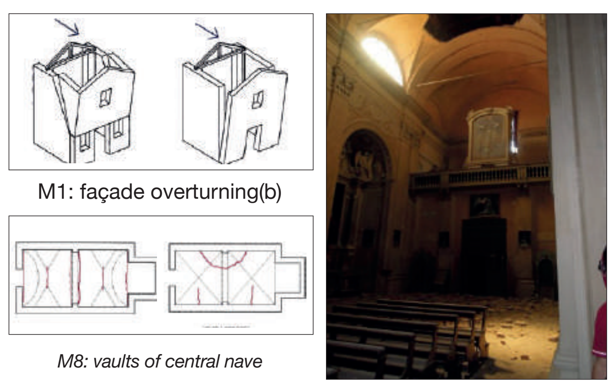


FIGURE 13 Cento (Ferrara) historic centre: the Church of San Pietro and main collapse mechanisms (middle above)



M1: façade overturning(b)

M8: vaults of central nave

FIGURE 14 Cento (Ferrara) historic centre: the Church of the Rosario and main collapse mechanisms (middle bottom)

Inside the historic centre of Cento (Ferrara), most of the damage occurred after the shock of May 29th (Cento recording station, PGA 0.30g): Church of San Filippo Neri (detachment of the façade, Fig. 10); Church of San Sebastiano and San Rocco (collapse of the tympanum, Fig. 11); Church of San Biagio (instability of the top part of the bell-tower, Fig. 12); Church of San Pietro (detachment of the façade, Fig. 13); Church of the Rosario (vault collapse, Fig. 14).

Surveys carried out under teams arranged by the Regional Directorate for Cultural Heritage and Landscape in Emilia-Romagna

A first team involving ENEA experts and the representatives of the Regional Directorate for Cultural Heritage and Landscape in Emilia-Romagna (Paola Ruggieri, Valentina Oliverio, Sandra Manara, and other experts) operated in Modena, investigating the Temple of Fallen, the Cathedral of San Geminiano together with its Tower Ghirlandina, in Minerbio (Parish of San Giovanni Battista in Triario), and Budrio (Church of San Lorenzo).
The methodology adopted is a well-established quick survey form, specifically conceived for churches [8], whereas a similar one was used for monumental palaces and other buildings [9], which is not dealt with in this article.

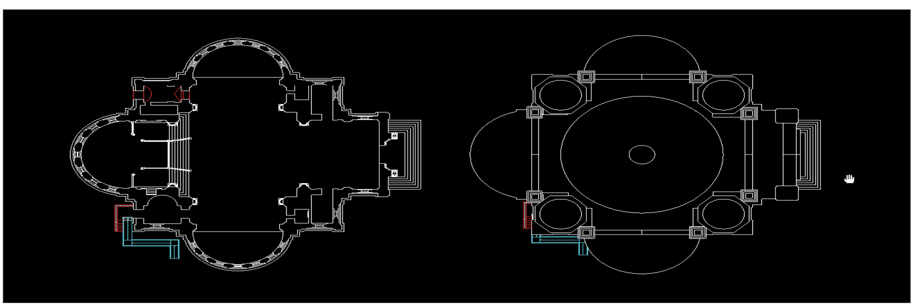
The Monumental Temple of Fallen in Modena

Description - The Monumental Temple of Fallen in Modena (Fig. 15), located in Natale Bruni Square, was built for the perpetual memory of the Fallen of Modena, dead during the First World War. The building, designed by the architect Domenico Barbanti in cooperation with Achille Casanova, is dedicated to St. Joseph.
The edification started in 1923 (completed in 1929), at the presence of King Vittorio Emanuele III and Archbishop Natale Bruni, main creator and benefactor of the temple.
His funeral chapel, with a beautiful medallion sculpted by Giuseppe Graziosi, is located inside the building. The names of the 7300 Fallen are carved on the pillars and the walls of the crypt. The church has a Greek cross plan, surmounted by a main dome, which is surrounded by four small towers.
Both the dome and the small towers have an internal iron skeleton: a reticular structure for the dome and polygonal frames for the small towers. In the main facade is possible to admire the bas-reliefs made by Adam Rubens Pedrazzi.
During the 2012 seismic events, the church experienced a PGA maximum value of 0.037g and 0.055g (Modena recording station), respectively on May 20th and 29th.

Damage survey and observed mechanisms - The survey evidenced damage due to the recent seismic event, but also previous ones. The latter are caused by subsidence, because of different soil mechanical properties.
In particular, the ground under the crypt is more deformable in comparison with the adjacent area; therefore, this part of the construction shows an in-progress sinking mechanism.
The old cracks (Fig. 16) increased with the recent earthquake, which originated new local/global damage mechanisms.
The major cracks of the main façade are highlighted with a red line (Fig. 17), and the mechanisms plotted in Fig. 18. It is worth noticing that the mechanisms related to church lateral apses have been considered as chapel mechanisms (M22 and M23).
Finally, a damage index of about 0.27 has been obtained. Soil geotechnical survey and seismological microzoning is considered mandatory, in order to evaluate how to enhance the foundations.
Moreover, also extensive material diagnostics and dynamic characterization should be carried out, aiming at a general (conventional and/or innovative) antiseismic reinforcement. Restoration should regard all the decorative apparatus.

Main façade

The small tower



Plan

Prospects

Internal dome iron frame

Internal iron frame of the small towers

FIGURE 15 The Monumental Temple of Fallen in Modena

FIGURE 16 Subsidence phenomena: a) external view; b) internal view

FIGURE 17 Façade overturning mechanism (M1), internal view

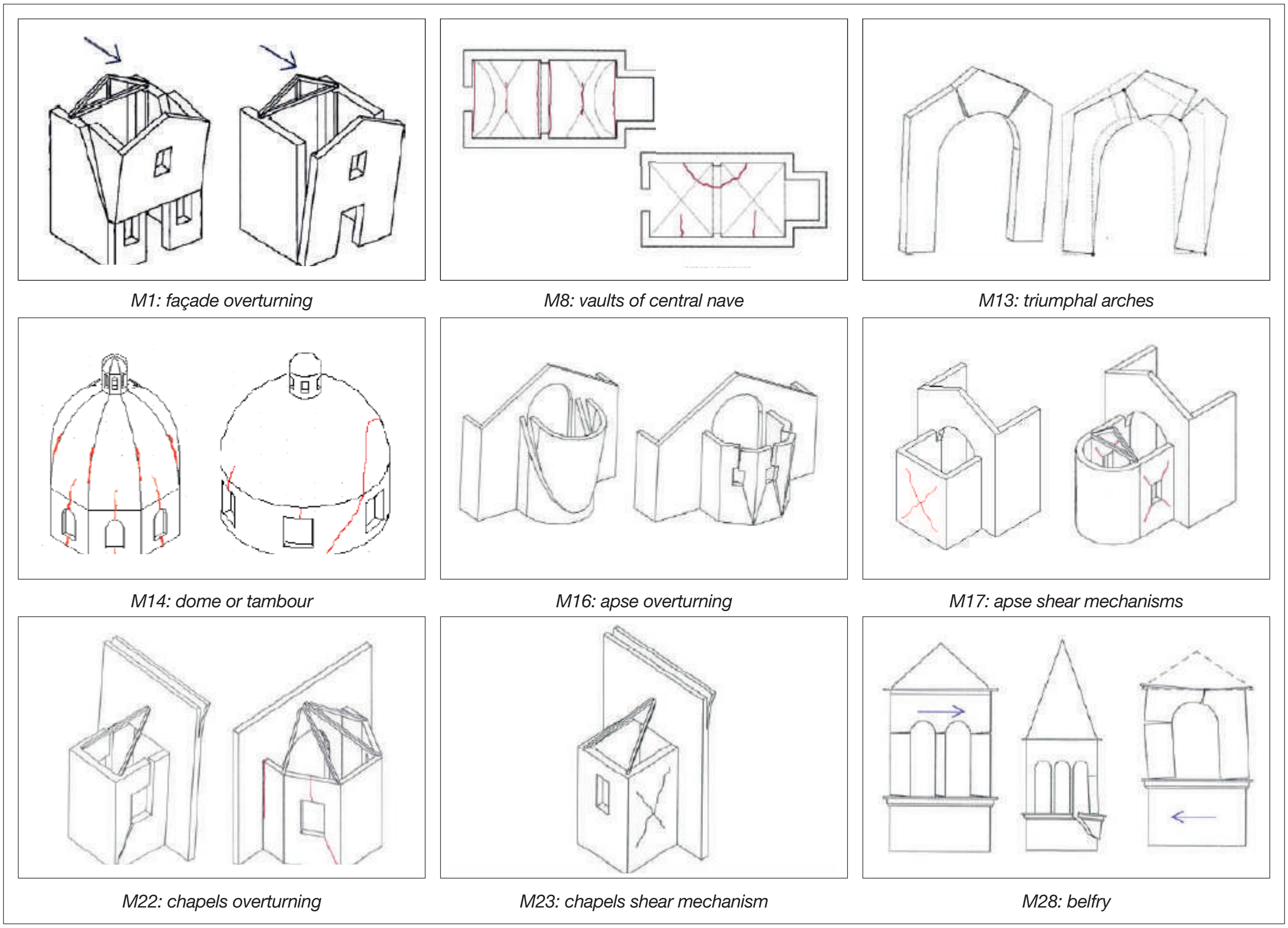
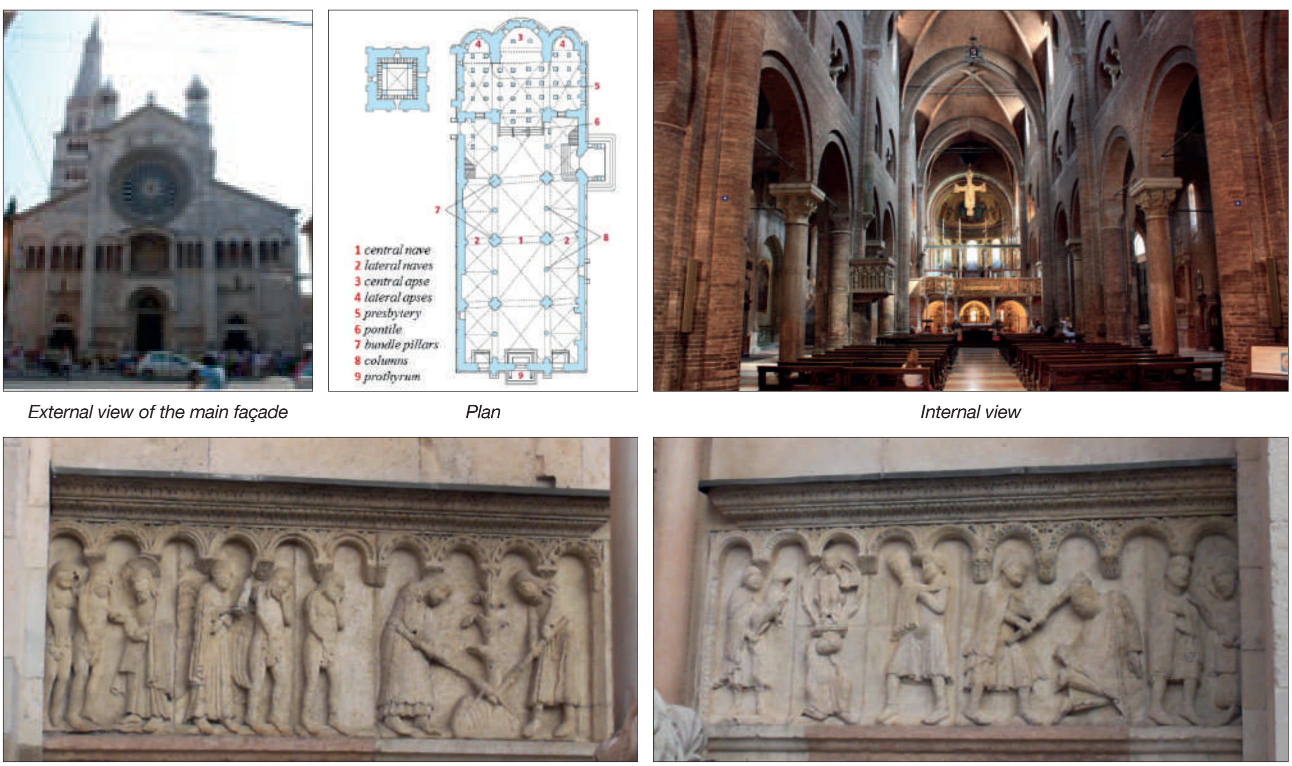


FIGURE 18 Damage mechanisms observed in the Monumental Temple of Fallen (Modena)

The San Geminiano Cathedral and the Ghirlandina Tower in Modena

Description - The San Geminiano Cathedral in Modena was constructed from 1099 onwards, on the rests of two previous churches, and consecrated by Pope Lucio III in 1184. It is one of the best masterpieces of the European Romanesque, thanks to the architectural structure of Lanfranco and the sculptural pieces of Wiligelmo (Fig. 19). In 1106, the building was already covered and the rests of Saint Patron Geminiano were moved from the old church to the new cathedral crypt. As told in Section 2, during the 1117 catastrophic seismic event, the church did not suffer any damage. The original project was later modified, starting from 1167, by the Campionesi Masters; they: opened the gothic rose-window and two lateral doors on the façade, together with the Regia Door, which enriched the lateral prospect on Piazza Grande; modified the presbytery, building the beautiful pontile; completed the Ghirlandina Tower.

Other main structural interventions, realised during the following centuries, are: the original wooden-truss covering structure was hidden by a new one (masonry cross-vaulted ceilings, between 1437 and 1455); the floor was lowered about twenty centimetres, in order to give a greater upsurge to the internal area; the external lateral buildings,
firstly laying on the church perimeter walls, were demolished (from late XIX to early XX century); realisation of the new elevated walkway to the sacristy; construction of the two transverse walls with arches, linking (without a real structural connection) the cathedral to Ghirlandina and sacristy (Fig. 20).



