The 29th May 2012 Emilia Romagna Earthquake

EPICentre Field Observation Report

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EPICentre Field Observation Report
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The Emilia (Italy) Earthquake of 29th May 2012

1.0 INTRODUCTION

The 5.9M_w earthquake, which hit the Emilia-Romagna region of Italy on 20th May 2012 (see Rossetto et al, 2012) was followed on the 29th May 2012 by a 5.8M_w earthquake with epicentre 15km North West of the former event. This earthquake caused further damage to locations hit by the 20th May earthquake, and extended the affected area to the East-side of the province of Modena, resulting in 17 deaths and 14,000 homeless.

A team consisting of Dr Ioanna Ioannou, Randolph Borg and Jose Melo from EPICentre, and Viviana Novelli from University of Bath, travelled to the affected areas on 2nd June 2012. The team spent four days in the field, re-visiting Finale Emilia, San Felice sul Panaro, San Agostino and Mirabello as well as visiting new areas such as Mirandola, Cento, Cavezzo and San Possidonio. Rapid surveys were conducted that focused on the overall performance of residential, commercial, industrial and historical structures, emergency management and on geotechnical features of the two recent events.

The present report complements the first reconnaissance report (Rossetto et al, 2012) and should be read in addition to it in order to obtain a complete picture of the impact of the two moderate events. Both reports can be downloaded from the EPICentre website (www.epicentreonline.com) , where kml files with the georeferenced photos collected in the field for the two events can also be downloaded (for viewing on Google Earth).

2.0 THE 29th MAY 2012 EMILIA ROMAGNA EARTHQUAKE

2.1 Earthquake Characteristics

At 07:00 on Tuesday May 29th, an earthquake of magnitude M_W = 5.8 occurred with an epicentre approximately 50km northwest of Bologna in the Emilia Romagna region of northern Italy as shown in Figure 2.1. Both the USGS (2012a) and INGV (2012a) recorded a depth for this event of around 10km. This event occurred whilst the Emilia Romagna Region was still recovering from a magnitude M_W = 5.9 event (INGV, 2012b) that struck on Monday May 20th with an epicentre approximately 15km to the east near the city of Ferrara (INGV, 2012c).

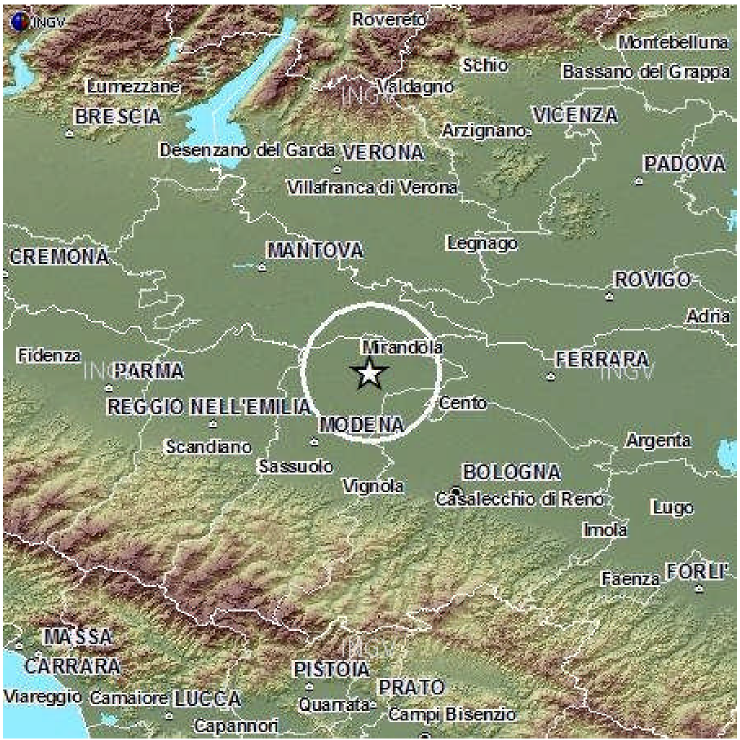


Figure 2.1 – Location of epicentre of May 29th earthquake (INGV, 2012a).

These earthquakes have occurred as part of a series that began on May 18th (INGV, 2012d). The daily distribution of earthquakes in this sequence by magnitude is shown in Figure 2.2 up to June 15th. The spatial distribution of these earthquakes is shown in Figure 2.3.

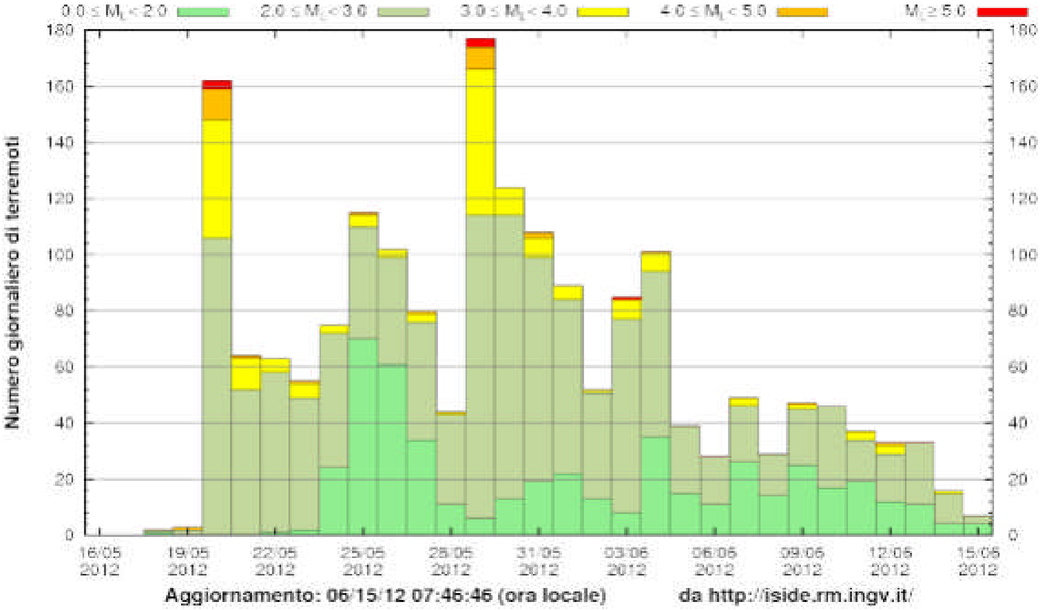


Figure 2.2 – Distribution of earthquake sequence by date and magnitude (INGV, 2012d).

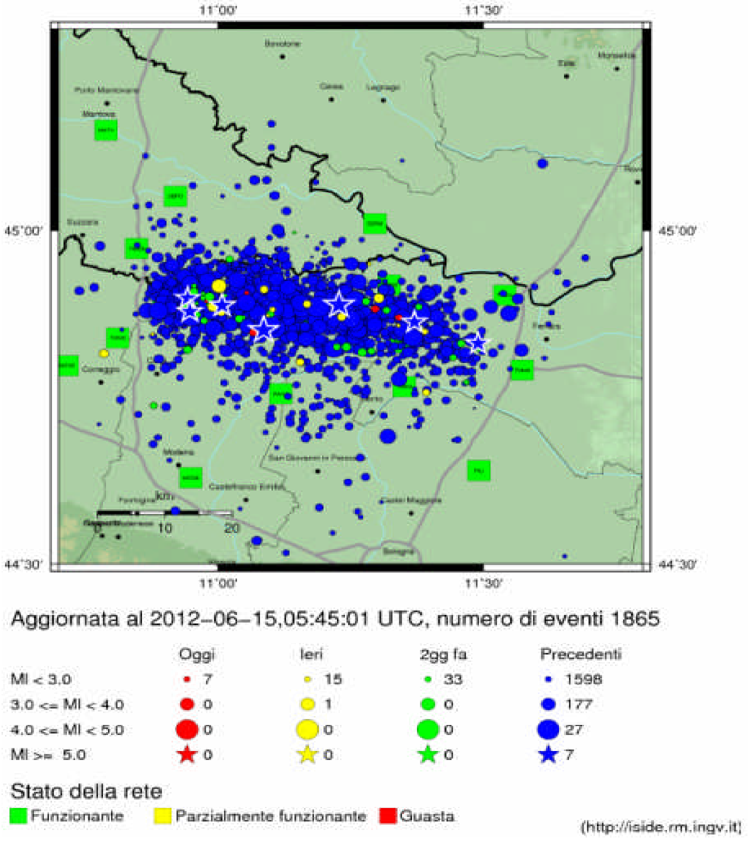


Figure 2.3 – Spatial distribution of earthquake sequence (INGV, 2012d).

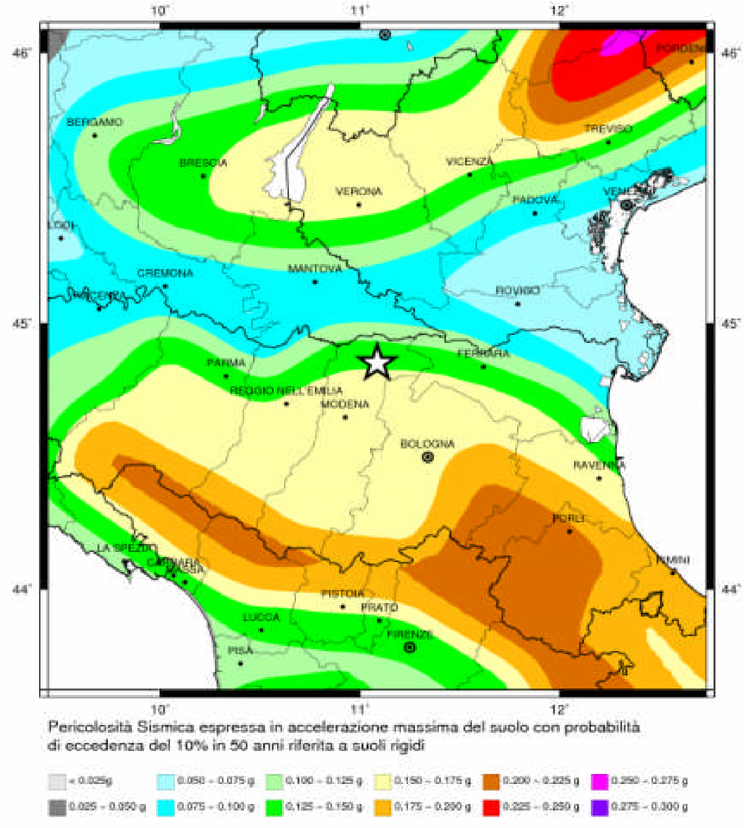


Figure 2.4 – Seismic design accelerations in Emilia Romagna (INGV, 2012d).

INGV (2012d) have identified the seismic hazard across Italy based on a 10% exceedance probability of peak ground acceleration within 50 years. This hazard map for the affected is shown in Figure 2.4, and indicates peak ground acceleration values between 0.125g – 0.15g.

Acceleration contours for the May 29th event are shown in Figure 2.5. The map indicates peak ground accelerations at the epicentre of around 0.30g, approximately double the design acceleration identified by the INGV seismic risk map. The earthquake occurred due to thrust faulting (USGS, 2012a).

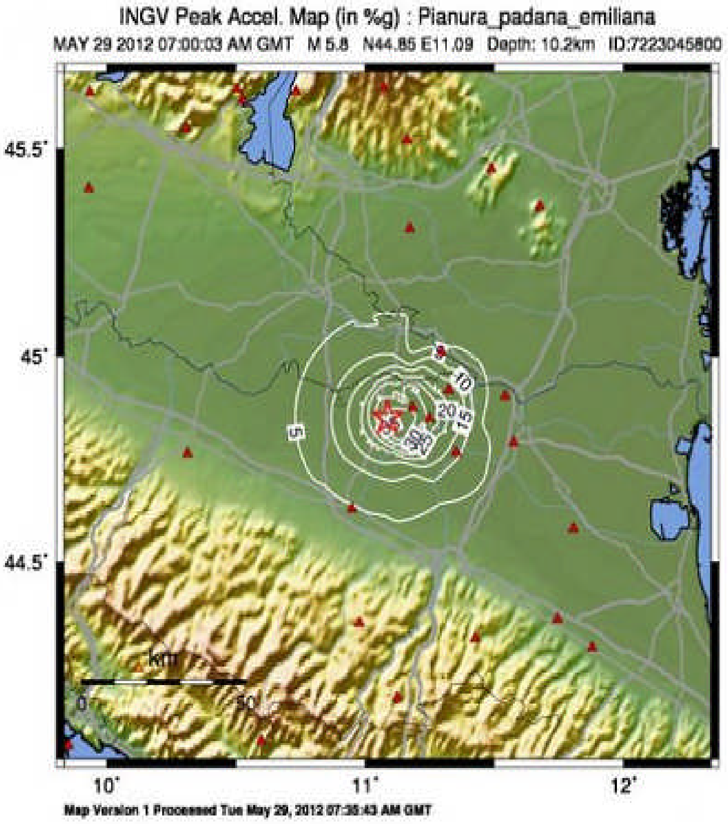


Figure 2.5 – PGA contour map for May 29th event (INGV, 2012d).

2.2 Tectonic environment

The Mediterranean region is seismically active due to the northward convergence of the African plate with respect to the Eurasian plate at a rate of approximately 7mm per year. The specific geology in this area, i.e. Pianura Padano, is dominated by compressional tectonics forming thrust-belt type structures such as the Appenine Mountains (USGS, 2012a). The compressive tectonic phases have produced asymmetric folds, and thrust and reverse faults verging north-northeast.

2.3 Historical seismicity

The historical and recent seismicity of the area is discussed in detail in EPI-FO-200512 (Rossetto et al, 2012). Here we highlight that according to the INGV historical catalogue (see Figure 2.6) no significant events (except for the earthquake of the 20th May 2012), have taken place within the immediate vicinity of the epicentre of the May 29th event. Based on analysis of the historic catalogue, Toscani et al. (2008) suggest a maximum magnitude for future events in this region of around $M_W = 5.8$, equal to the magnitude recorded by the USGS for the May 29th event but slightly lower than that for the May 20th event.

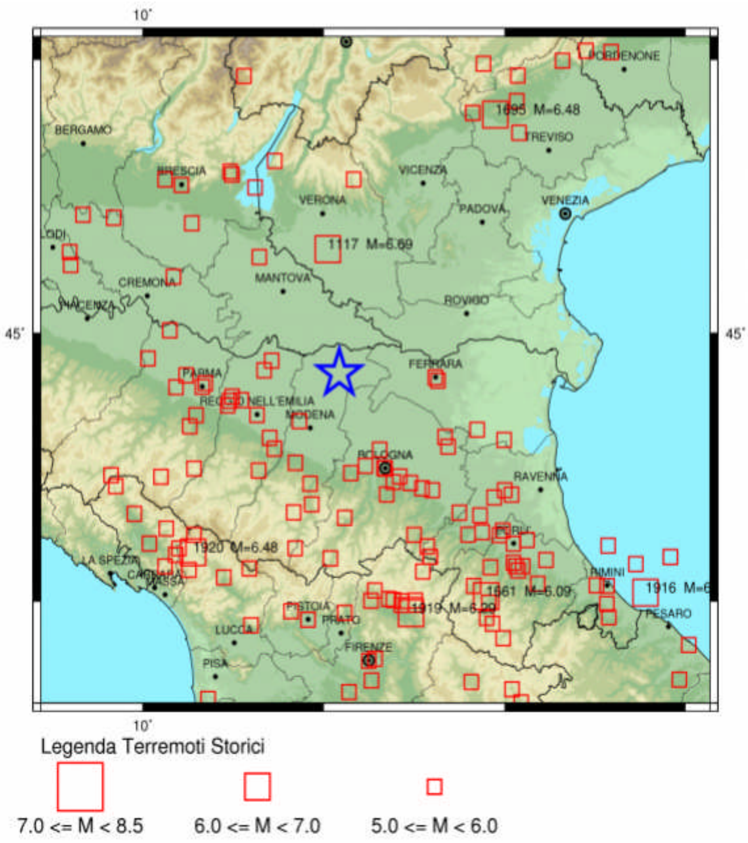


Figure 2.6 – INGV historical earthquake catalogue (INGV 2012d).

3.0 GENERAL OVERVIEW OF OBSERVED DAMAGE

The EPICentre earthquake reconnaissance team was re-deployed in Emilia-Romagna on 2nd June 2012 and spent 4 days surveying areas affected by the 20th May and 29th May 2012 events. These areas are depicted in Figure 3.1. The towns of Mirabello, Sant Agostino, Finale Emilia, Rivara and San Felice sul Panaro were revisited in order to observe the increase, if any, in the levels of damage caused by the 29th May event. In addition, the towns of Mirandola, San Possidonio, Cavezzo, Medolla and Camposanto located close to the epicentre of the second event, were visited. Finally, towns located further away from the epicentre such as Bomporto, Crevalcore, Cento and Novi di Modena were visited in order to compose an informed picture of the damage and disruption caused by the two events which shook Emilia-Romagna.

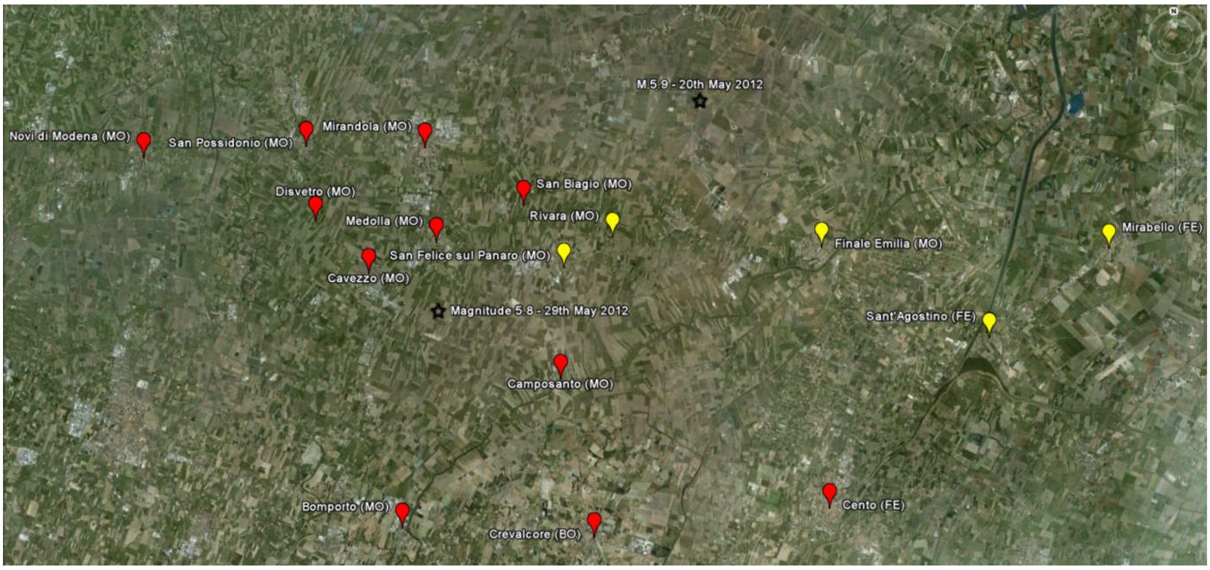


Figure 3.1 – Path of the mission: Towns and villages visited only in the 2nd mission (red) and revisited in the 2nd mission (yellow), epicentres of the two events (black stars) (MO:Modena, FE- Ferrara, BO: Bologna).

With respect to the areas located closest to the epicentre of the May 29th event, the team was able to access the red zones of Mirandola, consisting of the historical centres of the two towns. However, they were unable to access the red zone in San Felice sul Panaro, Concordia and Novi di Modena. In Concordia two concentric zones were noted. The inner red zone was controlled by the fire-brigade and the outer larger circle was controlled by the council with limited access. They were also unable to access the red zones in the centre of Cavezzo and Medolla. However, the latter two zones were too small, i.e. in Cavezzo the red zone consisted of the main square only. These towns were also affected by the 20th May event.

Cavezzo was found to be the worst affected town, with a few partially and/or totally collapsed masonry and reinforced concrete buildings. Overall the EMS-98 Intensity assigned by the team to this town is VIII, as the majority of these buildings suffered DS2, and collapses were limited. Lower intensities can be attributed to San Felice sul Panaro, Mirandola, Concordia, San Possidonio and Novi di Moden, where a few buildings suffered partial collapse (almost exclusively) at the top floor due to out-of-plane failure of one or more facades. This damage mechanism was also observed in many rural masonry buildings located in the area between Lodi and Motta, Disvetro and San Biagio in the outskirts of San Felice sul Panaro. By contrast, slight to moderate damage was observed in the ordinary residential/commercial buildings of Medolla, expressed mainly by in-plane shear failures. Pounding was also noted in few cases in historical centres due to the building practices of constructing buildings of different heights side-by-side.

Given the close proximity of these areas to the epicentre of the second event, the overall levels of damage suffered by the buildings are likely to have increased compared to that sustained in the May 20 event. In Cavezzo, local residents informed the team that a masonry building built in 1968, had suffered damage during the first event and collapsed in the second. In San Felice sul Panaro, the fire-fighters informed us that the level of damage suffered by the buildings during the 29th May event had increased for some buildings. However, it was not possible to record any increase in damage from rapid external observations of the buildings surveyed in the first mission. Two notable increases in structural damage were observed. The first was the water tower which suffered additional formation of plastic hinges in its beams and columns as well as damage in the infill brick masonry walls. Finally, a four storey masonry building with RC porticoes in via Largo Luca Sangi in Camposanto in the ourskirts of San Felice sul Panaro suffered moderate damage during the 2nd event only.

With respect to the areas located further away from the epicentre of the May 29th event, the towns of Crevalcore, Novi di Modena, Bomporto and Finale Emilia were visited. The former two towns had red zones, which were not accessed by the EPICentre team. Few buildings in Crevalcore were slightly affected by the May 20th event. After the second event, the red zone was expanded in order to include the additional damaged buildings. The maximum damage observed from surveying the area outside the red zone was moderate, i.e. large diagonal cracks in some masonry buildings. The maximum observed damage in Novi di Modena was associated with a single case of partial collapse of the upper floor due to out of plane failure and a few buildings with excessive and large diagonal cracks. Bomporto and Finale Emilia did not have a red zone. In Bomporto, light levels of damage were noted. By contrast, many severely damaged or partially collapsed masonry buildings were observed in the outskirts of Finale Emilia and very few cases of partially collapsed or severely damaged masonry buildings or RC buildings were observed in the city centre. Overall, there was little evidence of additional damage as a result of the May 29th event. In fact, the most evident increase in the level of damage in the city centre was the increase of the damage suffered by the infill brick masonry walls of an irregular RC building. This comparative assessment, however, was based only on the observable state of the exterior of the buildings as inspection of the interiors was not possible.

Finally, Cento, Sant Agostino and Mirabello were surveyed. These were mostly affected from the May 20th event. The team surveyed the red zone of Cento, where they observed the presence of porticoes in the façade of the, (largely) unreinforced, brick masonry buildings. The buildings had overall suffered slight damage, expressed as diagonal cracks and dislodged tiles or chimneys. Partial collapse of the upper floor due to out of plane failure as well as extensive and large shear cracks was also noted in a handful of buildings. With respect to the revisited towns of Sant Agostino and Mirabello, no additional damage was noted. In addition, no conclusive evidence of further liquefaction was found in Mirabello.

In line with the observations during the first mission (Rossetto et al, 2012) historical buildings such as churches, bell and clock towers as well as castles, suffered high levels of damage ranging from moderate damage to partial collapse. A common failure mechanism suffered by the churches was the partial or total overturning of the top end of the façade. The detachment of the façade was often caused by the lack or the scarcity of the connection with the rest of the structure and/or by the poor quality of the materials. With the exception of the two surveyed churches in Mirandola and the bell tower of the church of Nativita di Maria Santissima in Rivara, and the bell tower in the historical centre of Finale Emilia, the historical buildings were not substantially affected by the May 29th earthquake. A notable exception is the castle in Cento which was not damaged by either event.