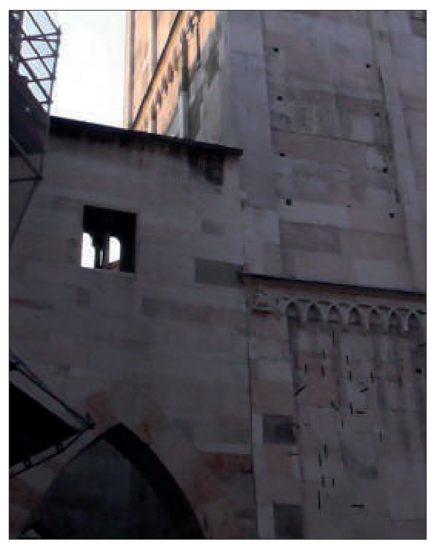
External view of the main façade *Plan* *Internal view*

The bas-relifs of Wiligelmo

FIGURE 19 The San Geminiano Cathedral in Modena

The Ghirlandina Tower

The Ghirlandina Tower



Arches between Tower and cathedral

FIGURE 20 Pictures of the Ghirlandina Tower

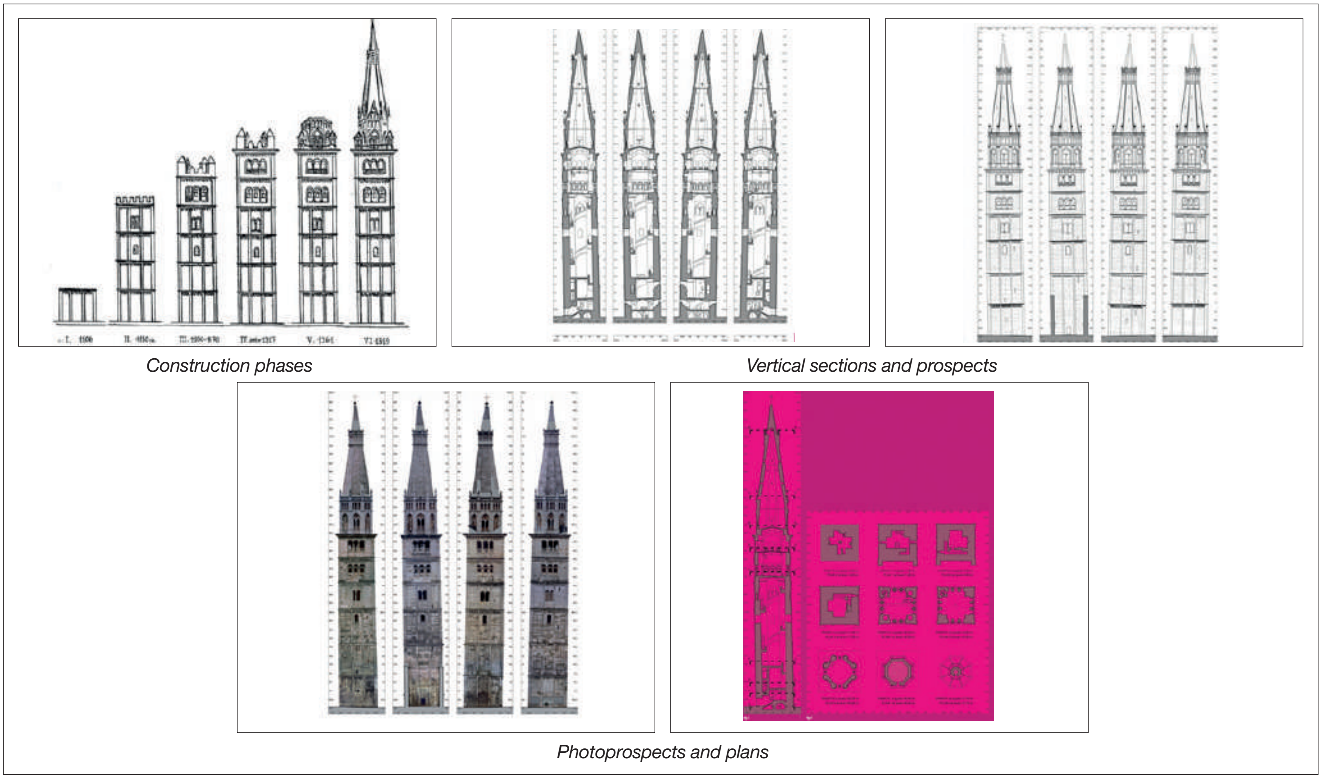


FIGURE 21 Drawings of the Ghirlandina Tower [10-11] in [14]

The chronology of Ghirlandina (pictures in Fig. 20) is still uncertain, as primary historical sources were destroyed during a fire in the XI century. The Tower (height 88 m) knew different construction phases over time (Fig. 21, [10] in [14]); the square levels can be attributed to Lanfranco and Wiligelmo (XII century), while the Campionesi Masters realised, in exquisite gothic style, the octagonal tambour and the cusp between 1261 and 1319. Prospects, sections and plans are reported again in Fig. 21 ([11] in [14]). Since the beginning, the Tower was subjected to subsidence and inclination ([12] in [14]). The constructors placed the heaviest stones on the opposite side of the slope; therefore, the centre of mass changes level by level. Nowadays, the sinking depth is about 1 m and the inclination more than 1.5 m. In 1997 UNESCO inscribed the Cathedral and the Ghirlandina Tower in the World Heritage List, together with the Piazza Grande.

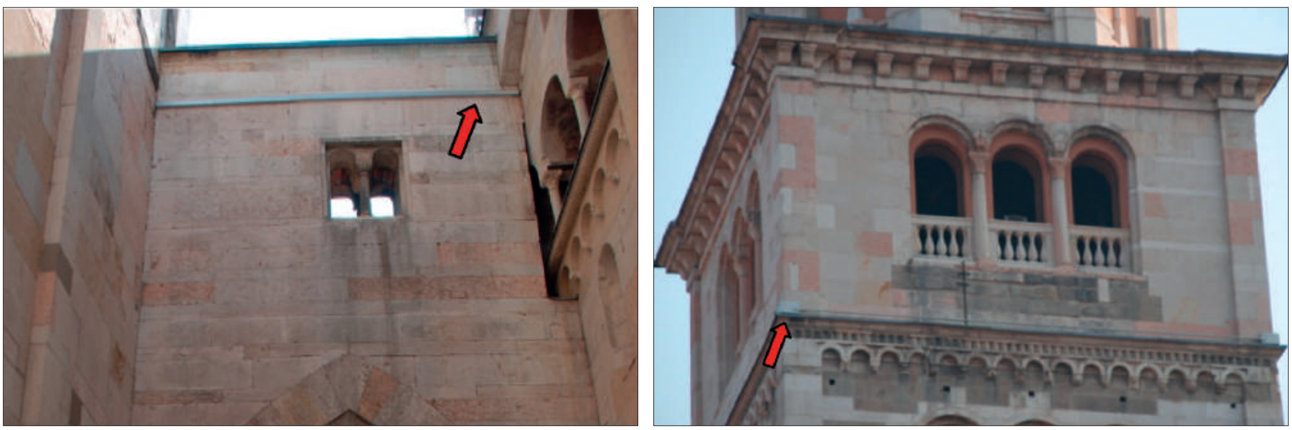
The 1996 earthquake (see again Section 2) affected all the complex, which was restored between 2007 and 2008; the cathedral underwent: the substitution of some timber trusses, the repairing of masonry cracks, the restoring of the rose window, the small columns and the XV century polychrome glass-windows, together with diagnostic and monitoring campaigns [13]. Ghirlandina was subjected to a whole conservation project [14]. Among other interventions, monitoring systems and reinforcement devices are shown by Fig. 22.
During the May 2012 seismic events, the whole complex supported the PGA maximum value of 0.037g and 0.055g (Modena recording station), respectively on May 20th and 29th.

Damage survey and observed mechanisms - The cathedral survey permitted to detect some damage, mainly related to the masonry cross-vaults of the lateral nave. Cracks along the ribs and falling of bricks were found. Such damage has been repaired through prompt interventions (almost completed at the time of our visit), ringing of the ribs with metallic plates fixed to the vaults (Fig. 23a), and filling the cracks with resin (Fig. 23b).

In addition, the main façade showed a potential overturning mechanism, slightly triggered, highlighted with a black line in Fig. 24. Moreover, the opening of the transversal walls (corresponding to the lateral nave) from the longitudinal one has been observed (Fig. 25), due to the variability of the mechanical properties of the soil foundation.

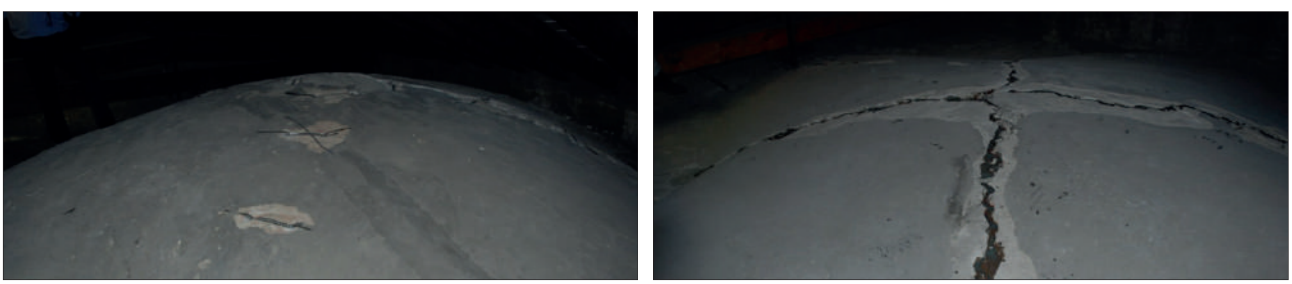
All the detected main mechanisms are summarised in Fig. 26 (Cathedral, global damage index equal to 0.16) and Fig. 27 (Ghirlandina, global damage index equal to 0.27), respectively.

The following several interventions were suggested after the investigation: structural re-establishment of damaged vaults, arches, ribs and unconnected wall portions. The implementation of the monitoring system – for a deep and permanent dynamic characterization of the whole complex, evaluating in particular church/tower interactions – is considered necessary and propaedeutic to complete the existing strengthening systems, in both the Cathedral and the Ghirlandina.



(a) (b)

FIGURE 22 Monitoring and seismic devices: relative displacement measure device between Cathedral and Tower (left); b) steel tie all around the last square level of the Tower (right)



(a) (b)

FIGURE 23 The San Geminiano Cathedral: a) ringing of the vault ribs; b) filling of the cracks

FIGURE 24 The San Geminiano Cathedral: potential overturning of the façade

FIGURE 25 The San Geminiano Cathedral: overturning of the lateral transversal walls

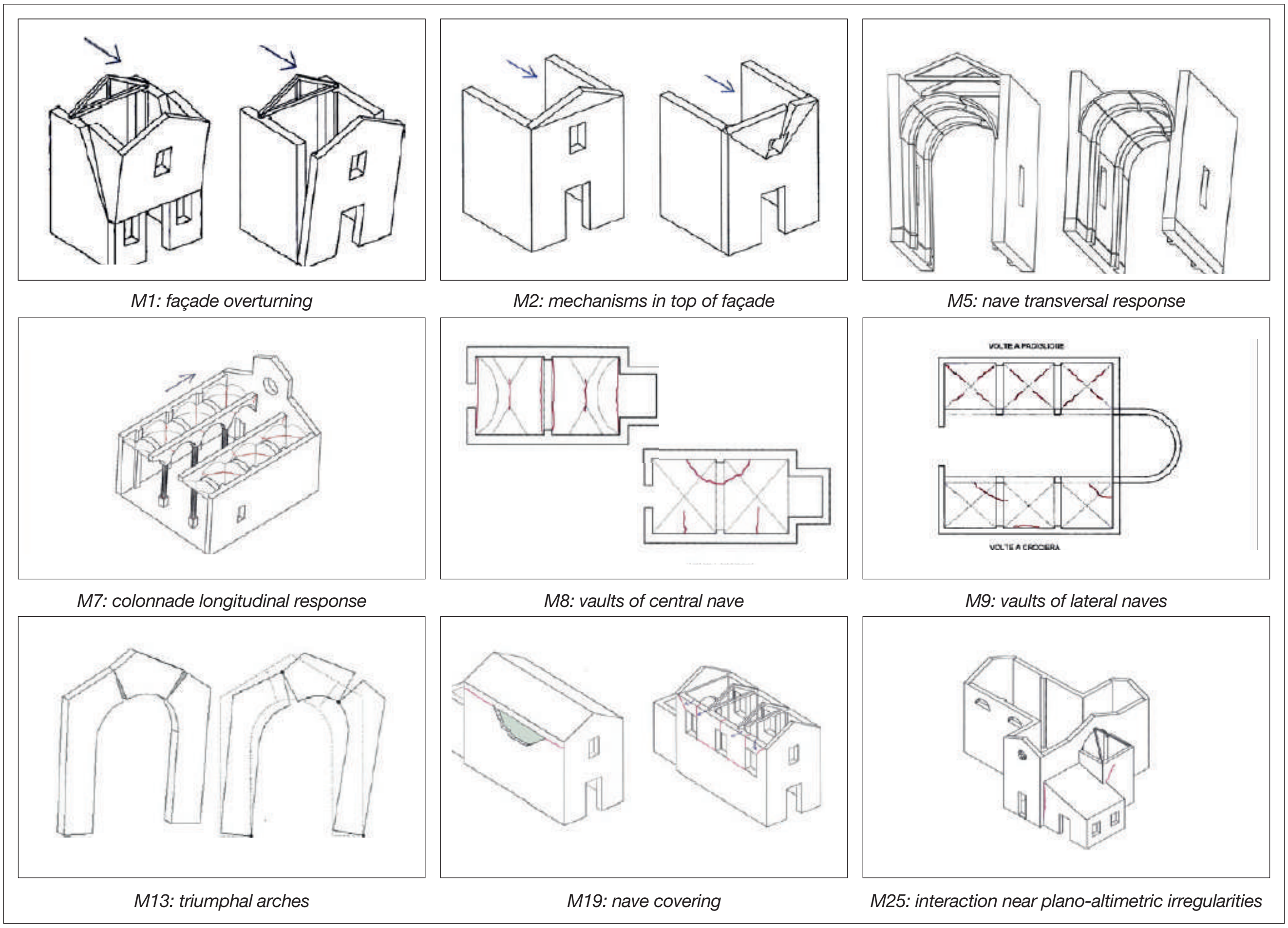


FIGURE 26 Damage mechanisms in the Cathedral of San Geminiano (Modena)