Significant damage occurred in the surveyed industrial facilities in the industrial zones of Casumaro in the outskirts of Cento, Cavezzo and san Biagio and in scatteredsome isolated facilities in Medolla, San Lorenzo della Pioppa, Mirandola, and San Felice sul Panaro. Structures presenting large spans and double T-beam roofing systems were observed to have been the most severely affected by the earthquake. Except for a few cases of minor importance, transportation and lifelines did not suffer damage as a consequence of the ground shaking. Overall, bridges also appear to have performed well. With regards to geotechnical observations, no additional evidence of liquefaction was found during the deployment following the second seismic event. Evidence of immediate temporal repair of arterial roads was found in Cento and Mirabello.

Overall, the May 29th earthquake caused significantly greater economic and human losses when compared to the first event on May 20th. The higher economic loss can be attributed to the collapses suffered by industrial facilities, especially the precast RC as well as the historical buildings. The time of the earthquake occurrence (9:00am), when all factories were open, should be blamed for the high death toll, i.e. 13 confirmed deaths have been caused in industrial facilities. In addition to the extensive damage to industrial facilities and historical buildings, the second mission clearly identified the high levels of damage (which reached partial or total collapse in some cases) suffered by masonry as well as RC buildings. This can partially at least be attributed to the increase in the levels of damage by the 29th May event, especially in areas close to its epicentre, i.e. Cavezzo.

4.0 OVERVIEW OF THE PERFORMANCE OF BUILDINGS

4.1 Reinforced Concrete (RC) Buildings

The surveyed RC buildings appear to have been affected in larger numbers and more severely in the May 29 event than the May 20 event, which had mainly inflicted non-structural damage to infill walls of clay block or brick masonry.

RC buildings located in Cavezzo were particularly affected and in some cases collapsed during the May 29 earthquake. The collapsed buildings had the following characteristics:

i) low-rise structures with two or three storeys
ii) reinforced concrete frames built with plain or deformed steel reinforcement bars;
iii) infill masonry and
iv) slabs made with joists, tiles overlain by a thin concrete layer.

As was mentioned in the first report (Rossetto et al, 2012), the Emilia Romagna region was not classified as a seismic zone in Italian hazard maps until 2003. As a consequence, the structures built prior to this date were not seismically designed. This could be the main reason for their collapse. Other types of damage to RC buildings included damage to columns and secondary elements such as balconies and infill masonry walls.

Figure 4.1 shows two collapsed RC buildings in the Cavezzo region. The first building (Figure 4.1a) was built with deformed bars and the second building (Figure 4.1c) was built with plain bars. In both buildings the exact failure mechanism is difficult to identify, however, they both present examples of failures in columns, beams and joints, and examples of damage due to lap-splice failure. This indicates poor detailing and non-seismic design. Evidence of inadequate reinforcement detailing of joints and insufficient concrete confinement in joints is shows in Figure 4.1b. Inadequate lap splice length and beam shear failure is shown in Figure 4.1d. In both structures the concrete appeared to be of poor quality with high levels of large aggregate content.

a) b)

c) d)

Figure 4.1 - RC building collapsed in Cavezzo with hollow clay brick infill: a) RC structure with deformed bars; b) inadequate reinforcement joint detail; c) RC structure with plain bars; d) joint detail.

a) b)


c) d)

Figure 4.2 - RC building collapsed in Cavezzo with hollow clay brick infill: a) and b) overview; c) plastic hinge at the beam; d) insufficient lap splice length.

Partial collapse of an RC building in Cavezzo is shown in Figure 4.2. The collapse of the ground floor of the building with 3 floors, and adjacent one-storey building is likely to have been due to a soft-storey mechanism with collapse precipitated by the inadequate link between the circular columns and the beams at the ground floor level. The columns were made with a steel round tubular profile element filled with concrete reinforced with four longitudinal bars. The link between the circular columns and the beams was provided by the column longitudinal reinforcing bars, but the lap splice length was too short (Figure 4.2d). The masonry infill walls collapsed in some parts of the facades as shown in Figure 4.2a,b. Inadequate concrete confinement was also observed as well as shear failure in beams (Figure 4.2c).

Shear failure at the top of the ground floor columns was observed in a four storey RC building in Cavezzo (Figure 4.3). Several columns of the building suffered shear failure which led to an unstable structure. At the time of the reconnaissance, steel column elements were observed to have been placed to prop-up the floor at locations of damaged columns in an attempt to prevent the building from collapsing in aftershocks, (Figure 4.3b). The shear failure of the columns may be attributed to the large spacing between stirrups, which were closed with 90º hooks instead of 135º. Parts of the masonry infill walls of the ground floor were also seen to have collapsed.


a) b)

Figure 4.3 - RC building in Cavezzo with hollow clay brick infill: a) overview; b) shear fail at the columns in the ground floor.

In Novi di Modena, plastic hinges were observed in the ground floor columns of a 6 and 8 storey RC frame structure. This damage is reported to have been caused by the May 20 event (Figure 4.4), and may or may not have been further damaged in the May 29 event. At the base of these columns, shear failure was observed (Figure 4.4b) whilst at the top, flexural failure was noted (Figure 4.4d). The infill masonry sustained small cracks but did not fail.

a) b) c) d)

Figure 4.4 - RC buildings in Novi de Modena with hollow clay brick infill: a) overview of building A; b) shear fail in building A; c) overview of building B; d) plastic hinge at the columns in building B.

a) b) c)

Figure 4.5 - RC buildings with non-structural damage: a) balcony wall fail in Concordia b) infill masonry fail in San Possidonio; c) lower damage due to pounding in Cento.

Damage to non-structural elements are also important due to their potential contribution to human casualties. RC buildings with damage in non-structural elements are shown in Figure 4.5. The main damage observed in secondary and non-structural elements are:

i) balcony wall failures (Figure 4.5a);
ii) masonry infill wall damage (Figure 4.5b);
iii) minor damage in cold joints due to pounding between the buildings (Figure 4.5c).

Figure 4.6 shows the evolution of damage suffered by the brick masonry infill wall of an RC building located in Finale Emilia. The second seismic event increased the number and width of the cracks and caused the partial collapse of the infill masonry panel. The plastic hinges at the top end of the columns of the ground floor caused by the 20/05/12 event did not appear to have sustained an increase in damage level with the 29/05/12 earthquake.


a) b) c) d)

Figure 4.6 - Building in Finale Emilia with damage in the hollow clay brick infill: a) and c) 20/05/12 earthquake; b) and d) 29/05/2012 earthquake.

It can be argued that overall recent (after 2003) seismically designed RC structures behaved well. Figure 4.7 shows two undamaged recent RC buildings, one in Medolla and another in San Possidonio.

a) b)

Figure 4.7 - RC buildings without damage: a) in Medolla; b) in San Possidonio.

Figure 4.8 – Two masonry buildings in Finale Emilia. Comparison of damage sustained in the 20/05/12 event (left) and after the 29/05/12 earthquake (right).

4.2 Masonry Buildings

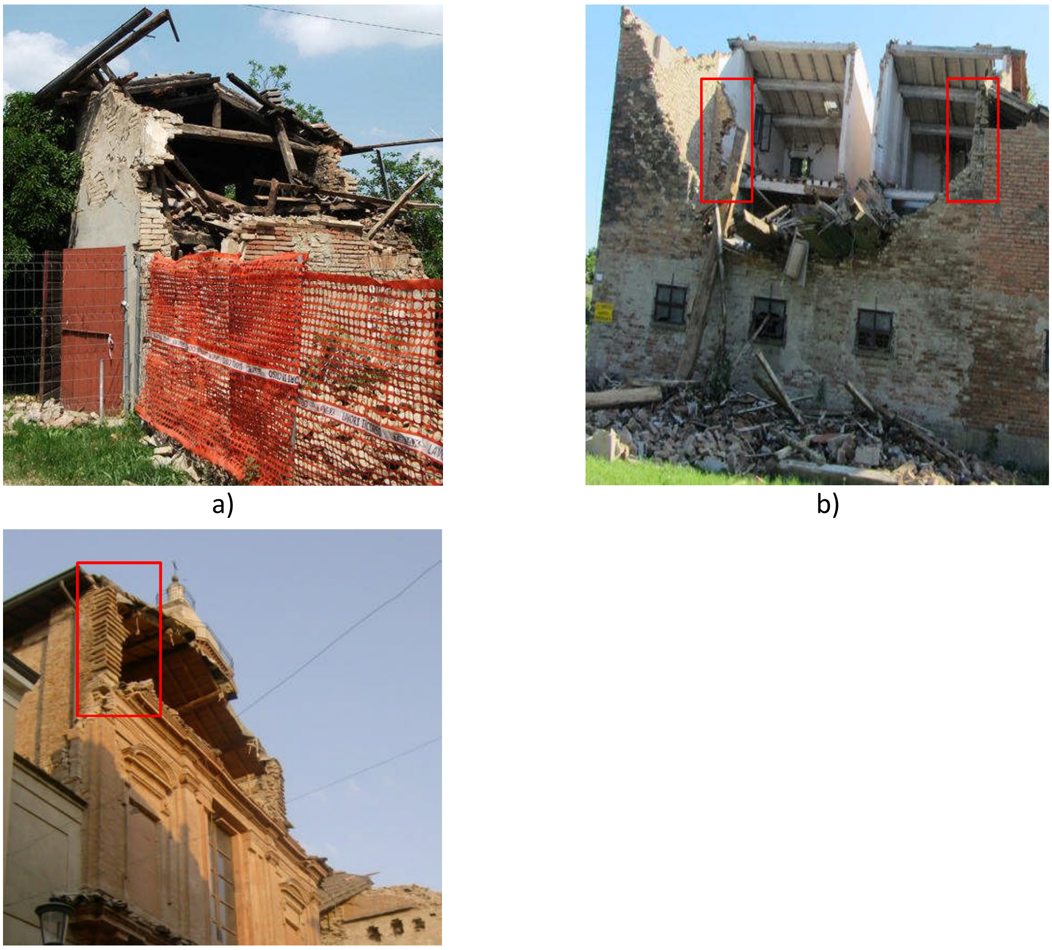
The historical centres close to the epicentre of the May 29 seismic event are: Cavezzo, Mirandola and San Felice del Panaro. Finale Emilia was also surveyed by the EPICentre team, and although local fire-fighters mentioned an increase in the level of damage to buildings, we found it very difficult to observe any substantial increase in damage levels suffered by the masonry buildings (see Figure 4.8). However, it is stressed that these observations are based on external inspections of buildings made from street level. The team was only able to conduct internal building inspections in a few buildings located in Cento, thanks to the support of the Italian Civil Protection.

The mentioned historical centres include a large variety of buildings, which range in height between one-storey (older) and five storeys (in this case the buildings are usually refurbished). The buildings are built alongside each other with no or small gaps between them. In a small number of cases, reinforced concrete frame buildings are also present in adjacency to masonry houses. This layout has direct implications on the seismic behaviour of single buildings and clusters, and leaves some buildings at severe risk of pounding, when height differences or differences in structure types are present in adjoining buildings, as shown in Figure 4.9.

Figure 4.9 – Pounding effect due to different heights of buildings (Cento).

The ground story of these buildings is commonly used for commercial activities and upper floors for dwellings. The bearing walls are connected to orthogonal walls and the original alignments are often preserved. Typical alterations to these buildings, observed on site, are the replacement of the original horizontal floor systems with a reinforced concrete slab.

The masonry fabric typologies most frequently observed in the historical centres were brick with regular courses. Lime mortar is typical. Large squared stone units are used for quoins both in common buildings and mansions, which improve the structural behaviour of the constructions. In general, the masonry fabric is of good quality and the buildings are well-maintained. Few exceptions of poor quality of materials or construction techniques were noted in collapsed buildings. Figure 4.10a-b shows cases of poor quality of mortar and walls having independent wythes. In addition, the slenderness of the facades (especially observed in older buildings) was seen to be the major cause of in-plane and out-of-plane failure mechanisms, see Figure 4.10c-d.



a)

b)

c)

Figure 4.10: a) poor quality of mortar in building in San Felice sul Panaro, b) masonry walls of building in Lodi built with two independent wythes, c) out of plane of the building in Curtatone street close to the Cathedral in Mirandola.

Horizontal floor systems include both masonry vaults and timber floors and roofs, see Figure 4.11. These are replaced in recently refitted buildings by reinforced concrete slabs. Masonry vaults are usually present at the ground floor and they are often supported by porticoes, see Figure 4.12.

Figure 4.11: Timber floor and timber roofs.

Figure 4.12: Masonry vaults supported by porticoes.

The presence of porticoes at the ground floor, see Figure 4.13, where shops and building's entrances are located, is a representative feature of the constructions in the North of Italy. Indeed this element of discontinuity of the façades has been already identified in several regions such as: Vittorio Veneto in the NE of Italy (Benardini et.al, 2008).

a) b)

Figure 4.13: Porticoes in a) Via Malagodi and in b) Via Provenzali in the historical centre of Cento.

As in many other historic centres in Italy, cross ties are a common feature. The ties are inserted longitudinally into the masonry, just below each floor level or above openings, with metallic elements resting on the surface of the façades to improve the connections between orthogonal walls, and between the walls and horizontal structures, see Figure 4.14. In the arches of the porticoes, ties/anchors have been introduced to counteract the horizontal thrust generated by the vaults, and to protect the facades from out-of-plane failure, see Figure 4.15.

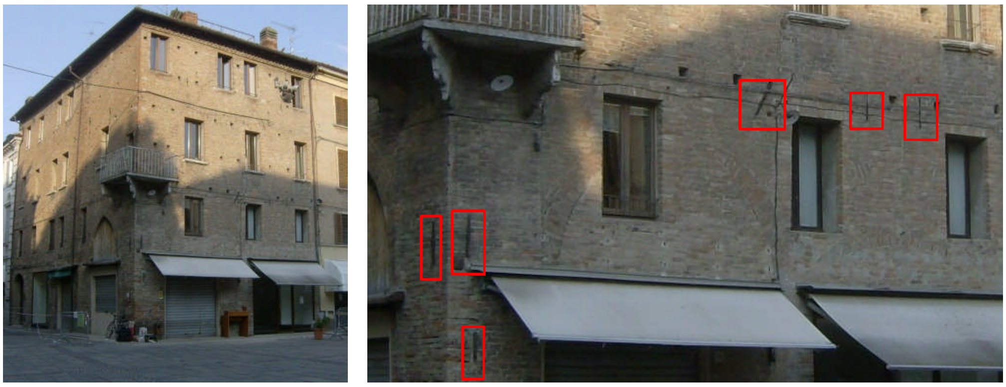


Figure 4.14: Metallic elements on the façades of the buildings on the corner between Piazza Costituente and Via Volturno in Mirandola.

a) b)

Figure 4.15: a) Metallic elements and anchors in the arches of the facades of the building on the corner between Piazza Costituente and Via Felice Cavallotti in Mirandola, b) anchors in the arches of the façade in Via Cesare Battisti in Mirandola.

However, this constraining action is effective only when ties are regularly spaced over the façade, placed at all floor levels and at the roof, and correctly anchored and connected through to the orthogonal walls or the floor structures. When ties are not properly anchored and the unrestrained length of the façade is considerable respect to its thickness, it has been observed that a central trapezoidal portion of this facade, under the effect of the seismic action, tends to shift outwards, see Figure 4.16.

Figure 4.16: Examples of out of plane of the top level in Mirandola and Rivara and sketch related to the identified mechanism (D'Ayala and Speranza, 2003).

In some buildings, for which more detailed inspection has been carried out, timber plates, often used to keep the bottom of the rafters in place, were observed. However, it is also observed that the presence of these plates can cause out-of-plane failure of the top storey façade if the timber plates are damaged or not well connected along the top of the wall to ensure diaphragmatic behaviour (see Figure 4.17).

(a)

(b)

Figure 4.17: a) Typical timber plate found at roof level in Cento and out of plane failure of the related façade.

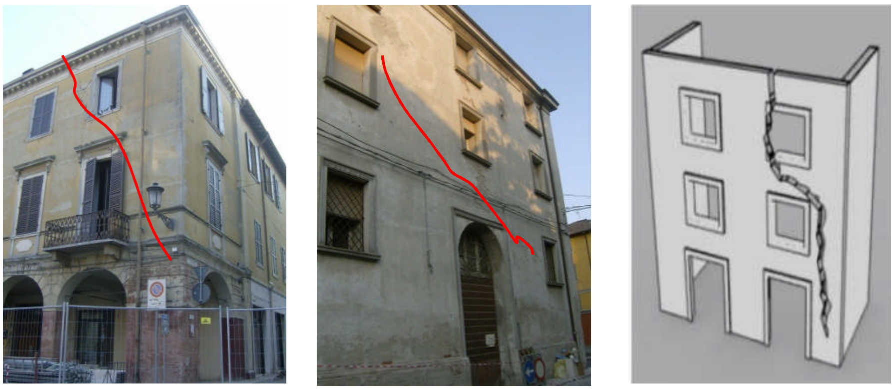
Quoins were observed in many masonry buildings and are used to aid interconnection between orthogonal walls, see Figure 4.18. However, the efficiency of these elements is limited when coupled with poor masonry fabric or internally unconnected masonry. It should also be noted that in some cases what appear to be quoins are actually only veneers applied to the building facades as architectural features and do not contribute to the structural response.

Figure 4.18: Typical quoins on both edges of the facades. The building on the corner between Via Guglielmo Marconi and Via Costa in Crevalcore has suffered shear failure in the spandrels.

In some cases, in particular for those buildings with commercial activities at the ground floor, damage was observed to be concentrated at the 1st floor due to the ground floor of the building having been strengthened with an additional structure, usually consisting of RC frames, see Figure 4.19.

(a) (b)

Figure 4.19: Malagodi street n.8 in Cento a) South west and b) north west façade.



a) b) c)

Figure 4.20: Examples of in plane in a) and b) Giovanni Pico Street in Mirandola and c) sketch related to the identified mechanism (D'Ayala and Speranza, 2003).

The most common form of in-plane failure for unreinforced masonry walls with regular openings is commonly considered to consist of recurring patterns of diagonal X shaped cracks in the spandrels or in the piers. Here however, as the horizontal structures (timber or masonry vaults) are not rigid in their plane, the redistribution of lateral forces amongst the piers depends on their connection with internal walls and the position of the timber beams or groin of the vaults (Casapulla & D'Ayala 2006). This means that in any one building some piers are more vulnerable than others, and their failure occurs as a combination of bending and shear, rather than just shear; see Figure 4.20.

The partial or total overturning of façades in masonry buildings (see Figure 4.21), was observed to have been caused by the following:

i. poor quality of the connections between walls or parts of walls
ii. poor quality of the masonry fabric and mortar
iii. lack of connection between horizontal structures and bearing walls
iv. lack of maintenance of masonry

a) b)

Figure 4.21: Examples of out of plane in Mirandola and Novi di Modena.

In the surrounding areas to the surveyed historical centres, most of the masonry buildings are detached and are characterised by regular configurations in plan and elevation. Many present alterations, typically related to the modification of the original opening layout, extension of the original plan and addition of a storey above the original level, see Figure 4.22.

Moreover, it has been observed that some of these houses are vacant and others are completely abandoned to their decay, since the lack of maintenance and low quality of their masonry fabric has contributed to decrease the structural performance to seismic events, see Figure 4.23.

a) b)

Figure 4.22: a) Modification of the original opening layout in the isolated house in the neighbourhood of Casumaro b) Alteration of the original plan of the isolated house between S. Felice sul Panaro and Rivara.

Figure 4.23: a) Isolated houses between S. Felice sul Panaro and Rivara and b) Isolated house in the neighbourhood of Casumaro characterised by low quality of materials and mortar

In summary, within the inspected historic city centres only few cases of total collapse were observed. Instead, the number of partial collapses of upper storeys is perhaps greater than would been expected. In a minority of cases the total collapse of façades was observed, and these were usually associated with buildings that presented specific vulnerabilities, mainly due to:

i. Intrinsic weaknesses of the materials
ii. Inappropriate strengthening or repair interventions
iii. Lack of maintenance of strengthening elements such as anchors and timber plates
iv. Substitution of the original floor/roof systems with heavier horizontal structures

Although the number of undamaged masonry buildings is very modest, the majority of ordinary residential/commercial masonry buildings were observed to have sustained either minor damage or structural damage that is deemed repairable.

4.3 Historical Buildings

A general overview of the damage suffered by the historical buildings surveyed in the field mission following the May 20 earthquake is presented together with observations regarding the increase in levels of damage caused by the May 29 event.

With respect to brick masonry churches, the churches of Matildica in Sorbara (Figure 4.24) and of San Lorenzo della Pioppa (Figure 4.24) did not suffer any damage. Slight to moderate damage patterns were noted in a few other churches in the same area. A church in Cento (Figure 4.26) appeared to have suffered slight damage with long but light cracks on the façade and the south wall. Another church in Cento suffered out-of-plane failure of the façade due to loss of connection between the north wall and the façade (Figure 4.27).

Figure 4.24 – Undamaged church of Pieve Matildica in Sorbara.

Figure 4.25 - Church of San Lorenzo della Pioppa: undamaged church

4.26 - Slight damage in a church in Cento

4.27 Out of plane failure of the façade in a church in Cento.

a) b)

Figure 4.28 - Church of San Michele in Novi di Modena: a) extensive cracks north side and on the east side; b) dislodged decoration from the top of the bell tower.

The church of San Michele in Novi di Modena (Figure 4.28) was surveyed from a distance due to lack of access. Extensive diagonal cracks on the south and east side were noted. The church of Cavezzo (Figure 4.29a) suffered moderate damage with extensive cracks on the south wall and a vertical crack on the wall indicating out-of-plane failure of the façade. A dislodged statue was also observed and extensive shear cracks seen on a masonry extension (Figure 4.29b). A vertical crack was noted on the façade of the church of San Lorenzo in Casumaro FInalese.

a) b)

Figure 4.29 - Church in Cavezzo: a) Partial collapse of the church, dislodged decoration from the bell tower, b) extensive and large shear cracks on the bell tower.

Figure 4.30 - Church of San Lorenzo in Casumaro Finalese.

Seven churches were noted to have suffered partial or total collapse of the upper part of their nave (Figure 4.31-34 and 4.36-37). A notable exception is the collapse of the roof over the transept of the church in San Possidonio (Figure 4.35). A common failure mechanism was the overturning of the upper part of the façade which led in most cases to the collapse of the gable (Figure 4.32-4.36).

a) b)

Figure 4.31 - Church in Cavezzo: a) Partial collapse of the church, dislodged decoration from the bell tower, b) extensive and large shear cracks on the bell tower.

a) b)

Figure 4.32 - Church in Disvetro: a) partial collapse, collapse of gable; b) vertical crack on the connection the façade to the north wall.

a) b)

Figure 4.33 - Church of San Martino in Buonacompra: a) Partial collapse of the church, b) extensive and large shear cracks on the bell tower.

a) b)

Figure 4.34 – Partial collapse of the church of San Biagio in San Biagio (a) and adjacent building (b).

a) b)

c) d)

Figure 4.35 - Church in San Possidonio: a) collapsed gable of the façade and collapse of the top part of the bell tower; b) extensive vertical cracks on the north wall; c) partial collapse of the ; d) extensive cracks on the extensions of the church and the apse and the south transept.

A complete assessment of the level of damage suffered from the bell towers was not possible in all cases due to the limited access to areas where these towers were located. Overall, the bell towers of the notably damaged churches also appeared to have suffered substantial damage. Partial collapse of the bell tower of the church of Disvetro (Figure 4.32) and San Possidonio (Figure 4.35) was observed. Notably, the collapse of the top end of the bell tower in Biagio (Figure 4.34) caused severe damage to an adjacent building. Apart from partial collapse, severe structural damage expressed by extensive and large shear failure at the lower end of the towers was also observed: i.e. the bell tower of Cavezzo (Figure 4.31), San Martino (Figure 4.33), San Lorenzo in Casumaro Finalese (Figure 4.30) and the Cathedral in MIrandola (Figure 4.36). Dislodged decorations on the spire were also noted (Figure 4.27b, 4.31a).

a) b)

Figure 4.36 – Cathedral of Santa Maria Maggiore in Mirandola: a) collapse of the gable of the façade; b) collapse of the roof.