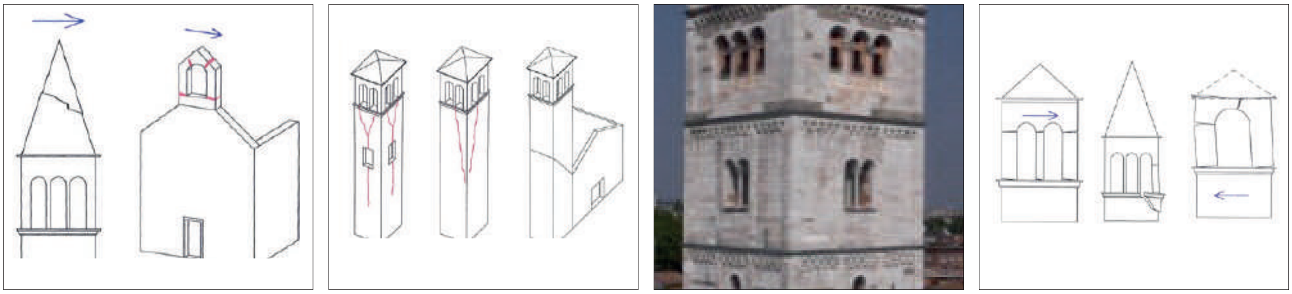


FIGURE 27 Damage mechanisms in the Ghirlandina Tower (Modena)

The Church of San Giovanni Battista in Triario (Minerbio, Bologna)

Description - The Parish of San Giovanni Battista in Triario (Fig. 28) is located in the hamlet of San Giovanni in Triario, countryside of Minerbio, a little town 15 km far from Bologna. The first building was probably built around the XI century, but the current neoclassic construction (full brick masonry, designed by the architect Francesco Gibelli) is relatively new, belonging to the Napoleonic period (1807-14), still containing an **ancient baptismal font**, as well as paintings attributed to **Daniele da Volterra.** It houses a very interesting **Museum of Popular Religion.**
Furthermore, the church has been one of the locations chosen for the 1976 Italian thriller cult movie "*La casa dalle finestre che ridono - The House with Laughing Windows*", directed by the Bolognese Pupi Avati [15].

FIGURE 28 The Parish of San Giovanni Battista in Triario (Minerbio, Bologna)

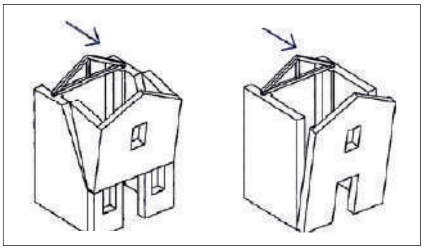
Damage survey and observed mechanisms - The church was bombed during the Last World War and the original bell-tower collapsed. Never completely restored, at the time of our visit it showed a generalised previous damage in walls, vaults and arches, worsened by the earthquake (Fig. 29). The main mechanisms are reported in Fig. 30, corresponding to a global damage index equal to 0.16. During the May 2012 seismic events, the church experienced a PGA maximum value of 0.040g (Medicina recording station). After the survey, it was considered safe, but the maintenance poor (previous cracks, humidity due to rain). Tying enhancements of nave and tympanum have been suggested.

External cracks

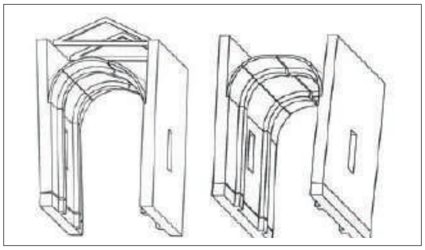
External cracks and traces of the old bell-tower (right)

Internal cracks

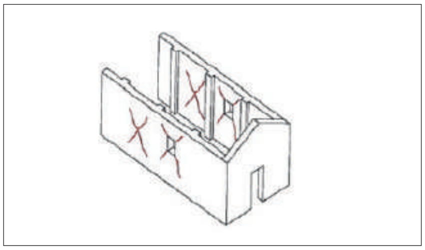
FIGURE 29 Damage mechanisms in the Ghirlandina Tower (Modena)



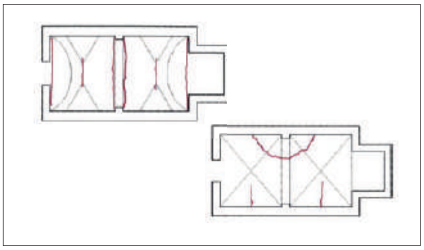
M1: façade overturning



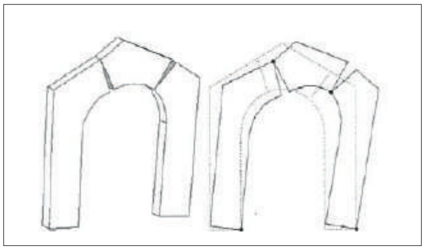
M5: nave transversal response



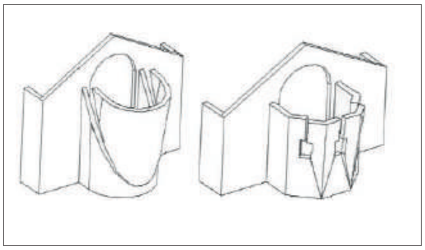
M6: shear in lateral walls (longitudinal response)



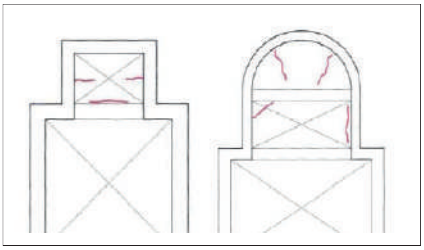
M8: vaults of central nave



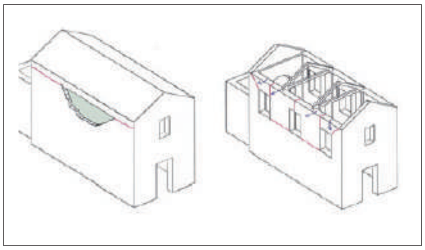
M13: triumphal arches



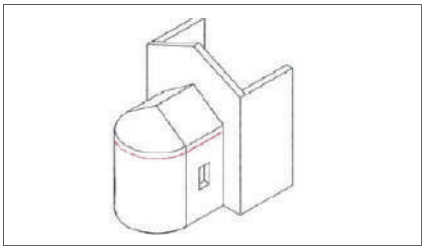
M16: apse overturning



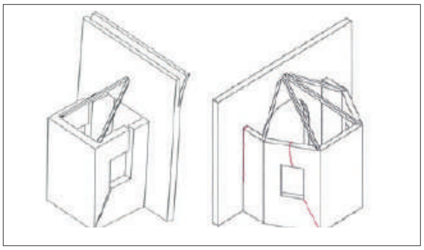
M18: vaults of presbyteryor apse



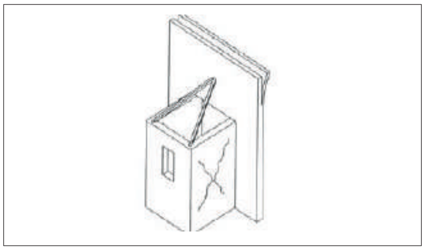
M19: nave covering



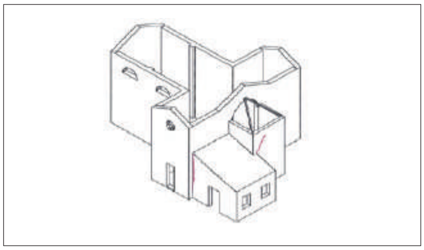
M21: apse covering



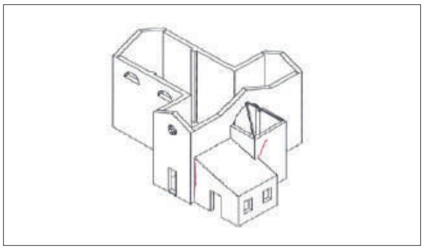
M22: chapels overturning



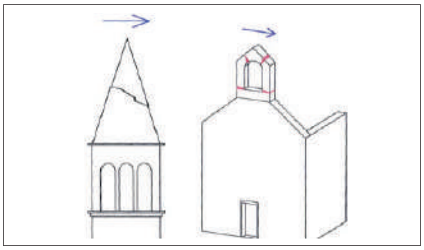
M23: chapels shear mechanism



M24: interaction near plano-altimetric irregularities



M25: interaction near plano-altimetric irregularities



M26: overhangs and projections

FIGURE 30 Damage mechanisms in the Parish of San Giovanni Battista in Triario (Minerbio, Bologna)

The Church of San Lorenzo (Budrio, Bologna)

Description - The Church of San Lorenzo (full brick masonry, see Fig. 31) is located in the historic centre of Budrio (Bologna), just in front of the Municipality Palace. Founded together with the convent between the XI and the XII century, it saw restorations and extensions after 1406, when the Friars Servants of St. Mary became the regents. Building modifications continued over time, and the final version took place in the XVII-XVIII centuries, when the church was completely renovated by the architects Alfonso Torreggiani and Giuseppe Tubertini. The original bell-tower was destroyed by the German soldiers in 1945 (fortunately without victims), ruining on the Western part of the cloister.

The current church showed external buttresses and transversal steel ties in the central nave arches. In good conditions of maintenance, it was declared unsafe after the last earthquake (shaken by a maximum PGA of 0.040g, Medicina recording station), and partially unsafe after our investigation.

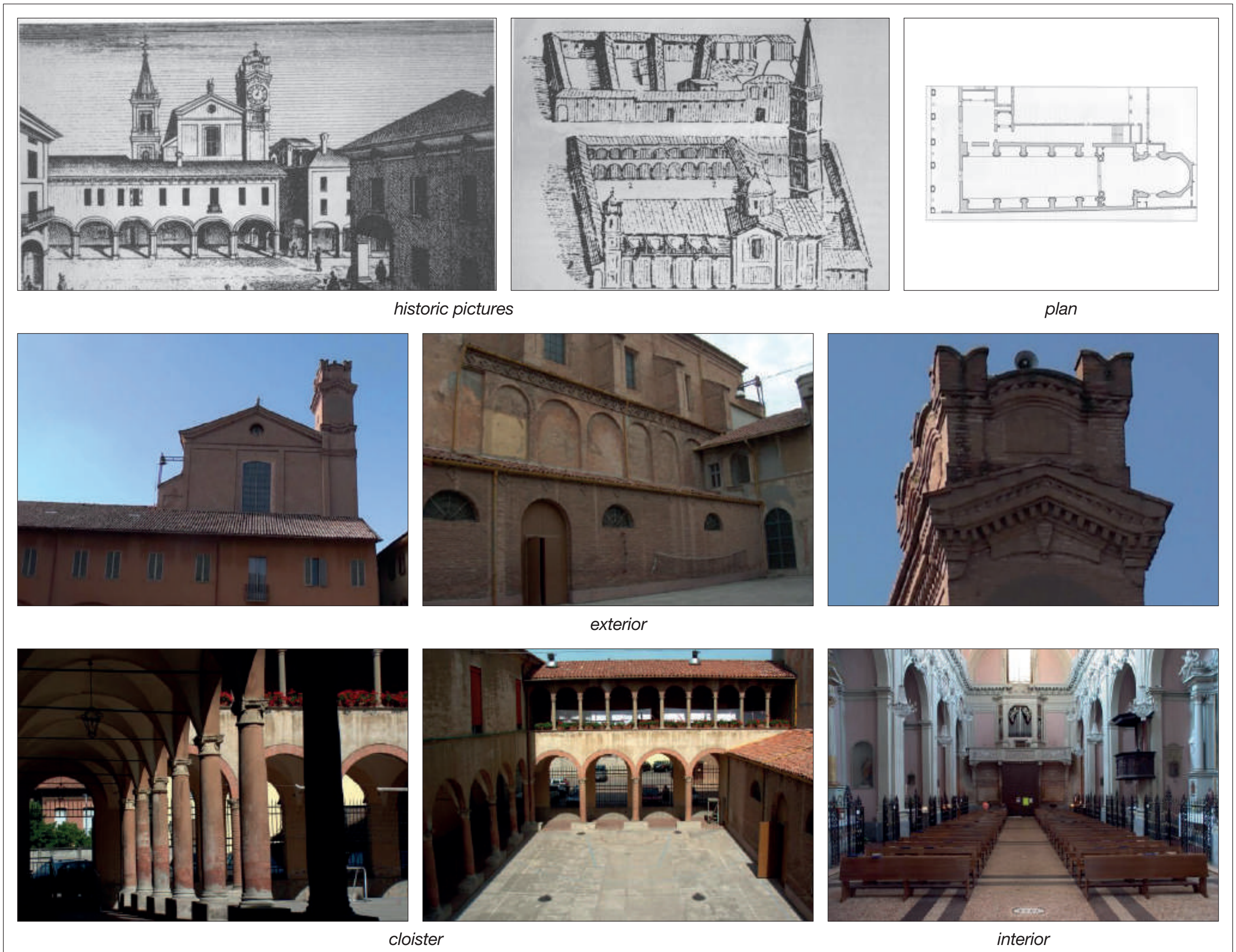


FIGURE 31 The Church of San Lorenzo (Budrio, Bologna)

Damage survey and observed mechanisms - The observed damage in the church was clear enough: in the dome, in the triumphal arches, in the central nave (vaults and colonnade); in the vaults of the lateral naves; in the apse vaults (Fig. 32). Probably, the construction moved with a longitudinal response, because steel ties were present only in the transversal direction. Many stucco pieces detached from the rich decorations and were collected by the church personnel. The fresco of the dome was also injured. The main mechanisms are reported in Fig. 33, corresponding to a global damage index equal to 0.13. Together with an overall restoration of the harmed parts, a strengthening intervention is recommendable, in particular in the nave longitudinal direction, anticipated by an accurate dynamic characterization of the structure.