Figure 4.37 – Dislodged decorations from the façade and partial collapse of the roof and south side of the church of San Francesco in Mirandola.

The 20 May 2012 earthquake caused the significant levels of damage observed during the second mission in San Martino in Buonacompra, San Biagio (Decanini et al, 2012) as well as in all the churches described by Rossetto et al (2012), i.e. Nativita di Maria Santissima in Rivara, San Bartholomew and the church in via degli Estensi in San Felice sul Panaro, San Pavlo in Mirabello and San Agostino in San Agostino. Most aforementioned churches were not affected by the 29 May 2012 earthquake. Two notable exceptions include the increase in spalling suffered by the base of the masonry bell tower in Rivara (Figure 4.38) and the partial collapse of the top of the façade of the church of DOM in San Felice sul Panaro (Figure 4.39). The most significant increase in the level of damage caused by the second event was noted at the two gothic churches in Mirandola. San Francesco suffered moderate to severe damage from the first event (Decanini et al, 2012) and partially collapsed during the 29 May 2012 event (Figures 4.26, 4.37). The levels of damage caused by each of the earthquake to the other churches remain unclear.

a) d)

Figure 4.38 – Bell tower of the church of Nativita di Maria Santissima in Rivara: a) after the 20/05/2012 earthquake b) after the 29/05/12 earthquake.

a) d)

Figure 4.39 – Façade of the church of D.O.M. in San Felice sul Panaro: a) after the 20/05/2012 earthquake b) after the 29/05/12 earthquake.

With regard to other historical buildings, the Castle in Cento, built in 1378 and enlarged a century later, is a reinforced brick masonry structure. This castle was found to have suffered no damage (see Figure 4.40). By contrast, the Castle in Mirandola (Castello dei Pico) suffered severe structural damage on an external wall as well as dislodged chimneys (see Figure 4.41). Overall, the damage suffered by these two Castles was significantly less than the partial collapse suffered by the Castles in Finale Emilia and San Felice sul Panaro damaged mainly by the 20 May 2012 earthquake (Figures 4.42a and 4.43a, respectively). These two Castles did not appear to have been notably damaged by the 29 May 2012 earthquake (see Figures 4.42b and 4.43b).

Figure 4.40 – Undamaged castle in Cento.

Figure 4.41 – Severe damage suffered by Castello dei Pico in Mirandola.

a) b)

Figure 4.42 – General view of the Castle in Finale Emilia: a) after the 20/05/12 event, b) after the 29/05/12 event.

a) b)

Figure 4.43 – General view of Rocca Estense Castle: a) after the 20/05/12 event, b) after the 29/05/12 event.

With reference to town halls, the town hall in Mirandola is a three storey brick masonry building with porticos. Nonetheless, there is reinforcement provided by the iron rods in the longitudinal direction to the columns. From the extensive stabilisation work undertaken under the porticos (see Figure 4.44a,b) it may be concluded that this building suffered some damage from the May 20 event (Decanini et al, 2012). Nonetheless, very little damage could be observed from the street. By contrast, the town hall in San Agostino suffered severe damage from the 20 May 2012 earthquake (see Figure 4.45a and for more details Rossetto et al, 2012). Figure 4.44b shows that the 29 May 2012 event did not notably increase the damage level. In fact only some loose bricks from the wall appear to have been dislodged.


a) b)

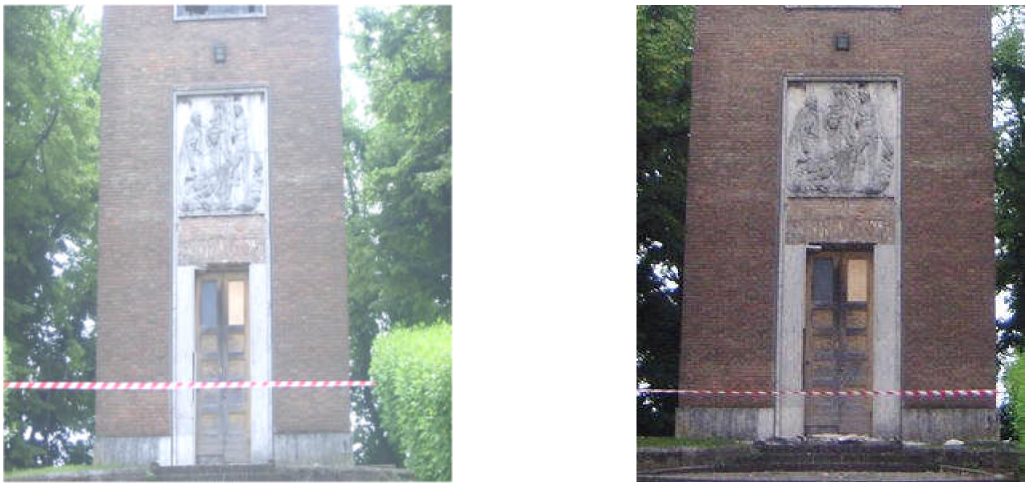
Figure 4.44 – Town hall in Mirandola: a) general view, b)side.


a) b)

Figure 4.45 – View of the most damaged side of the town hall in S. Agostino: a) after the 20/05/12 event, b) after the 29/05/12 event.

Finally, a severely damaged brick masonry tower was noted in Concordia (see Figure 4.46) and two towers in Finale Emilia were revisited (see Figure 4.47 and 4.48). The brick masonry tower, which was lightly damaged by the first event (Figure 4.47a), did not seem to have suffered any additional damage (Figure 4.47b). The partially collapsed bell tower instead had been removed by the fire brigade (Figure 4.48).

Figure 4.46 – Severely damaged tower in Concordia.



a) b)

Figure 4.47 – Brick masonry tower in Finale Emilia: a) after the 20/05/12, b) after the 29/05/12 earthquake.

a) b)

Figure 4.48 - Clock tower in Finale Emilia: a) after the 20/05/12, b) after the 29/05/12 earthquake.

4.4 Industrial Facilities

The EPICentre team observed damage in industrial facilities at: Casumaro, Finale Emilia, Novi di Modena, Concordia, Mirandola, San Giacomo Rancole, Cavezzo, Medolla, San Lorenzo della Pioppa and close to Cavezzo in the region between Lodi and Motta. Comparison is made with data collected from an earlier field mission carried out following the 20th May 2012 earthquake and reported in Rossetto et al. (2012). During the first field mission industrial facilities were surveyed close to San Carlo, Fondo Sabbione, Sant Agostino, Corpo Reno, Finale Emilia, Vigarano Mainarda and Massa Finale. Most of the damage caused to industrial facilities by the 20th May event occurred in the visited locations stretching from San Felice sul Panaro to Vigarano Mainarda. Some damage was also sustained by warehouses in the area between San Felice and Novi di Modena, however, this area was worse hit by the 29th May 2012 event.

The main industrial structures observed in the affected regions consisted in:

- Precast RC and Pre-stressed precast concrete structures
- Steel frame Structures
- Masonry structures with reinforced concrete or timber roof
- Silos
- Water Towers

The majority of the structures were constructed using RC and pre-stress precast techniques. Since the structures have large spans, and since most of the elements are pin connected, they may have long fundamental periods of vibration. As described in Section 6 the ground conditions amplify considerably the ground shaking particularly at smaller frequencies, and hence industrial warehouses may be subjected to high acceleration demands. These types of structures were also those observed to be mostly damaged by the earthquake. In the next sections each typology will be discussed separately.

4.4.1 Pre-cast reinforced and pre-cast pre-stressed concrete industrial structures

Most of the observed pre-cast reinforced concrete industrial structures consist of a series of single- or multi-bay portal frames, and are of a single level (with the exception of few which are partitioned to host offices as well). The transverse frame generally consists in precast RC columns, supporting pre-stressed long span beams. On top of the columns, RC precast T- or rectangular beams connect the series of portal frames in the longitudinal direction. The beams in either direction are generally simply supported on the top of the columns and are held in position by shear key U-shaped or L-shaped extrusions. In the absence of shear keys, the transverse beam is connected to the column by means of a system of steel plates and bolts. Many columns have also corbels in the transverse plain to support a bridge crane. Some of the columns have an I-shaped cross section in order to support precast wall panels between successive columns. For rectangular columns, the precast RC cladding is connected with the former using metal plate connectors and bolts. Other structures had masonry infill instead of RC precast panels. For most of the structures, the roof consisted in double T-precast pre-stressed slabs spanning in the longitudinal direction. In other cases, the roofing consisted in pre-cast pre-stressed hollow slabs also spanning in the longitudinal direction. These general characteristics were also similar to the structures observed during the first mission.

The lightly connected beams and columns are equivalent to a pin/roller connection at the upper part of the structure, and it is only the column to foundation connection that prevents the structure from having a mechanism under static load conditions. This made the structures very vulnerable particularly to lateral loads induced by the two earthquake events. As a result the most common type of failure mechanism observed, consisted in the rotation of columns in opposite directions such that the transverse and longitudinal beams slipped off the column connection and collapsed. Plastic hinges were also observed at the base of the columns. In most cases, the shear key also failed. It is observed that the latter was not adequately detailed with reinforcement, and no redundancy provisions were provided to make a monolithic connection. These characteristics were also observed in the structures investigated during the first mission.

a) b)

Figure 4.49 – a) Collapsed double T beam roof and prestressed concrete Beam of a warehouse at Casumaro b) Detail of a failed shear key connection.

Figure 4.49 represents a typical warehouse structure in Casumaro with the failure mechanisms described above. This shows similar failure characteristics of warehouses observed in the first field mission (Figure 4.50). Both these structures are reported to have sustained considerable damage due to the 20th May, 2012 earthquake event.

a) b)

Figure 4.50 - Industrial buildings close to San Carlo: a) overview of the pre-cast structure; b) joint detail.

Figure 4.51 shows the failure of the double T-beam roofing system spanning and some precast RC cladding. Failure of the shear keys is also observed. The structure in San Giacomo Rancole sustained most damage during the 29th May, 2012 earthquake, whereas the structure in Casumaro is reported to have sustained most of its damage in the 20th May event. The observed damage is similar to that observed in other representative structures during the first mission as shown in Figure 4.52.


a) b)

Figure 4.51 – Double T-beams as a roofing system spanning in the longitudinal direction a) warehouse in San Giacomo Rancole b) warehouse in Casumaro.


a) b)

Figure 4.52 - Industrial building in Sant Agostino: a) overview; b) joint failed detail.

Much damage was sustained by the cladding enclosing the warehouse precast superstructure. Figure 4.53a shows the permanent out-of-plane rotation of the precast column that has allowed the precast cladding to slip off the I-shaped grooves between successive columns. Out-of-plane failure of the masonry longitudinal cladding is also observed. Figure 4.53b shows the failure of precast RC cladding connected with the precast RC and pre-stressed superstructure by means of metal plates. Other similar structures sustained only minor damage to the cladding system. Long unsupported transverse walls sustained toppling failure as shown in the case of a warehouse at Mirandola (Figure 4.54). In Figure 4.55 it can be seen that some warehouses utilised steel trusses as the transverse system. Failure of the cladding here is also observed.


a) b)

Figure 4.53 – a) Failure of roof, column and masonry and RC panel infill in a warehouse at San Giacomo Rancole. b) Failure of precast RC panels in an industrial building in Casumaro.


a) b)

Figure 4.54 - a) Warehouse structure with slight damage in Mirandola
b) failure of masonry infill in a warehouse at Mirandola.

Figure 4.55 - Steel truss as the transverse support in a precast warehouse system close to San Felice sul Panaro.

Other RC precast and pre-stressed systems had slightly different configurations. Figure 4.56 shows a warehouse where the column shear keys consist in inverted T-shaped extrusions. These lock inside the groove of the longitudinal beams, which consist in H or inverted U sections. This detail prevents slipping in the transverse direction. The short spans in the longitudinal direction also ensured stability in this direction. As a result, only damage to the upper RC cladding system was observed.

a) b)

Figure 4.56 - a) Warehouse structure with H-section longitudinal beams in Mirandola detail of the b) H-section with the column shear key.

Other systems having a medium transverse span had double T-beams replacing the usual pre-stressed A-shaped beam. These were supported on precast RC beams as shown in Figure 4.57a for a warehouse in San Giacomo Rancole. Figure 4.57b shows another precast warehouse in San Giovanni Rancole where the roof consists of corrugated RC precast elements spanning horizontal transverse rectangular beams. In both structures the precast pre-cast cladding sustained failure. Figure 4.58 shows another precast system in Casumaro that did not sustain any damage. The warehouse was not very high. This, together with a good interlock between the precast elements and the column shear keys could have contributed to it not suffering any damage.

a) b)

Figure 4.57 – a) Detail of a transverse double T-beams as a roofing system of a warehouse in San Giacomo Rancole b) Corrugated precast RC sections as roofing system for a warehouse in San Giacomo Rancole.

a) b)

Figure 4.58 – a) Precast undamaged structure, b) details of the undamaged structure at Casumaro.

Some precast systems did not experience complete collapse of the roofing system after the failure of the transverse beam (Figure 4.59). This was because the transverse beam was partially supported by the corbel at intermediate levels of the column. This phenomenon was only observed in multi-bay warehouse structures with short transverse spans. This prevented the columns from developing large permanent rotations in opposite directions.

a) b)

Figure 4.59 – Secondary corbels preventing transverse beam from total collapse of the roof in San Giacomo Rancole.

As shown in Figure 4.60 some warehouse precast structures were observed to have suffered failure due to a combination of earthquake induced loading and fire outbursts as a secondary consequence. This phenomenon was particularly observed in two warehouses in Casumaro and San Giacomo Rancole.

a) b)

Figure 4.60 – Failure of warehouse industrial facility due to earthquake loading and followed by fire a) in Casumaro b) in San Giacomo Rancole

Two warehouse facilities housing a shelving system to store heavy materials and goods were observed to fail mainly in San Giacomo Rancole (Figure 4.61a) and Medolla (Figure 4.61b and 4.61c). In the first warehouse, the superstructure consisted of a series of portal frames supporting precast pre-stressed slabs as the roofing system. Longitudinal precast beams slipped over the column support, causing failure of the RC precast cladding, possibly connected with the former by metal plate connectors. The shelving system consisted of a system of metal frames which were simply connected. Lateral load from this system could have induced additional load on the superstructure.

The superstructure of the second system was very similar to the former, possibly having precast pre-stressed slabs spanning in the transverse direction and supported on precast longitudinal T-beams. The precast columns experienced out-of-plane rotation, causing the supported cladding and roofing system to fail. Some longitudinal beams were observed to have slipped off the column corbel. The shelving system consisting in slender Iron L sections, and was observed to experience a permanent displacement over 1m. The series of shelves were connected at the top and the foundation only. Lateral trusses in both directions were only provided at some intervals. The vertical and horizontal elements were connected using simple bolt connections.

These two warehouse structures contrast with the warehouse in Sant Agostino (Figure 4.61d and 4.61e) which failure was reported in the first mission. Whereas in the latter case partial collapse of the shelving system was observed, in the former two this was not observed. In the Sant Agostino facility, the shelving system was also the superstructure, while in the facilities observed in Medolla and San Giacomo Rancole the superstructure consisted in a precast pre-stressed system. The superstructure might have acted as a partial damper to the shelving system. In these two, no failure was observed at the foundation, whereas in the Sant Agostino warehouse failure was also observed at the shelf structure-foundation interface. Moreover, in this latter structure the stored material was observed to be at the upper levels. In the other two facilities, this was observed to be distributed over the whole areas. Finally, the Medolla and San Giacomo Rancole warehouses were lower in height, compared to the one in Sant Agostino.

a) b)

c) d)

e)

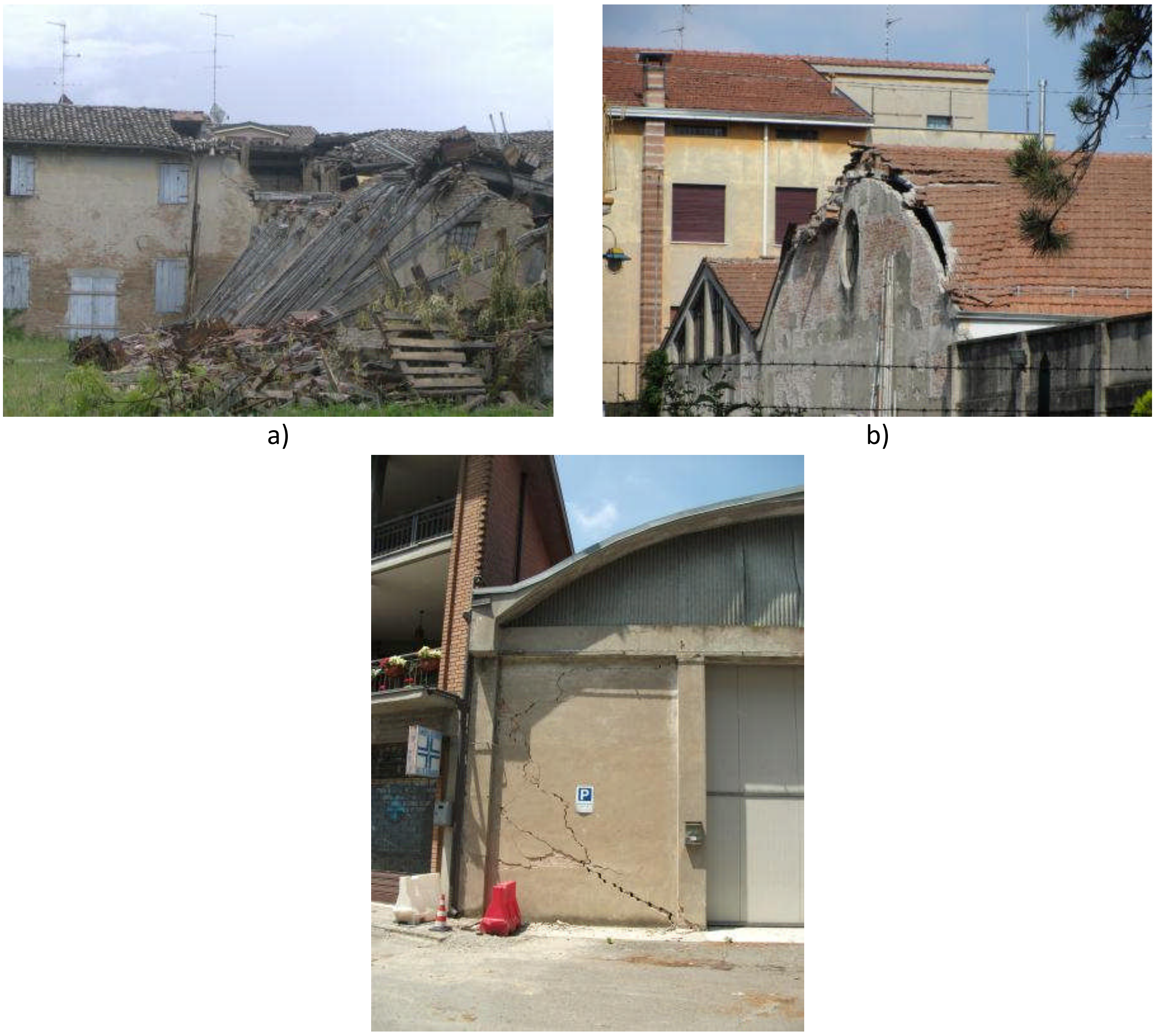
Figure 4.61 – a) Storage Facility in San Giacomo Rancole b) Storage warehouse in Medolla, c) detailing of the shelve in the storage facility at Medolla d) Ceramic Storage facility in Sant Agostino e) detailing of the shelving system in the storage warehouse at Sant Agostino.

4.4.2 Masonry industrial structures

A multi-storey industrial masonry structure in Mirandola was observed to experience failure in one of its blocks (Figure 4.62). The building was irregular in elevation and pounding and out-of-plane mechanisms at corners due to change in stiffness along the height could have contributed its damage.


a) b)

Figure 4.62 – Masonry multi-storey industrial building: a) general overview b) detail of supported masonry.


a) b)

c)

Figure 4.63 – Masonry industrial facilities in a) Cavezzo b) Mirabello c) Novi di Modena.

An agro-industrial facility in Cavezzo, consisting in load-bearing brick walls and a composite RC and masonry system experienced extensive damage due to overturning of the load-bearing wall and lateral sliding of the heavy roofing system (Figure 4.63a). An automotive warehouse in Mirandola consisting in a RC arch roof and masonry load bearing walls and partitions experienced out of plane failure of a transverse wall, and possible longitudinal slippage of the RC roof (Figure 4.63b). A similar structure consisting in a RC arched roof with RC transverse arch beam, possibly supported on load bearing masonry walls, experienced diagonal cracking in the masonry transverse walls (Figure 4.63c).

4.4.3 Silos

Two silo facilities were observed (Figure 4.64). The first one was on the outskirts of Finale Emilia. It is a recent construction and no damage was observed. The second was part of an industrial complex in San Giacomo Rancole. This was partially damaged as a consequence of pounding with the portal frame of the adjacent warehouse, and the collapsed cladding of the same warehouse.

a) b)

Figure 4.64 – a) No damage to Silos recently built close to Finale Emilia b) Damaged silo in a factory at San Giacomo Rancole.

4.4.4 Reinforced concrete structures - Water towers

The water tower observed in San Felice sul Panaro was damaged when first observed soon after the 20th may event (Figure 4.65a and 4.65b). The structure consists of an octagonal RC frame, with masonry infill panels, and only 1 RC horizontal diaphragm. Various masonry panels were observed to have fallen out of plane. Shear failure was observed in various beams at the lower 2 levels of the frame. Plastic hinging was also observed in some of the columns at the bottom. During the second field mission after the 29th May, 2012 event, plastic hinging and shear failure in beams was observed to extend to upper levels. Plastic hinging in the columns was also observed in the upper levels. More masonry infill panels had fallen out-of-plane. Some panels were reinforced with iron columns having angles sections, in order to prevent out of plane failure after the first event. Shear cracks were observed in these panels after the second event (Figure 4.65c and 4.65d).

a) b)

c) d)

Figure 4.65 - Water tank in San Felice sul Panaro: a) overview as observed after the 20th May, 2012 event; b) plastic hinge in the lower beams as observed after the 20th May event; c) overview as observed after the 29th May, 2012 event; d) plastic hinges extended in beams at upper levels after the 29th May, 2012 event.

5.0 LIFELINES

5.1 Roads

The main roads connecting the affected towns were not damaged by the earthquake and remained open, with one exception. The road between Lodi and Motta was closed because it had been blocked by a fallen electricity cable (Figure 5.1).

The centres of towns affected by the earthquake were cordoned off to prevent injury from the collapse of unstable or damaged buildings.

Figure 5.1 – Road closure due to fallen electricity cable.

5.2 Buried Services

One instance of damage to buried services due to ground movement was observed by the EPICentre team. In San Felice sul Panaro, ponding of sewage around a manhole in the town centre was visible (Figure 5.2), possibly due to a blockage as a result damage to pipes downstream.

Figure 5.2 – Ponding of sewage at foul manhole in San Felice sul Panaro.

5.3 Bridges

Scaffolding had been erected beneath a bridge of modern precast concrete construction located on the outskirts of Finale Emilia, perhaps in order to inspect the deck/pier connection. Overall the structure appears to have performed well and as expected. The only damage visible to the EPICentre team (who did not access the scaffolding) was some insignificant cracking in an external section of the deck at an expansion joint (Figure 5.3). No other damage was apparent, apart from some leaking uPVC drainage pipes, and it was not possible to establish if this was caused by the earthquake.

a) b)

Figure 5.3 - a) Precast concrete bridge outside Famile Emilia with no signs of significant structural damage; b) Minor damage to concrete at the expansion joint location.