FIGURE 32 Damage to the Church of San Lorenzo (Budrio, Bologna)

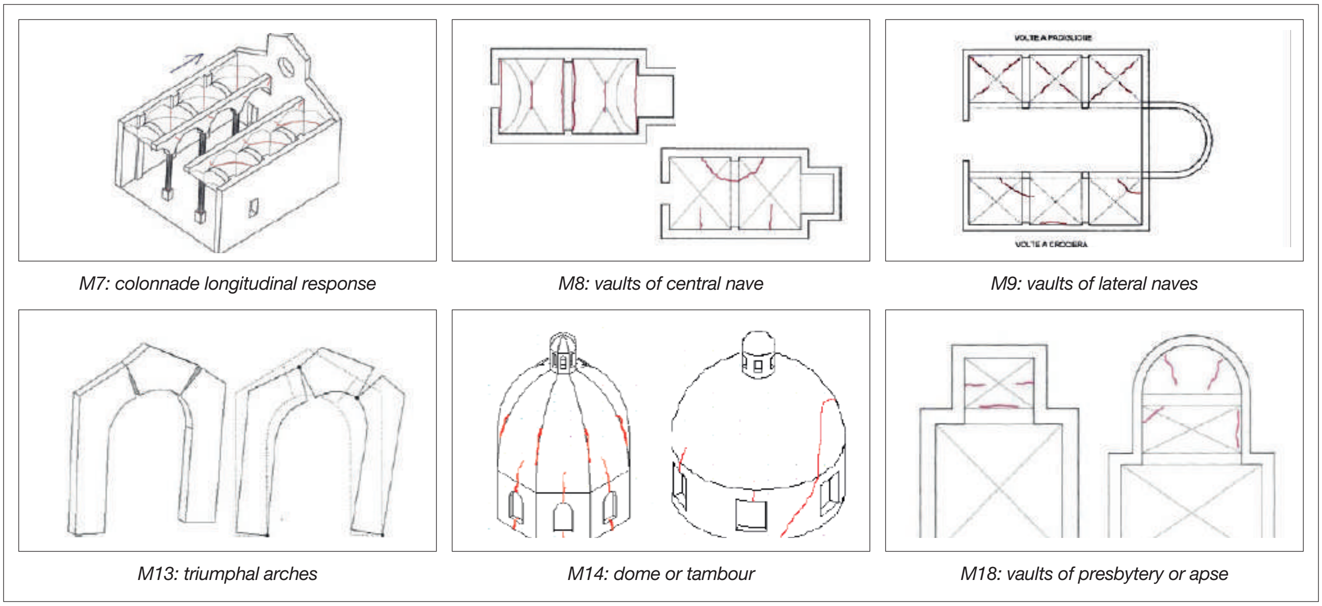


FIGURE 33 Damage mechanisms in the Church of San Lorenzo (Budrio, Bologna)

Conclusions

Although the May-June 2012 Emilia-Romagna seismic events can be considered moderate and geographically circumscribed, they caused heavy and widespread structural damage to cultural heritage construction, as churches, bell towers, palaces, and castles, together with loss and deterioration of mobile assets (frescoes, paintings, statues, ancient furniture, etc.). Several damage mechanisms were activated, at a different level of gravity, until collapse, detected by carrying out quick surveys through a well-established and effective Italian procedures (church and palace forms).

It should be certainly underlined that the Po Valley, including the affected area, was not classified as a seismic zone until 2003, so that past restoration projects did not consider loads due to earthquakes. That implies – particularly for cultural heritage, which must be handed down intact to posterity as far as possible – the duty to carry out our best as of now, in order to meet the antiseismic requirements.

It is not an easy task, because any improvement should be made in harmony with the conservation criteria, avoiding possible conflicts. About this remarkable matter, a valid reference is represented by the Italian Guidelines for the evaluation and mitigation of seismic risk to cultural heritage [16], which stresses, as first unavoidable step, the need to get a deep knowledge level of the monument.

Above all, the quality of materials is definitely important. In general, the collapse of full brick masonry walls (the most frequent typology encountered during the surveys) was facilitated by the scarce binding features of mortar, whose properties should be improved, in a compatible way, during future interventions. To this purpose, widespread diagnostics experimental campaigns (*in situ* and in laboratory) on construction materials shall be indispensable, together with structural dynamic characterisations and sharp numerical analyses.

In sequence, global and local overturning (out-of-plane) mechanisms should be avoided, achieving a structural "box behaviour" by means of adequate connections or anchors at each level, both in the longitudinal and transversal directions, and linking elements as tympana and sail bell-towers. The analysis

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of the heritage stock, presented in this article, has shown that overturning mechanisms (or others related with them) are the most frequent cause of heavy damage/collapse of churches, whereas buildings with stretcher bond stones and/or steel ties always exhibited an evident better response.

Particular attention should be devoted to bell-towers, planning improvements against failure due to pounding, bending and torsion.

Finally, it is necessary to emphasize the role of prevention in heritage preservation, setting up investigation programs before the disaster, focused on the vulnerability evaluation of structures not adequately designed, taking advantage of the outcome of innovative research and technology. On the contrary, medium-long periods of seismic inactivity reduce people's awareness and consciousness of the earthquake danger, resulting in inadequate strengthening of buildings.

Acknowledgements

Many thanks to Arch. Ilaria Braida, the very competent technical officer entrusted by the Modena Municipality about the preservation of the Temple of Fallen.

We want also to underline the wonderful support of the experts Ing. Mario Silvestri and Arch. Elena Silvestri (Cathedral), and Arch. Rossella Cadignani (Ghirlandina Tower), together with church representatives and personnel, guiding us inside the above said monuments and providing a lot of interesting material.

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THE PIANURA PADANA EMILIANA EARTHQUAKE

Following the earthquakes of May 20th and 29th,2012, which involved an extensive part of Emilia territory (the Western part of Emilia–Romagna), ENEA has been involved in the operations of usability testing and post-earthquake safety interventions on the various construction typologies existing on the territory.
This paper is focused on cultural and artistic interest constructions, only. After the seismic event, many churches and historic buildings have suffered significant damage. Some of these have undergone devastating and permanent damage.
Others can be restored if immediate safety interventions will be realized before carring out the appropriate retrofitting interventions, in order to preserve the historical construction from worsening the damage.
The example presented below, concerns the Visitazione di Maria Santissima Church in Reno Finalese (Modena). ENEA proposed a safety intervention, which has been approved by the Regional Directorate for Cultural Heritage and Landscape in Emilia-Romagna

Post-earthquake safety interventions on the Visitazione di Maria Santissima Church in Reno Finalese

Bruno Carpani, Giuseppe Marghella, Anna Marzo, Alessandra Gugliandolo, Maria-Anna Segreto

The church history

The Reno Finalese parish was built because the faithful could not reach the town of Finale Emilia when the Reno River flooded. It is datable before 1487. Information comes to us from the date when the baptismal font was placed, in 1465.
The oldest bell tower, rising on the West side, dates back to 1506, and was equipped with two bells and a clock. On the East side, in 1933 a modern bell tower was built and completed in 1948. It was 38 meters high and hosted three bells.

Damage analysis

Due to the earthquake that affected the Emilia-Romagna region in May 2012, the Visitazione di Maria Santissima Church in Reno Finalese (Modena) (Fig. 1) has

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FIGURE 1 Geographical context of the Visitazione di Maria Santissima Church on a GIS map

FIGURE 2 The main façade

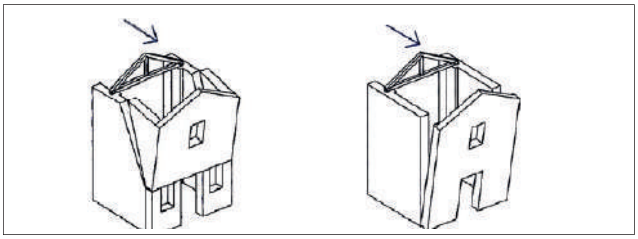


FIGURE 3 Overturning of the façade

suffered widespread damage, in terms of both structures and inside decorations. A group of engineers and scientists of ENEA has carried out a series of checks and on-site surveys, which allowed to identify the damage mechanisms and, thus, to propose a plan of post-earthquake safety intervention for the ecclesiastical building, while waiting for its overall consolidation.
The damage of the building is due to mechanisms typical of this type of construction, being evidenced in other churches located in the area affected by the earthquake, such as Buonacompra, Mirabello and San Felice sul Panaro.
The most evident effect of the seismic action is the collapse of the upper portion of the main façade of the church, due to the lack of connection with the transversal walls. The occurred mechanism is the vertical overturning of the Façade and the collapse of the top one. The non-collapsed part of the façade is separated from the transversal walls and greatly inclined towards the churchyard. The two façades of the lateral naves are connected to the transversal walls and are lower than the main one, therefore they are less damaged (Figs. 2-3).
Both the portion of the roof directly connected to the main façade and the façade itself collapsed at the same time. The timber trusses appear to be connected to the walls, with the "*capochiave*" (anchor plate) clearly visible outside. It is a light pushing structure, 16-18° inclined. Recently, the roofing completion elements located on the secondary frame timber structure, are restored by substitution of the damaged elements with hollow fine bricks.
The central nave has a painted false ceiling made of canes, on which a layer of stucco provides the base of the painting. It is connected to the upper

timber trusses and is severely damaged (Fig. 4). On the contrary, the frescoed ceiling of the lateral naves, which are made of "*in sheet*" arranged bricks, have collapsed in many parts, especially in the left nave (Fig. 5). In addition, the cracks' distribution and their depth outline a dangerous condition for the entrance.

The cracks' pattern (Figs. 6-8) related to the façades shows a rather critical situation: in addition to the overturning mechanism, many other deep cracks are visible, which are particularly severe. Moreover, a passing through vertical crack located between the second and third arch has been surveyed, also by using a thermal imaging camera (Figs. 9-10).

Other evident cracks are located between the central nave and the apse, where the walls seem unconnected to each other. A horizontal crack at about 2 meters from the ground level is surveyed on the pilaster on the right of the apse, in addition to a slight rotation. Moreover, diagonal cracks on the doors and separation of the corner have been evidenced on the wall located on the right of the apse (Fig. 11). On the contrary, on the left side of the apse, the presence of the oldest tower has provided a connection function between the two walls. In any case, the sacristy wall has been damaged because of the hammering action of the more rigid structure of the oldest tower on it (Fig. 12). Cracks are also present at the bottom wall of the apse.

An overturning mechanism is located on the right nave (Fig. 13), in addition to several diagonal cracks. An arch separating the naves shows a severe crack and a relative translation between the two realized parts, despite the presence of the metallic tie (Fig. 14). On the left nave, no mechanism has been evidenced.

Very serious damage have been surveyed on the two towers of the church. The oldest tower – which is the original bell tower nowadays substituted from the more recent one – is about 16 meters high. With masonry structure and equipped with metallic ties in both directions, it shows a very critical situation. The separation and expulsion of the corners (cantonal) occurred, which predicts a potential global collapse of the tower and the subsequent increasing in the damage of the structures below it (Figs. 15-16).