Slight to moderate damage was observed in the brickwork abutments of an older reinforced concrete arch and beam bridge (Bomporto Bridge) constructed in 1914. Steel reinforcement in the bridge deck had been previously exposed (either due to inadequate cover or removed for inspection). The reinforcement had rusted indicating that it was exposed for some time before the earthquake. There was no new visible damage to the reinforced concrete structure of the bridge. However, cracking in both masonry bridge abutments can be seen in Figure 5.5, which has in turn caused cracking in the road surfacing (Figure 5.6) This bridge was open to traffic when observed by the Epicentre team, although warning signs had been erected on the approaches (Figure 5.7).

Figure 5.4 – Existing rusted rebar exposed prior to earthquake (Bomporto Bridge).

Figure 5.5 – Typical cracking in the brickwork bridge abutments of Bomporto Bridge.

Figure 5.6 – Minor cracks in road surface due to damage to masonry abutments beneath.

Figure 5.7 – Bomporto Bridge (reinforced concrete and masonry) open to traffic.

5.3 Electrical Substations

A number of surveyed electrical substations were found to have suffered slight damage (see Figure 5.8). These buildings are unusually tall and slender masonry structures. One large horizontal crack in the masonry was visible in a substation in Disvetro, extending from the lintel above the door running fully around the building.

a)

b)

Figure 5.8 - a) Tall slender masonry electrical substation building in Disvetro; b) Horizontal cracking in the masonry extending the entire way around the structure.

6.0 GEOTECHNICAL OBSERVATIONS

In general, the soil surrounding the area where most damage was observed is characterised by unconsolidated ground layers. This may have contributed to the amplification of ground acceleration. These conditions have triggered damage in infrastructure and buildings due to settlement. Moreover, the region was susceptible to liquefaction since in general the ground is characterised by a clay material overlaying layers of sand, possibly saturated due to the flood plain region and other underlying clays. This resulted in observations of building damage due to liquefaction-induced differential settlement and lateral movement of the ground underlying the structures.

As the Emilia region slopes from south east to north west, the area extending from Concordia to Bondeno is characterised mainly by 3 rivers that flow into the Po. These are the Secchia river, the

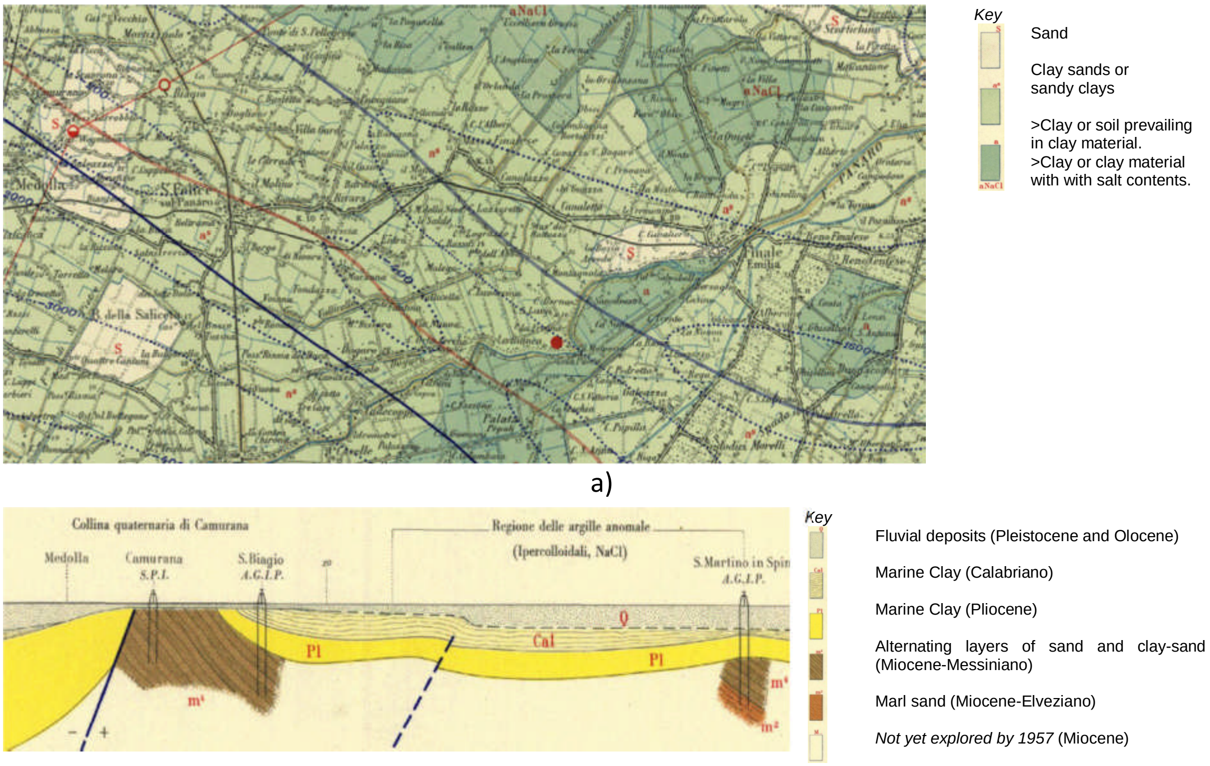
Panaro river and the Reno river. The Secchia nowadays passes through Concordia, but in Roman times it used to pass close to Cavezzo and then used to deviate suddenly towards Bondeno from which it linked with the Po. It was between 1288-1360 that the river stared passing specifically from Concordia. The town of Cavezzo itself was established as a result of the decay of Cesare which was destroyed after the overflow of the Secchia river in 1542. The river Reno used to pass through Sant Agostino and Mirabello, and it was often flooding. As a result the Cavo Napoleonico was constructed. The work started in the 1800's and it was only after the Gallo Renatio flooding of Poggio that took place between 1949 and 1951 that the channel was actually completed. As a result, the old trajectory of the river Reno passing through Mirabello was replaced by the main road. The long history of flooding and changing in paths of the 3 river flows indicates that the construction of the towns between Concordia and Viagano Mainardo are built on alluvial deposits which are not very optimal, and are the result of local ground amplifications and differential movements.

All the observations presented in this section relate to the route taken by the EPICentre team, and it is not excluded that other damage or other phenomena also occurred in areas that were not visited by the team.

6.1 Geological Lithology, Stratigraphy and Ground Amplification

The lithography of the area stretching between Modena and Ferrara consists mainly of clay or clay prevailing material, with areas of clay sand or sand as shown in Figure 6.1 and Figure 6.2. The area is quite flat and has a long history of flooding from various rivers mainly the Po and Reno. As a result, the ground consists mainly in an alluvial plane, stratified with alternating layers of fine sand often also containing silt. Intermediate alternating layers of silt, sandy silt and clay silt are also present and vary in thickness. In some areas, at the base of this series of layers, local medium to coarse sands and intercalating layers of clay are also present; the latter generally roofing the former.

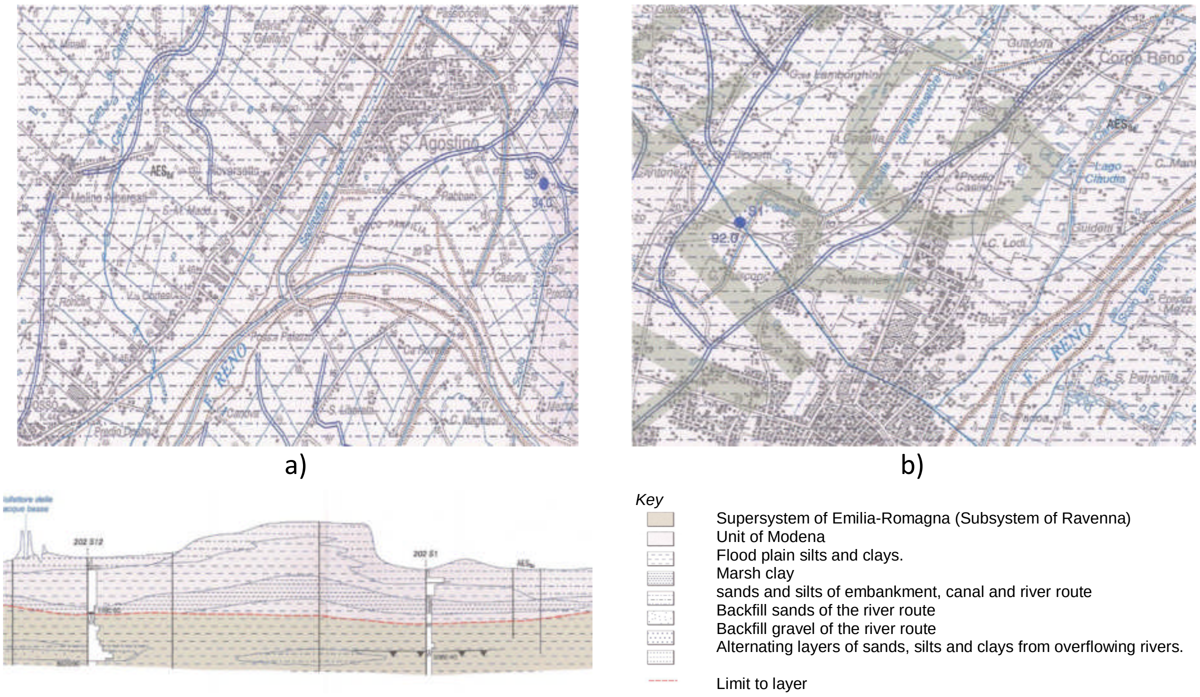
The stratigraphy is divided into 2 main parts: the top part of the sub-system of Ravenna, underlying the unit of Modena as the superstructure of the Emilia-Romagna region. Figure 6.1 and Figure 6.2 show a typical stratigraphy of the region and the lithology of Finale Emilia, San Felice sul Panaro, Sant Agostino and Corpo Reno. These are based on 2 geological Italian maps of the area. One is at a scale of 1:100,00 completed in the 1950's (Law 2/2/1960) and the other is a more detailed map at a scale of 1:50,000 (CARG, 2007).



a)

b)

Figure 6.1 - Geological map at a scale of 1:100,000: a) Surface lithology of Finale Emilia and San Felice; b) Stratigraphy Close to San Felice sul Panaro.



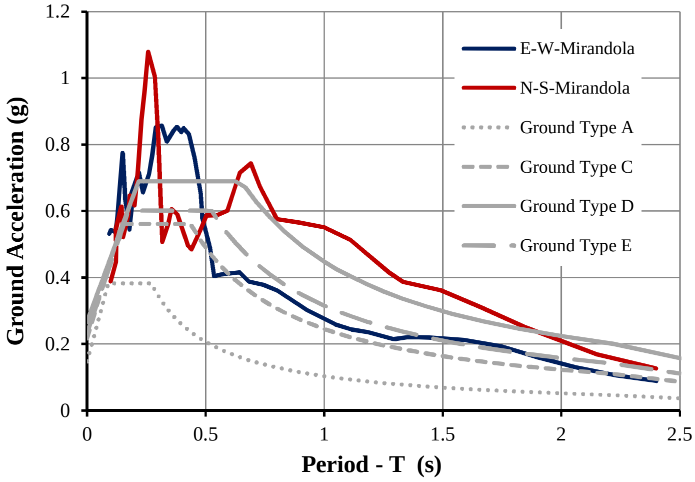
a)

b)

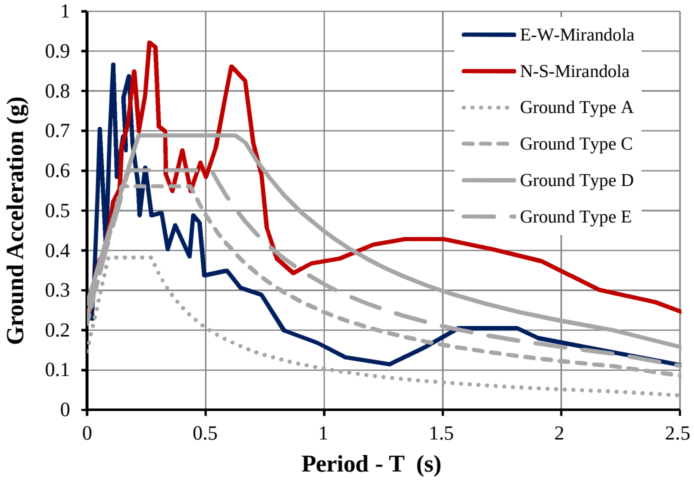
c)

Figure 6.2 - Geological map at a scale of 1:50,000: a) Surface lithology of Sant Agostino; b) Surface lithology of Corpo Reno; c) Stratigraphy between Cento and Corpo Reno.