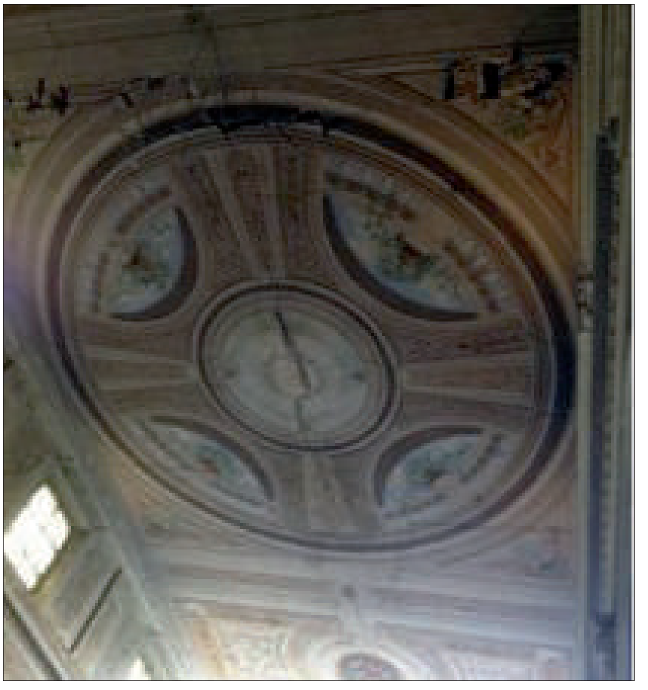


FIGURE 4 The false ceiling of the central nave

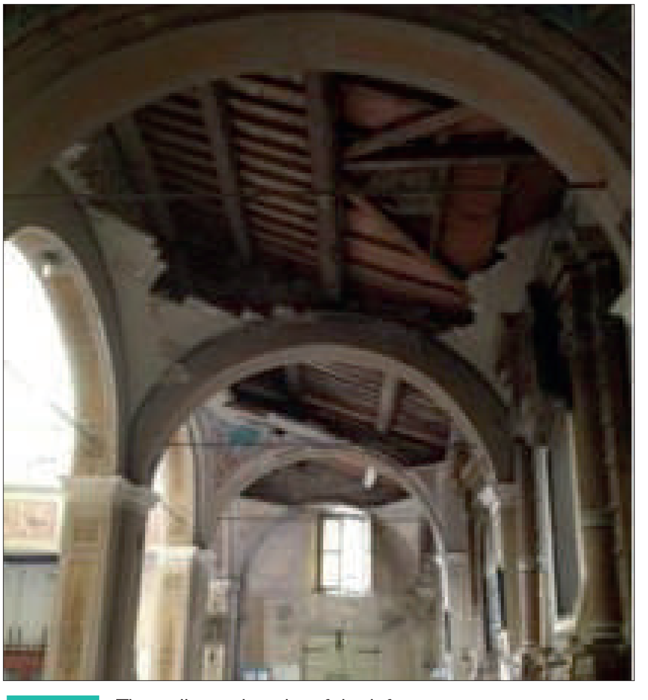


FIGURE 5 The collapsed vaults of the left nave

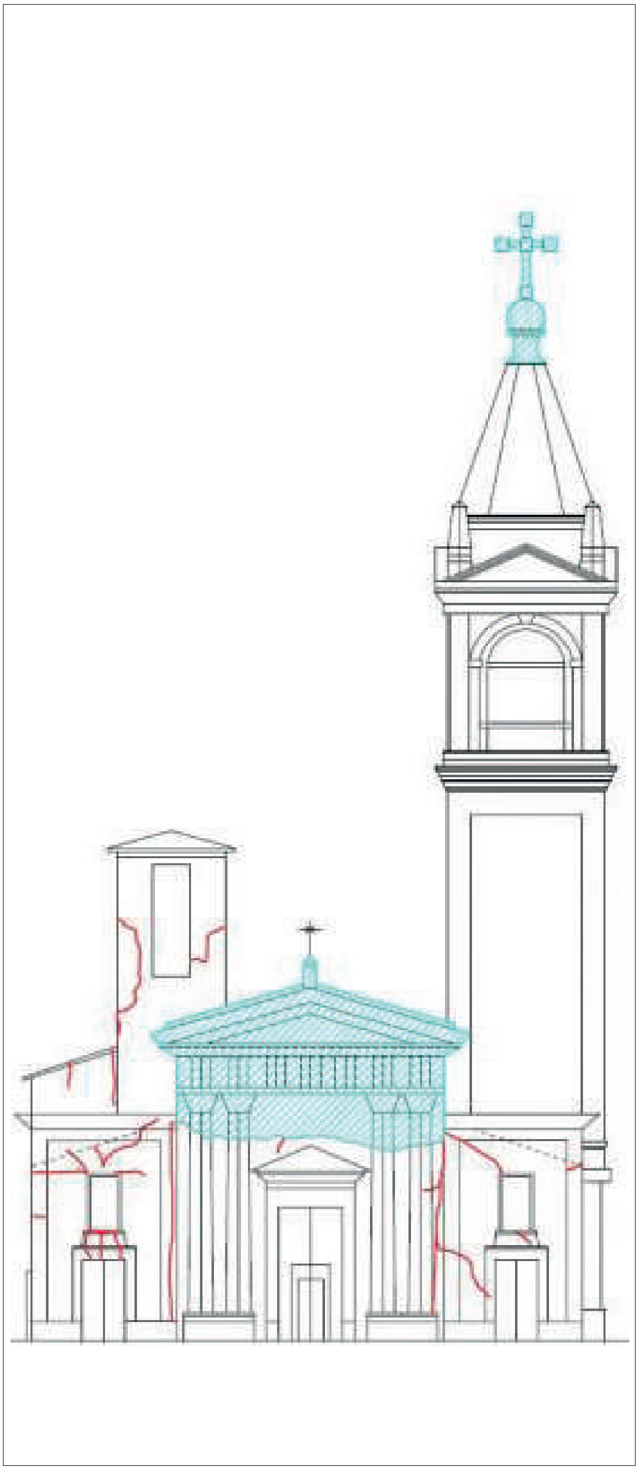


FIGURE 6 Cracks on the main façade

FIGURE 7 Cracks on the east side

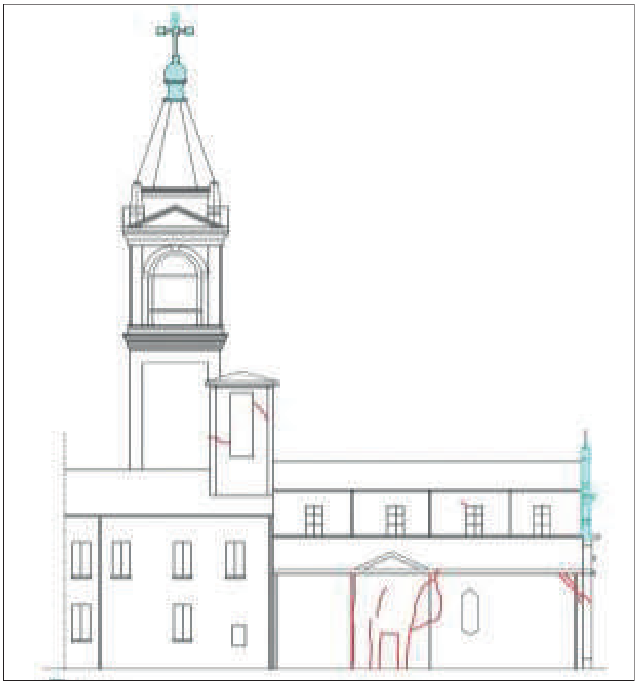


FIGURE 8 Cracks on the west side

FIGURE 9 Passing through vertical crack

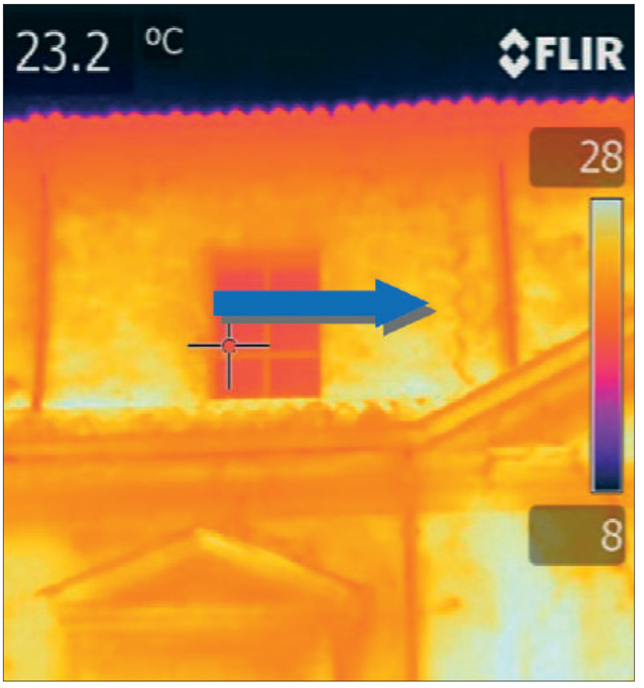


FIGURE 10 Passing through vertical crack (thermal imaging camera)

FIGURE 11 Horizontal crack on the pilaster

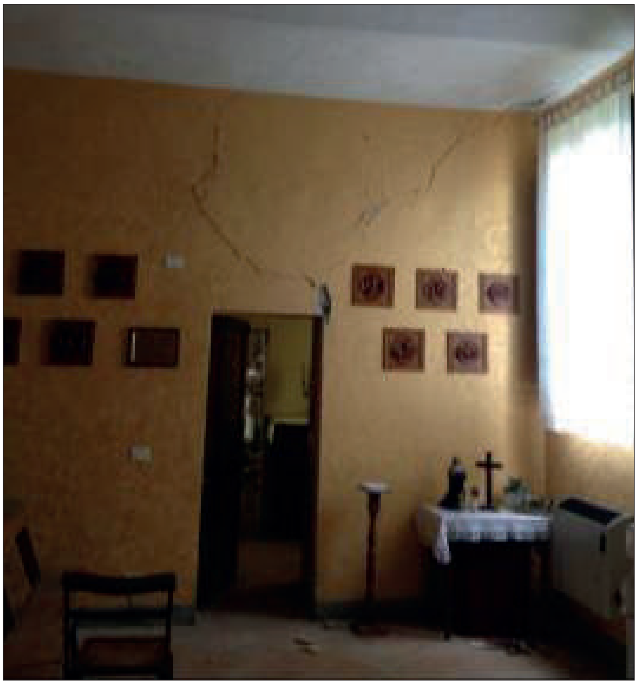


FIGURE 12 Diagonal crack on the sacristy wall

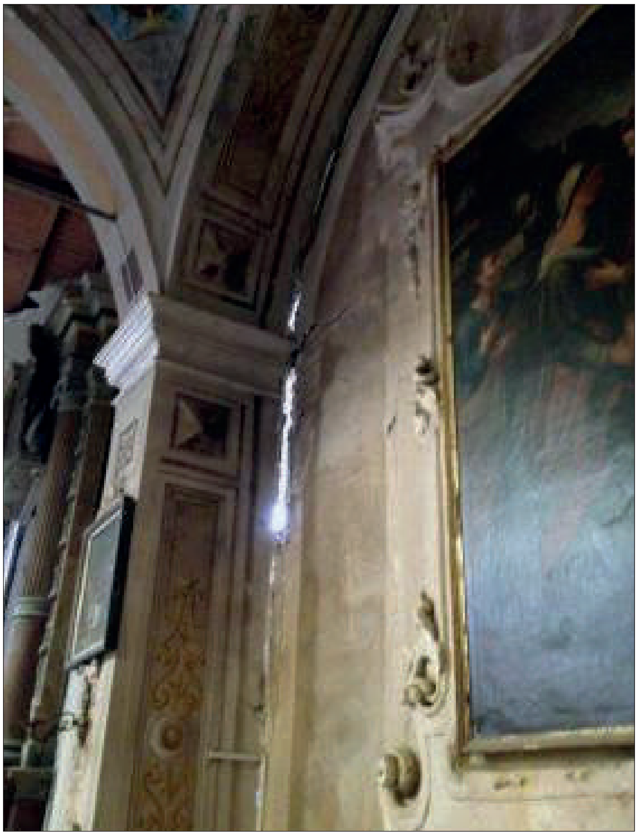


FIGURE 13 Overturning mechanism f the walls on the left nave

FIGURE 14 Crack and translation on the arch

The more recent tower, being made of solid bricks, is more than 38 meters high and was built adjacent to the right side of the church using bricks and concrete. The earthquake caused the twisting of the whole structure, cutting it at about 2 meters from the ground, in correspondence of a discontinuity in the material of the basement. In addition, a minor rotation occurred (Figs. 17-18).
Further damage has not been observed above the horizontal crack, at least from the outside. The steeple, which is also cut and rotated at the base, has been quickly removed in order to ensure the passage through the nearby street. Finally, the more recent bell tower is dangerous for the street users and surrounding buildings in case of collapse, in addition to the potential danger for the whole adjacent structure of the church.

Proposed safety interventions

Basing on the surveys carried out on site and the documentation provided by the Engineering Department of the City, we suggested and d signed an appropriate safety intervention.
The planned measures can be listed as follows:

1) Safety of the overturning mechanism of the façade;
2) Ringing of the perimeter walls;
3) Removal of the cover;
4) Ringing of the original bell-tower;
5) Ringing and insertion of vertical ties on the more recent bell-tower.

The intervention should be articulated in two phases and should be realized from outside of the church, in order to guarantee the safety of the


FIGURE 15 Separation and expulsion of the corner


FIGURE 17 The more recent bell tower

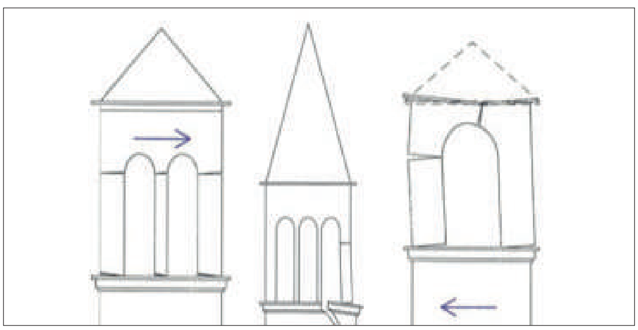


FIGURE 16 Typical damage mechanisms for bell cells

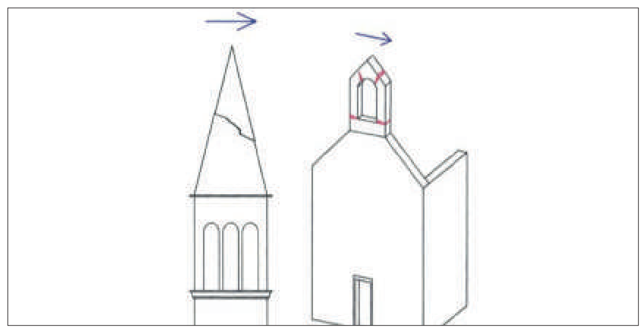


FIGURE 18 Typical damage mechanisms for projections

operators. In particular, the first phase consists in blocking the overturning mechanism of the façade and ringing the perimeter, in order to give a box behaviour to the whole complex structure. The second one consists in removing the cover and ringing the more recent bell-tower.

Afterwards, the existent covering structure, which is severely damaged, should be removed by means of a telescopic mobile platform, on which workers can operate safely from the external side. A new temporary steel structure will be realized, which accomplishes three functions (Fig. 19): it realizes the temporary cover of the church, protecting it against both rain and snow; it provides the upper protection plan and allows to enter the church for the subsequent consolidation phases; it provides the work plan support below the ceiling, when the latter is being restored. In particular, both vertical and horizontal structures are realized by coupled C profiles, while the inclined one consists of a reticular structure made of box profiles. The horizontal working floor is realized by wooden planks, which are light and of easy realization. The whole structure is reversible and easy to assemble and dismantle. It is worth noticing that the vertical structures are Y-shaped and are located at the windows' position, aiming at avoiding additional damage to the frescoed ceiling (Fig. 20).

With reference to local safety interventions, all doors and windows of the façade should be ribbed. The elimination of the overturning mechanism of the façades is realized by ties made of high-resistance, 20mm-diameter steel cable (Fig. 21), anchored to the masonry walls by employing the Bossong system (Fig. 22). At the corners, the cables are anchored to the corner-shaped, 50x40 cm steel plates, in order to adequately distribute the actions on the masonry walls.

A very important aspect of the intervention concerns the recovery of the decorations, severely damaged by the earthquake. This stage occurs after the completion of the phases described above, in order to allow to access the building under adequate safety conditions. The first step should consist in collecting all the collapsed portions of decorations, storing them in a suitable place for their preservation, and then re-adhering the detached parts to the proper support. With regard to the lateral naves vaults, the collapsed frescoes are still adherent to the surface of the single bricks, therefore a possible intervention could consist in restoring the original painting layout. Regarding the original bell tower, the new intervention allows for the application of steel cables equal to those used for the church, which ensure the complete ringing of the tower in addition to the existing metallic ties, thus preserving the structure from collapsing. Finally, with reference to the more recent bell tower, the proposed intervention has been designed as permanent. It consists of four steel ties located at the four internal corners of the structure and fixed to both the upper floor and the ground floor by means of steel plates, each equipped with shape memory alloy (SMA) devices located at their middle length.

A similar solution has already been adopted in another consolidation intervention of the bell tower of the Church of San Giorgio in Trignano (Reggio Emilia), severely damaged by an earthquake in 1996, per-

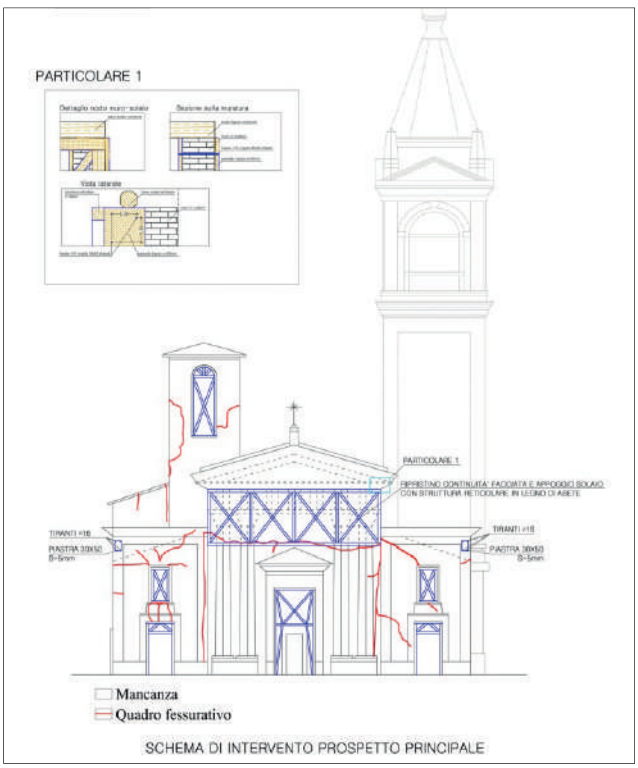


FIGURE 19 Main façade

FIGURE 20 Covering protection systems

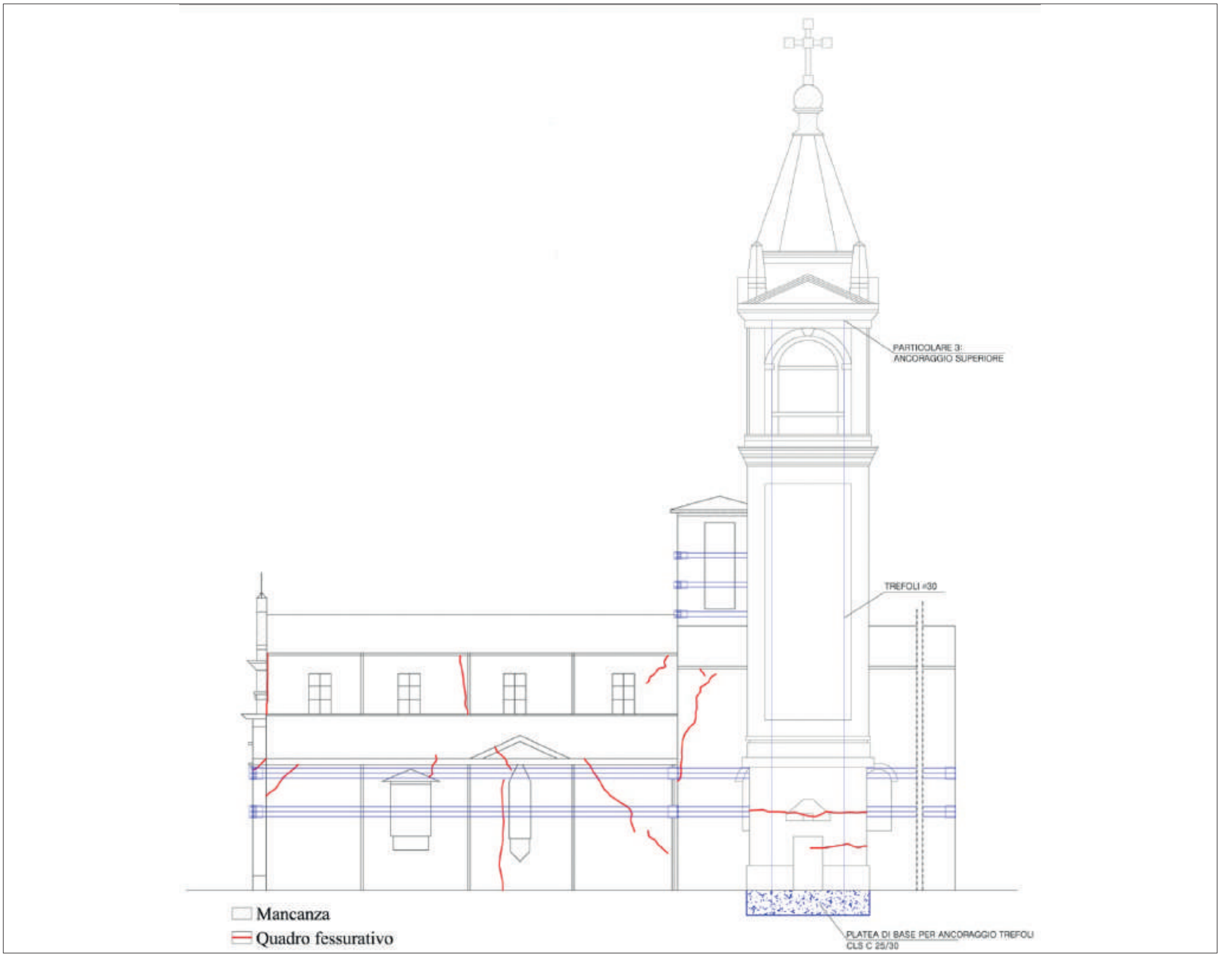
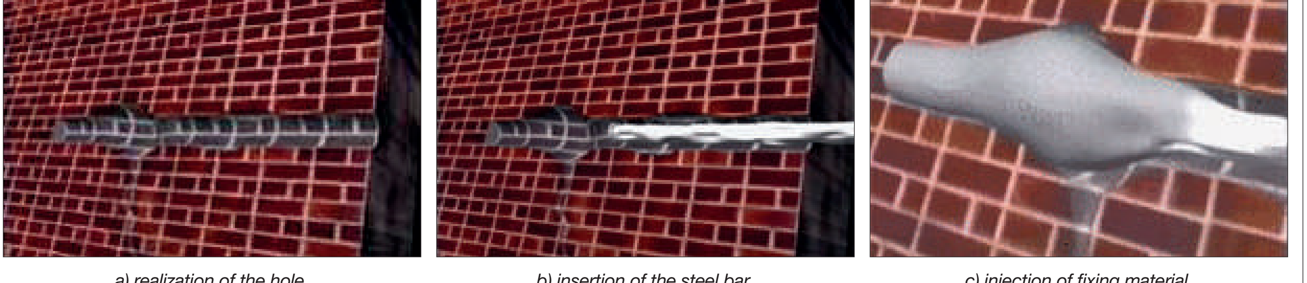


FIGURE 21 Ties' positioning on the East façade



a) realization of the hole *b) insertion of the steel bar* *c) injection of fixing material*

FIGURE 22 The Bossong system

FIGURE 23 The San Giorgio in Trignano bell-tower

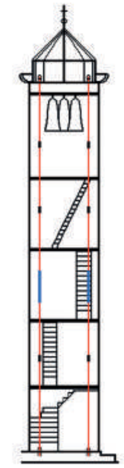


FIGURE 24 The San Giorgio in Trignano bell-tower: consolidation system

formed under the scientific supervision of ENEA [1]. The innovative intervention – chosen as the subject of the pilot application of seismic Innovative Techniques (TIA) within the EU project ISTECH (Development of innovative techniques for the improvement of stability of cultural heritage) – consisted in inserting four post-tensioned metal ties formed by six modular units at the inner corners of the tower, in order to increase the structure's resistance to bending without perforating the masonry (Figs. 23-24).

In series with the ties, four shape memory devices (SMAD, Shape Memory Alloy Devices) have been incorporated, tested to ensure the constancy of compression on the masonry, by maintaining the applied force at a set value. Each SMAD is composed by 60 wires (each of 1 mm in diameter and 300 mm in length) made of hyperelastic nickel-titanium alloy. In addition, suitable anchorages have been realized (in the foundations and at the top of the tower) in order to support the concentrated actions transmitted by the ties. Dynamic identification tests have been performed immediately after the earthquake, aiming at the validation of the system. The ENEA researchers have installed an accelerometric pattern to record the behaviour of the structure under the action of 67 earth tremors. The last experimental campaign was carried out when the consolidation intervention was completed.

The proposed safety measures for the Visitazione di Maria Santissima Church were evaluated and approved by the Regional Directorate for Cultural Heritage and Landscape of the Emilia-Romagna region, thus the safety intervention should start by October 2012.

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THE PIANURA PADANA EMILIANA EARTHQUAKE

This work shows some results of the damage survey carried out on several localities by the ENEA teams in the post-earthquake emergency phase. The analysis is focused on residential buildings, which represent the most common construction types, namely masonry buildings and reinforced concrete (RC) frame structures. The main damage mechanisms of the buildings are pointed out as well as the factors that affected their seismic vulnerability

Damage mechanisms in some residential building typologies during the Pianura Padana Emiliana Earthquake

Bruno Carpani, Maurizio Indirli, Giuseppe Marghella, Anna Marzo, Alessandra Gugliandolo, Maria-Anna Segreto

The seismic events that seriously affected the Emilia-Romagna region on May 20th and 29th, mobilized throughout Italy the scientific community that is dedicated to the study of the earthquake impact on construction and infrastructure. The greatest damage to buildings occurred in the territory near the three main epicentres, a wide area in which the towns of Cavezzo, Concordia sulla Secchia, Mirandola, Novi di Modena, Finale Emilia, Rovereto sulla Secchia, San Felice sul Panaro, Cento are located [1]. As concerns the residential buildings, the affected area shows different typologies, ranging from historic buildings, dating back to a few centuries ago, to recent concrete constructions. The extent of the affected area and the large difference between the various structures make it impossible to recognize single patterns of damage: thus, the study of damage mechanisms occurred after this earthquake would give useful information about the seismic behaviour of a wide range of building typologies.

Immediately after the first event, which struck the Districts of Ferrara, Modena, Reggio Emilia, Bologna (Emilia-Romagna Region), Mantova (Lombardia Region) and Rovigo (Veneto Region), an ENEA team of experts (Maurizio Indirli, Bruno Carpani, Elena Candigliota, Alessandra Gugliandolo, Francesco Immordino, Giuseppe Marghella, Anna Marzo, Giuseppe Nigliaccio, Alessandro Poggianti, Maria-Anna Segreto) supported the Italian Civil Protection Department, in order to perform prompt investigations [2] on the safety evaluation of different typologies of structures

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(bridges, industrial factories, residential houses, etc.), made of various kinds of materials (masonry, reinforced concrete, precast/pre-stressed reinforced concrete, mixed).

Civil buildings

The old traditional houses are very common among the prevalent building typologies: mainly distributed in the city centres and aggregated in blocks, they date back to before the First World War and have 1 or 2 storeys, solid brick masonry walls and wooden roof. The façade is often characterized by arcades (Fig. 1), while seismic protection systems like metal ties are not widely diffused: it seems that local building practice does not include such precautions among its constructive rules [3]. Also common are the typical isolated rural buildings, which show the same structural characteristics (Fig. 2).
The seismic behaviour of such structures was generally good when compared to the recorded ground acceleration values: the great part of the traditional buildings showed only slight damage, particularly to chimneys, plasters or non-structural elements already weakened by the lack of maintenance. The shape regularity and the limited number of storeys, the light covers, the good quality and texture of the solid brick masonries, despite their small thickness (30-40 cm), the connection between the walls, the presence of spine walls and of seismic protection systems are all elements contributing to the good seismic behaviour observed during the post-earthquake surveys.
However, moderate damage was observed in some cases, due to the absence of one or more of the above mentioned elements. The most common mechanisms are the façade overturning (out-of-plane) due to the lack of connection between walls and the formation of shear cracks, mainly due to in-plane actions; mixed mechanisms (out-of-plane plus shear) were also observed. A great role in the damage intensity is played by the quality of building materials, especially mortar. Generally, it is a lime mortar with poor mechanic properties compared to the brick ones, which affects the strength of the masonry structures. In a rural building in Casumaro, near Cento, adobe bricks were found in some perimeter walls (Fig. 3): although this could be a further element of weakness, the building showed a good seismic behaviour, with no damage to the structural elements.

FIGURE 1 Traditional buildings in the town of Cento

FIGURE 2 An isolated rural building

FIGURE 3
Adobe bricks observed in Casumaro (Cento)

The outskirts of towns host recent residential constructions, which are numerically dominant on the historic buildings. For the former buildings we can distinguish three different kinds of structures: buildings made with solid or hollow bricks masonries, buildings with floors and roofs in RC insistent on a supporting masonry structure, and buildings with a RC structure and internal partition walls. The first two typologies are generally employed for small two-, or three-storey buildings, while the concrete structure is employed for multi-articulated condominium agglomerations.
Even if geological and geotechnical characteristics of the sites must be also taken into account, the seismic response of these structures was strongly dependent on the appropriateness of the project and on the quality of the materials employed.
Below are illustrated some case studies of particular interest, encountered during the inspections for the usability of buildings after the earthquake, carried out by ENEA experts.

The Rovereto di Modena buildings

This small town was one of the most damaged localities, especially after the May 29th shocks. Many buildings suffered heavy to very heavy structural damage, with few cases of total or near-total collapse.
Apart from the ecclesiastic complex (church, bell-tower and rectory, subject of another paper in this report), the town retains little of its historic fabric; in fact, the traditional construction type goes back to the first half of the XX century. These houses are usually two-storey buildings with solid brick walls, floors made of steel beams coupled to hollow flooring blocks and wooden roof. Despite the presence of vulnerability factors, such as the modest thickness of the load-bearing walls (15-25 cm), this type of building performed quite well. It seems that good seismic behaviour lies in low height, in-plan regular-

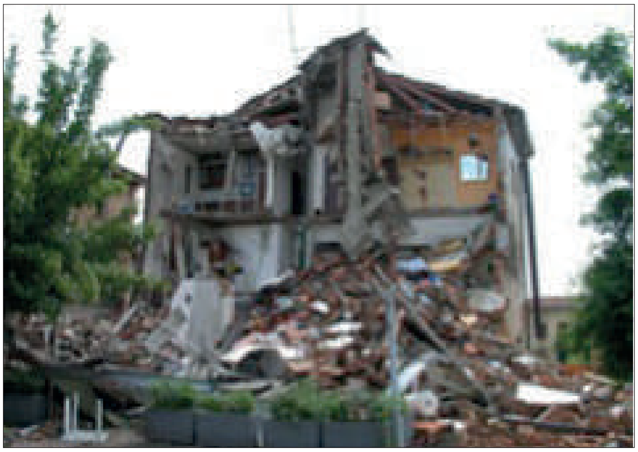


FIGURE 4 The front part of the building has completely collapsed; the damage grade is 5

FIGURES 5-6 Details of RC elements

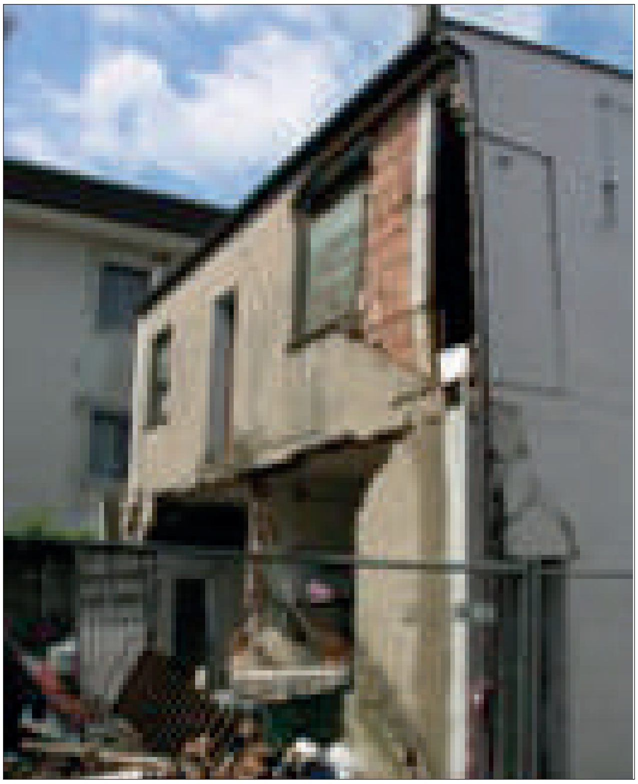


FIGURE 7 Serious failure of the walls, the damage is grade 4

FIGURE 8 Heavy diagonal cracks with partial loss of connection between external walls (damage of grade 4)

ity and well preserved conditions. On the other hand, where heavy structural alterations were introduced (for example the insertion of RC floors not properly connected to the walls or the replacement of light wooden roofs with heavy RC ones), the vulnerability increased dramatically. Fig. 4 shows a case of near to total collapse (damage of grade 5 EMS98). Note the heavy roof structure bearing on slender walls, the poorly reinforced beams (Fig. 5) and ring course concrete, as well as the absence of steel reinforcement in the floor slabs (Fig. 6).

A further example is shown in Fig. 7. Besides structural weaknesses (lacking in connection at wall corners as well as between walls and floors, openings near the corners, use of non-bearing hollow bricks), vulnerability was also affected by the addition of an external stair.

In the example of Fig. 8, the presence of rigid concrete slabs combined with wide openings at the first floor affected the seismic response of the building, which shows severe shear cracks in the external walls.

Looking at the damage patterns, it should be noted that first mode damage mechanisms (outward overturning of the walls) are not numerous. A clear example is shown in Figs. 9-10, where roof thrust load plays an evident role.

The urban development that took place in the last thirty years was marked by the coming of new materials and techniques and witnesses the evolution of the traditional building type. In new houses, RC-brick mixed slabs replaced steel joist floors and wooden roofs, whereas bearing-load walls were no more built in solid brick but in hollow brick masonry. If the weight of heavy horizontal elements rests entirely on such a masonry, vulnerability can be severely affected by geometry, size and layout of openings. An emblematic case, and a very impressive one, is represented by a cottage on three levels that was literally split by the earthquake.

The collapse was caused by the presence of a soft storey in which there were large openings and small piers between openings and corners. Due to the absence of any reinforcements, the masonry corner pier on the right (Fig. 11) completely crushed, with the consequent opening up of the structure up to the top (Fig. 12). Even though the change in stiffness between the rigid upper floors and the ground soft storey has further aggravated the response of the building under the seismic stress, undoubtedly the main cause of the collapse depends on the type of masonry used (hollow bricks) and its inadequate dimensioning.

FIGURES 9-10 Out-of-plane mechanism of the upper part of the longitudinal façade

FIGURES 11-12 The soft storey has collapsed, the damage grade is 5

The weakness of ground floors walls built in perforated bricks is again dramatically shown in Fig. 13, where the failure reached almost the collapse. Making of niches in load-bearing walls, containing pipelines and boiler (Fig. 13, on the left), contributes considerably to increase the seismic vulnerability of masonry buildings.

The above said damage mechanism has been diffusely observed in this type of construction. Common examples of this damage (of lower level, if compared to the previous ones) are shown in Figs. 14-15.

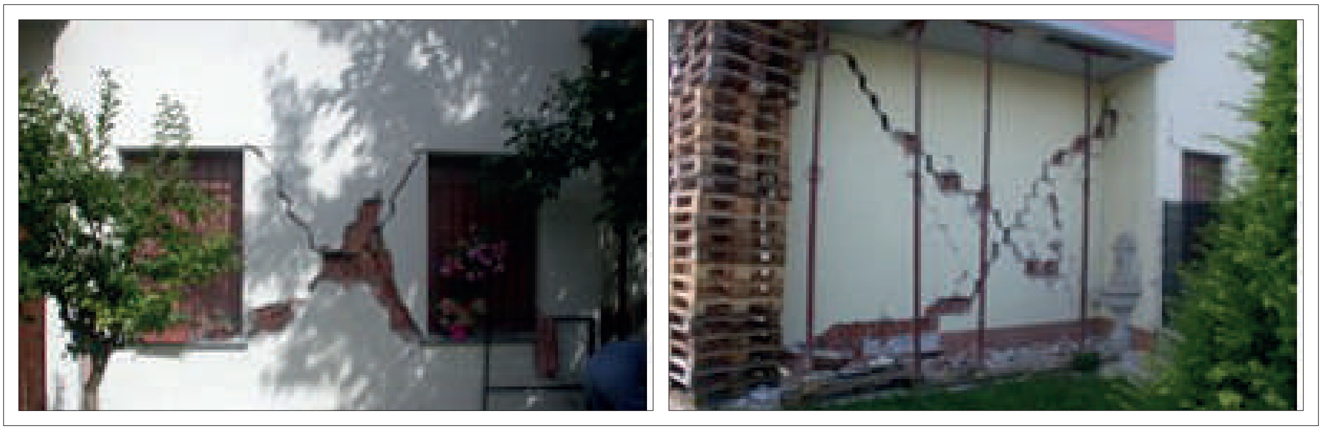
In recently erected buildings, the structure is often provided with RC columns and beams, but they are never placed in all the four sides of the building, in order to perform as a moment resistant frame. In other cases (Fig. 16), when a sort of RC frame is present, the beams run in the thickness of the floor slab ("thickness beam" is the equivalent Italian technical term), making the beam-column joints very vulnerable to lateral loads. This type of structure performed badly and suffered heavy damage (Fig. 17).

Different damage modes of the columns are worth noticing: shear failure in the column-slab corner joint (Fig. 18) and compressive breaking in the central one (Fig. 19).

FIGURE 13 Serious failure of the walls, the damage is grade 4

The CE.RES. residential complex in Cento (FE)

A very interesting case, among those encountered during the inspections for the usability of buildings after the earthquake, is the residential complex named CE.RES. Located in Cento, it was built in the early 70s and consists of 21 buildings having an RC structure and arranged in two parallel aggregates, one almost linear and one nonlinear (Fig. 20).



FIGURES 14-15 Large shear cracks on exterior walls; the damage level il 3

FIGURE 16 Example of mixed structure

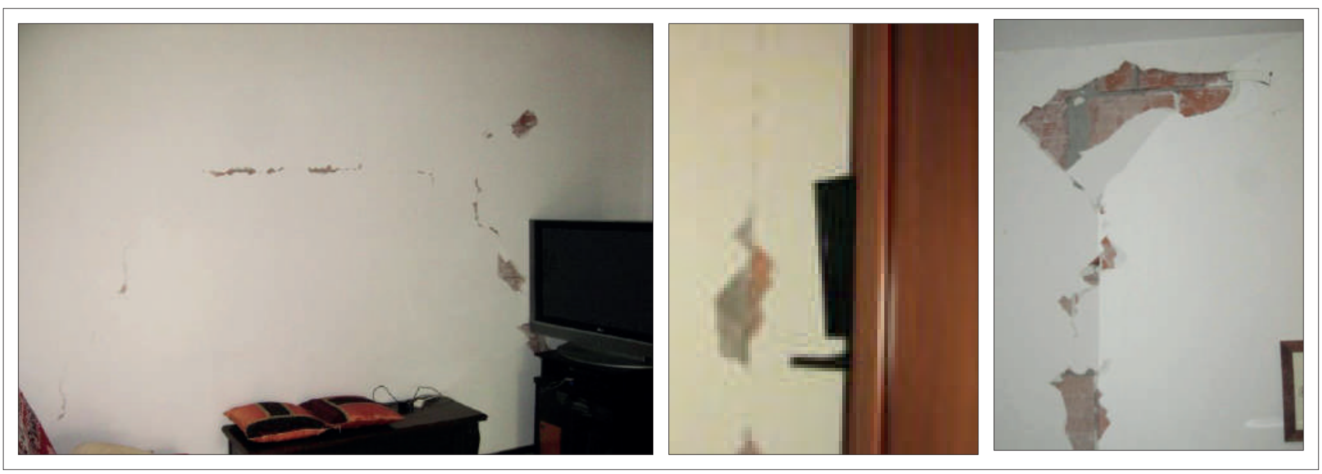
FIGURE 17 Damage to ground floor wall

FIGURES 18-19 Failure of RC columns

FIGURE 20
Satellite view of the CE.RES. residential complex in Cento

The two blocks of the building complex host commercial activities at the ground floor and have residential destination at the five/six upper levels, for a total of almost 200 apartments (Figs. 21-22).
In the days immediately following the May 29th earthquake, which affected the town of Cento more intensely, the occupants of the complex left home and business, gathering in a tent city set up spontaneously in the surrounding gardens; the large number of people living or working in the buildings, more than a thousand, and their different ethnic origin (the construction hosts many immigrant families) have converted the CE.RES. complex into a social problem in the emergency time, with the urgent need for the Municipality and Civil Protection to establish whether the buildings were usable or not, in order to organise the necessary support services.
During the inspection, carried out over three days to include almost all the apartments –with the imaginable difficulties in finding the owners, whose presence was necessary to access the different units– no damage to structural elements was observed, although the complex was not built with seismic criteria (missing of seismic joints, frames in both directions, etc.), because at the building construction time the town of Cento was not classified as seismic zone. Furthermore, no failures in the foundation were detected.
Damage related to the seismic action was found in the non-structural parts, especially in the cladding and the partition walls (Figs. 23-25), where both shear cracks and separation between cladding and structure were observed (Figs. 26 and 28), as in the chimneys, the covering structures and the parapets of some balconies (Fig. 27). As expected in this kind of structure, damage to partition walls and claddings was much larger on the lower floors

FIGURES 21-22 The CE.RES. residential complex in Cento



FIGURES 23-24-25 Damage to the partition walls

of the buildings, whereas the upper floors suffered a greater deformation, that caused the downfall of many objects, the moving of furniture, even of big dimension, but no significant damage.
More specifically, the aggregate marked by even civic numbers, whose buildings are not aligned, suffered only slight damage to non-structural elements and has been declared usable, whereas the aggregate characterized by odd civic numbers, whose structural units are virtually aligned, presented some localised situations requiring the provision of usability after prompt interventions, albeit limited to a few apartments.
In particular, in the apartments on the first floor of the buildings located at the two ends of the aggregate, the damage to cladding was stronger, making the overturning of the cladding itself possible in case of aftershocks, with consequent danger to the occupants. Some apartments (civic numbers 5, 7 and 17) have also been declared usable after prompt interventions thanks to the separation of the parapet of the balcony.

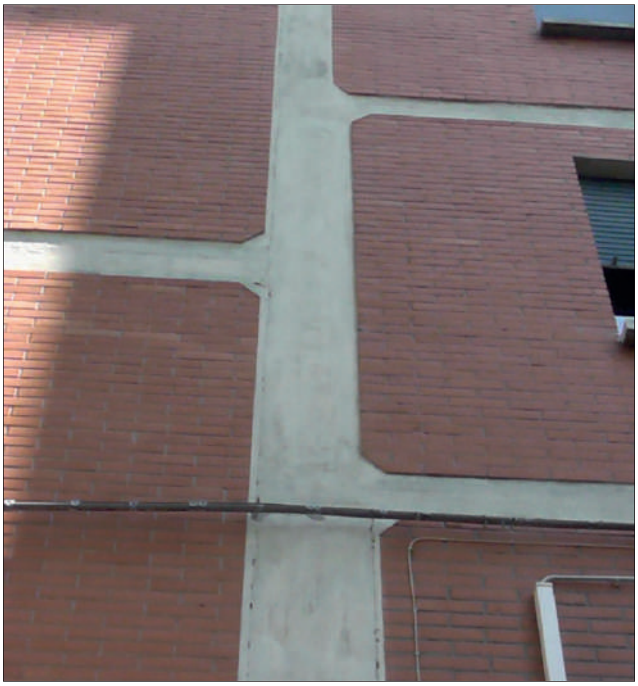


FIGURE 26 Separation between adjacent buildings

FIGURE 27 Detachment of the parapet of some balconies

With regard to the detachment of plaster, observed in some parts of the façades, and the damage to covering structures and chimneys, the urgent removal of loose or damaged parts was requested to the Fire Department, in order to ensure the safety of passers-by. As a result of these actions, the occupants of all the usable units were invited to return to their homes, also considering that the good performance and good quality of construction materials are evidence of the more than satisfactory seismic response of the aggregates, if compared to the earthquake intensity.In the following days, as many families were reluctant to return to their homes due to the great fear of aftershocks, the mayor of the City of Cento encouraged the CE.RES. inhabitants to re-enter their dwellings, during a public meeting held in the gardens of the complex. On that occasion, he was assisted by the technical advice of the ENEA experts, who gave their contribution to help inhabitants clarify their doubts, answering questions about their home safety, and suggesting them how to behave in case of aftershocks.

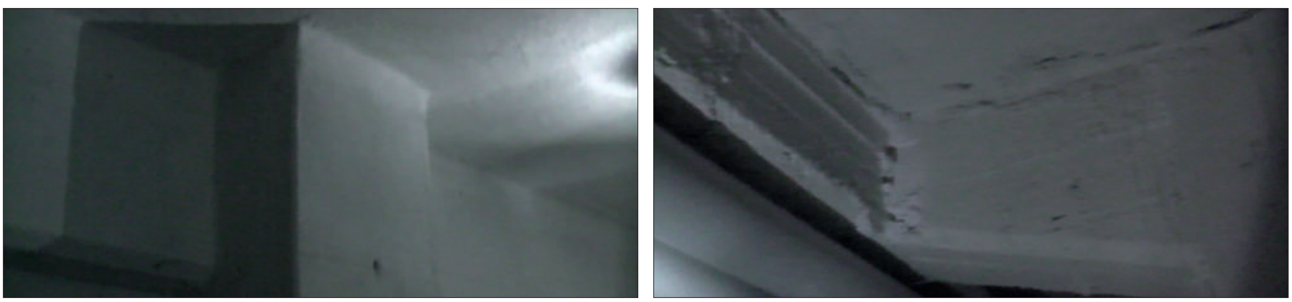
FIGURE 28 Separation between cladding and structure elements

The Cento skyscraper

The Cento Skyscraper is an RC construction realised in the Fifties of the 20th century, made of thirteen levels, in addition to the cellar floor. Four commercial activities take place at the ground floor, while, on the upper levels, five or six flats per floor are occupied by

(a) (b)

FIGURES 29 The Cento Skyscraper: a) external view; b) detail of the main façade



(a) (b)

FIGURE 30 Detail of the frames on the underground floor

about 150 people (Fig. 29). The area in plan is about 500 m^2. A television aerial, about 9 m high, is placed at the roof level (Fig. 29a). Both separation walls and cladding are made of hollow bricks. The façades are covered by mosaic and plaster layers in vertical and horizontal direction, respectively (see Fig. 29b).
The survey, which has been carried out at all the levels of the building, evidenced some structural lacks against the seismic actions, being the building realised before the application of the anti-seismic code. In fact, there are not closed frames in the two main directions; moreover, in several cases the existing frames are not complete, or intersect transversal beams far from the pillar (Fig. 30).
In addition, the building shows an irregular distribution of the resistant elements, which induces an irregularity in plan, again affecting the seismic behaviour of the structure (Fig. 31).
Both structural and non-structural damage have been surveyed after the seismic event.
The first pattern consisted of cracks on both sides of all the beams located on the right of the stairs, with reference to the upper direction, at each floor level (Fig. 32a,b). The cracked beams are about 1.90 m long and are present only on one side of the stairs. As a consequence, this is a small element inserted in a rigid body (the stairs), and it can be classified as a stocky beam. The damage has been probably due to the high stiffness of these elements with respect to the adjacent ones. Furthermore, the lintels of the east balcony were cracked almost at all the floors.
The second pattern was referred to façades, which showed partial fall down of the covering completion layers (plaster and mosaic), in addition to the partition walls cracks (Fig. 33).

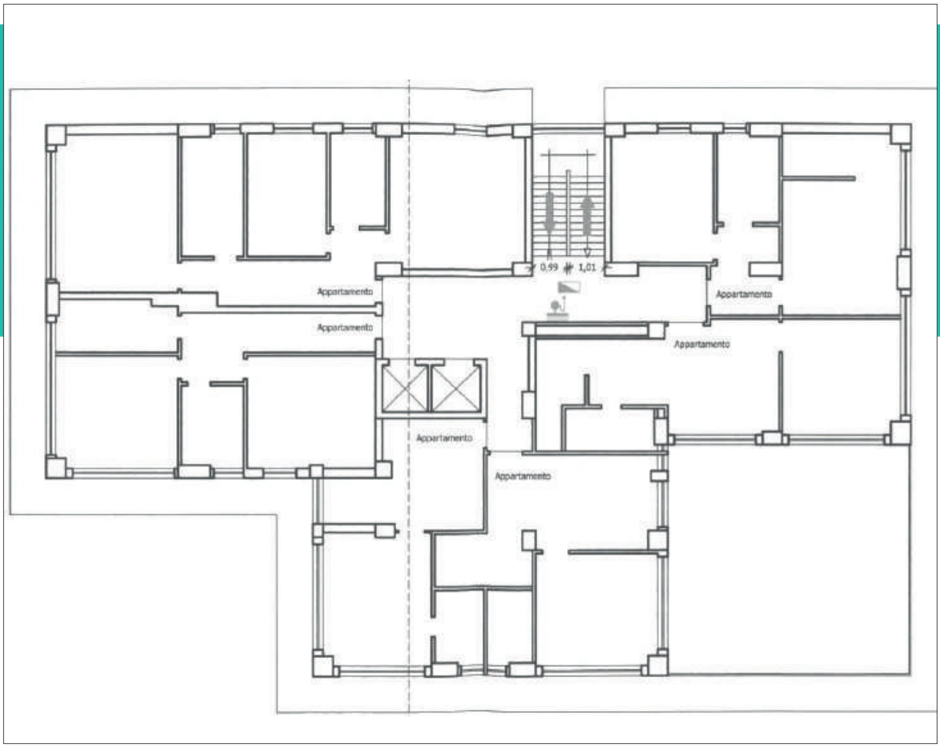


FIGURE 31
In plan distribution: first floor

(a) (b)

FIGURE 32 Structural seismic damage: a) location of the cracks on the stair beams; b) crack detail

FIGURE 33 Non-structural seismic damages: a) façade covering layers; b) partition walls

FIGURE 34 Local consolidation system: a) preparation phase; b,c) FRP application; d) plaster application

After the survey, a non-usability assessment (i.e., usability only after prompt interventions) has been filled up in the investigation form. In order to permit a quick re-entering of the skyscraper's inhabitants, a rapid and effective local consolidation has been suggested. It consisted in binding the damaged elements (both beams and lintels) with Fibre Reinforced Polymer (FRP) strips. Hence, the plaster was firstly removed from the damaged elements, then the primer layer was applied, and finally the FRP strips were fixed (Fig. 34).
Finally, the people living in the skyscraper came back to their flats as soon as possible, after the completion of the above said intervention.

Conclusions

The damage survey conducted in the post-seismic phase provides sufficient data to draw some general considerations.
First of all, it must be considered that the affected municipalities had been included among seismic zones after 2003 and, therefore, only a negligible percentage of buildings was designed according to anti-seismic criteria. Nevertheless, this it is not sufficient to explain the damage extent. In fact, traditional masonry construction performed quite well, whereas substantial damage occurred especially in those houses where transformations have not been correctly executed. In other words, where the good building practice, or "rule of art", was ignored.
It should also be noted that pre-modern anti-seismic precautions like metal tying were rarely used, confirming that the long return period seismicity experienced in this region was not sufficient to permit the development of a consolidated seismic culture.
As regards the more recent structures, it is important to underline the basic structural concept of the Italian Code for masonry structures relating to not seismic areas, in force from 1987 until 2009, which is clearly stated under paragraph 1.3: "Load-bearing masonry building must be designed as a three-dimensional structure consisting of a set of resistant systems connected to one another and to their foundations, arranged in such a way to resist to both vertical and horizontal actions." [4].
Had buildings been constructed in compliance with such a regulation, as it ought to be, certainly that damage would not have been so extensive.

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Sostenibilità dei sistemi produttivi

Strumenti e tecnologie verso la *green economy*

Il tema della *green economy* come strumento di uscita dalla crisi economica mondiale è al centro della Conferenza delle Nazioni Unite sullo Sviluppo Sostenibile denominata "Rio+20" (Rio de Janeiro, giugno 2012). Parlando di *green economy* si corre il rischio di associare quest'espressione soltanto a una parte dell'economia, l'economia verde, in contrapposizione all'economia tradizionale. Invece con *green economy* si intende un nuovo sistema socio-economico da attuare con l'applicazione integrata di un insieme di strumenti di pianificazione e regolazione, metodologici e strategici, tecnici e tecnologici, realizzativi, di monitoraggio e controllo. Si tratta di un vero e proprio cambiamento radicale che implica una riconversione di tutto il sistema produttivo, e non solo della cosiddetta "industria ambientale", verso processi e prodotti sostenibili.

Il volume ENEA, a cura di Laura Cutaia e Roberto Morabito, offre una panoramica su tecnologie, politiche, strategie, normative e strumenti legislativi, necessari sul percorso della sostenibilità; costituisce un tentativo di descrizione sistematica, seppur non esaustiva, della "tool box" da utilizzare per rendere sostenibili i sistemi produttivi.

Il volume è scaricabile gratuitamente dal sito www.enea.it

SPECIALE

Verso la green economy: strategie, approcci e opportunità tecnologiche

La *green economy* non deve essere considerata semplicemente come la parte "verde" dell'economia, operante esclusivamente all'interno del settore della cosiddetta "industria ambientale" (ad esempio, il settore delle energie rinnovabili), ma deve essere considerata come uno strumento da applicare a tutti i settori della produzione di beni e servizi, oltre che per la conservazione e l'utilizzo sostenibile delle risorse naturali, ai fini di una transizione verso un modello di sviluppo migliore e più equo.

La *green economy* costituisce quindi una formidabile occasione di sviluppo e di miglioramento ambientale, a patto che le autorità e le imprese abbiano comportamenti proattivi, e non semplicemente reattivi, che vengano elaborate e messe in atto le giuste politiche, che le imprese possano destinare una quota adeguata dei loro guadagni in ricerca e sviluppo.

Con questo Speciale della rivista *Energia, ambiente e innovazione*, l'ENEA vuole dare un contributo alla discussione per avviare la transizione verso la *green economy*.
Pur non essendo esaustivo, lo Speciale intende fornire un quadro, schematico ma completo, dei campi da considerare e degli strumenti da utilizzare sul percorso della *green economy*.

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