The unconsolidated ground and its stratigrafic structure give rise to large seismic acceleration amplification. In Figure 6.3, elastic response spectra for various soil conditions at 5% damping and complying with DM14/01/2008 (Italian seismic code 2008), are compared with the response spectra derived from the acceleration history measured in perpendicular directions at Mirandola (Protezzione Civile, 2012) for both the 20th May, 2012 and the 29th May, 2012 events. From the description of the ground stratigraphy, the ground condition may be expected to vary between types C, D and E. The code spectra for ground types D and E seem to match the spectra of the earthquake. Nevertheless, the corresponding measured PGA was higher than the corresponding code value for both events. Given that towns like Mirandola are very close to the epicentre of the 29th May event and the ground amplification, the vertical component of the ground motion acceleration was extremely high (8.7m/s^2 according to RAN, Protezzione Civile, 2012). This may have increased the risk, particularly to simply supported structures such as the observed damaged precast structures. A combination of large vertical with a moderate horizontal acceleration causes non-monolithic components to slip over each other, causing collapse.



a)



b)

Figure 6.3 - Comparison of the response spectra at 5% damping for different ground typologies with the response spectra derived from the acceleration history measured at Mirandola for:
a) the 20th May, 2012 event and for b) the 29th May, 2012 event.

According to much earlier Italian seismic codes (MLP 14-07-1984) the region was not classified as a seismic region. In 2003 it was upgraded as Seismic Zone III, i.e. having minimum seismicity. As a result, it is not excluded that geotechnical issues associated with dynamic loading and soil structure interaction may have not been considered in the design and construction process for structures built before 2003. The ground amplification factors indicate that geotechnical aspects play an important role in definition of seismic hazard and hence seismic risk of the region. It was only in 2008 (DM 14/01/2008) that a considerable seismic design acceleration was attributed to the region. The average PGA of the region is 0.15g for 10% probability of exceedance in 50 years, 475 years return period.

6.2 Liquefaction

Although liquefaction was observed in Mirabello, San Carlo and San Felice sul Panaro during the first field mission due to the 20 May event, no further liquefaction or particular ground failure was observed in the second field mission, that can be attributed to the 29th May earthquake. This is true despite the epicentral distances of areas observed to liquefy in the first event being very similar to those of the second. Berardi (1991) states that no liquefaction was observed in the region after the 1796 Ferrara earthquake and the 1898 Argenta earthquake, both having an intensity I = VII MCS. Nevertheless The Ferrara 1570 earthquake, the 1505 Zola Pridena earthquake and the 1624 Argenta earthquake showed signs of liquefaction (Berardi, 1991).

7.0 OBSERVATIONS ON DISASTER MANAGEMENT

There were significant differences between the impact of the earthquake on Sunday 20th May and that of Tuesday 29th May. The latter shifted the focus geographically and virtually doubled the scale of the emergency response.

7.1 Casualties

Seven people died in the earthquake of 20th May, as follows:-

- a 29-year-old male worker died in the collapse of the Uru polystyrene factory at Bondeno (Province of Ferrara)
- two male workers (aged 35 and 50 respectively) died in the collapse of parts of the Sant'Agostino Ceramics factory
- a 55-year-old male worker died in the collapse of the Tecopress aluminium pressings factory at Dosso, Sant'Agostino Ferrarese
- at Sant'Agostino a 103-yr old woman died when the roof of her house fell in
- a 37-year-old woman died of a heart attack at Sant'Alberto di San Pietro in Casale (Province of Bologna)
- at Vigarano Mainarda (Province of Ferrara) an 86-year-old woman died from a stroke.

About 50 people were injured, mostly lightly. However, a fireman was seriously hurt when he fell from a wall at Finale Emilia.

Five of the seven deaths resulted from the sudden, spontaneous collapse of aseismic factory buildings affecting workers on the night shift. Most of the other buildings that collapsed were abandoned farmhouses, churches or ancient monumental constructions (towers and castles), none of which had any inhabitants. As damage to vernacular housing was light or absent, few problems of entrapment, rescue and injury were associated with these processes. Nevertheless, in one such case, the collapse of the Palazzo dei Veneziani at Finale Emilia, 11 local residents were trapped and had to push a wall down to get out. Given that there were various cases in which vehicles were crushed by falling masonry, and numerous examples of façade elements of buildings crashing down into streets, there was a significant propensity for a larger number of casualties (Figure 7.1).

Seventeen died in the 29th May earthquake (mag. 5.8), which occurred at 09:03 hrs local time. Thirteen of the victims were killed in the collapse of five factories (the companies Meta, BBG, Haemotronic, Aries and an undisclosed firm). Two of the remainder died when their houses collapsed, one was killed in another building and the last, a 65-year-old parish priest, was killed in the collapse of his church in Rovereto, a satellite town of Novi di Modena. Figure 7.2 illustrates how the locus of casualties shifted to the west in the second earthquake. Clearly, death and injury were avoided by preventing access to town centres damaged by the first earthquake.

Figure 7.1 Car crushed by falling chimney, Finale Emilia.

Figure 7.2. Location of deaths in the 20th and 29th May earthquakes.

Figure 7.3 shows that the age distribution of fatalities is dominated by people of working age, and by men (with some extension for both sexes into old age). As 70 per cent of victims died in factories, this is to be expected, and it changes the pattern with respect to earthquakes elsewhere, in which age is the principal factor that correlates with mortality.

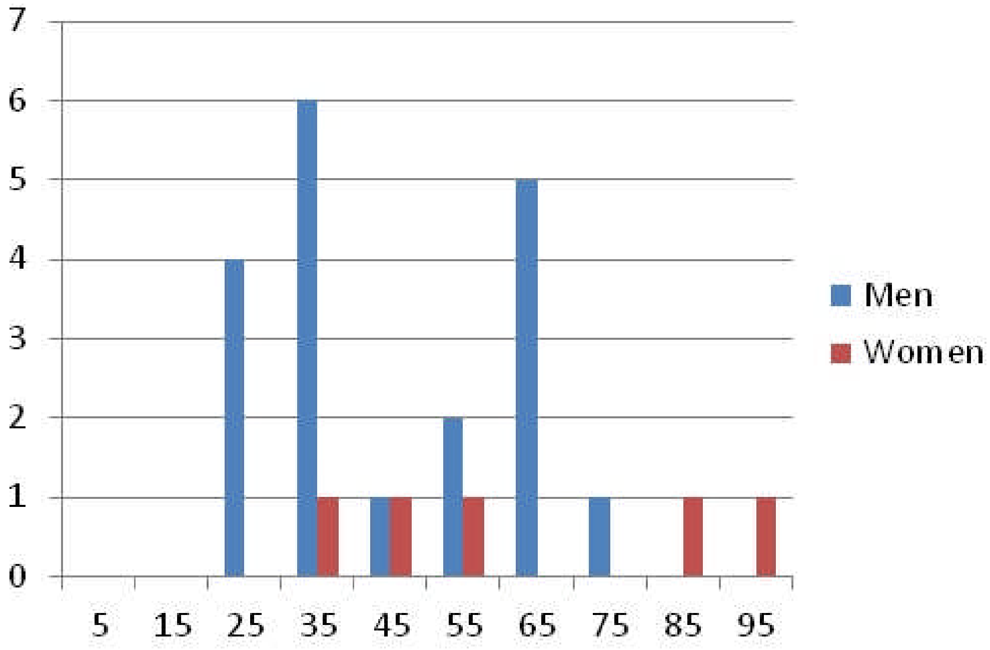


Figure 7.3. Age distribution of people killed in the two earthquakes (n=24).

In the 29th May earthquake, 350 people were injured, mostly by falling debris (entrapment, however, led in most cases to death). Between the two events, the death/injury ratio fell from 0.14 to 0.05. This variable tends to have low values in earthquakes of limited power and to be higher for larger events or very violent tremors.

7.2 Disaster management and shelter provision

The Region of Emilia-Romagna (area 22,446 km^2, population 4.4 million) is frequently affected by floods, landslides and minor-to-moderate earthquakes. In civil protection terms, it is one of the best equipped and organised in Italy, with a well-developed response system headquartered in Bologna and developed at the level of the nine provinces and many of its 348 municipalities. Like other regions, and the national forces, it has constituted a regional relief column, composed of the vehicles, manpower, equipment and supplies that are needed in a significant emergency. It was one of the first Italian regions to introduce TETRA radio communications.

The earthquake of 20th May can be classed as a sub-regional disaster that solicited a reaction from national and regional forces. It involved a total population of about 80,000 people distributed across 8-10 municipalities, all of them the locations of small towns, in four provinces (Modena, Ferrara and Bologna in Emilia.Romagna, and Mantua in Lombardy Region). In contrast, the three shocks on 29th May severely affected 40 municipalities: 16 in the Province of Modena, 7 in Mantua, 7 in Bologna, 6 in Ferrara and 4 in Reggio Emilia. It thus changed the situation from a sub-regional disaster to an inter-regional one that clearly required co-ordination at the national level. Damage also occurred to historic buildings in the larger towns Ferrara, Mantua, Modena and Bologna, but evacuations in these places were limited to brief exits at the time of the tremors.

As is usual in Italian earthquakes, the National Fire and Rescue Service (*Corpo Nazionale dei Vigili del Fuoco*) led the initial response to the emergency, assisted by medical emergency services. Within days of the first earthquake, some 1,400 volunteers were at work in the area, three quarters of whom were from the civil protection services of Emilia-Romagna Region and its provinces. Two hundred were from the Italian Red Cross and 137 from national sources. There were 700 firemen and 2,000 other emergency responders.

A week after the initial disaster some 5,262 people were in need of shelter, either through reluctance to return home or because their houses were inside areas that had been cordoned off and interdicted in order to maintain public safety. The breakdown by province was as follows: 62 per cent from Modena, 30 per cent from Ferrara, 5 per cent from Bologna and 3 per cent from Mantua. Damage to housing was slight (except for the case of the liquefaction areas at Sant'Agostino Ferrarese and its outlying settlement San Carlo), but people remained acutely fearful of aftershocks. Hence the number of residents who would not or could not return home rose over the week after the earthquake to about 7,000. Many of these were accommodated in second homes, with family members, or in camper vans or local hotels. Communal shelters were set up in the main affected settlements, followed by tent camps. In addition, tents were pitched in an ad hoc manner on small green spaces outside the cordoned areas.

The earthquake of 29th May left 15,000 people in need of shelter. In addition, about 110,000 old-age pensioners were at risk in the 25 most seriously affected municipalities. In many cases the demand for alternative accommodation was driven more by precautionary reasons than by damage that rendered homes unusable. Nevertheless, the practice of cordoning off town centres, now standard in Italian earthquakes, rendered inaccessible both homes that were unserviceable and those that were free of damage. More than 50 per cent of the displaced people were to be found in the Province of Modena, where 8,500 of them were accommodated in 23 tent camps and 17 rest centres in buildings. Almost 1,000 of these people were accommodated in hotels, including about 150 pensioners who had been evacuated from a rest home and needed constant assistance. Eight towns in the Province of Reggio Emilia accounted for a further 938 people in need of shelter, and 2,400 needed accommodation in Lombardy Region, almost two thirds of them in the Province of Mantua.

The response to the first earthquake emergency was coordinated and directed by a combination of national and regional forces. The Autonomous Province of Trento directed the regional relief columns and the main input came, logically, from Emilia-Romagna. Tent camps were set up by the regional civil protection services of Emilia-Romagna, Tuscany, Friuli Venezia-Giulia, Marche, Umbria, Molise and Lazio, and in addition by ANPAS (Public Assistance) and the National Alpine Regiment, both of which are nationally constituted volunteer organisations. Locations are shown in Figure 7.4. Each tent camp module is designed to accommodate 200-250 people and includes wash rooms, toilets, a canteen and social and health-care facilities. Nine days after the first earthquake, 53 schools and gymnasia were being used as rest centres, along with 17 hotels and 19 tent camps.

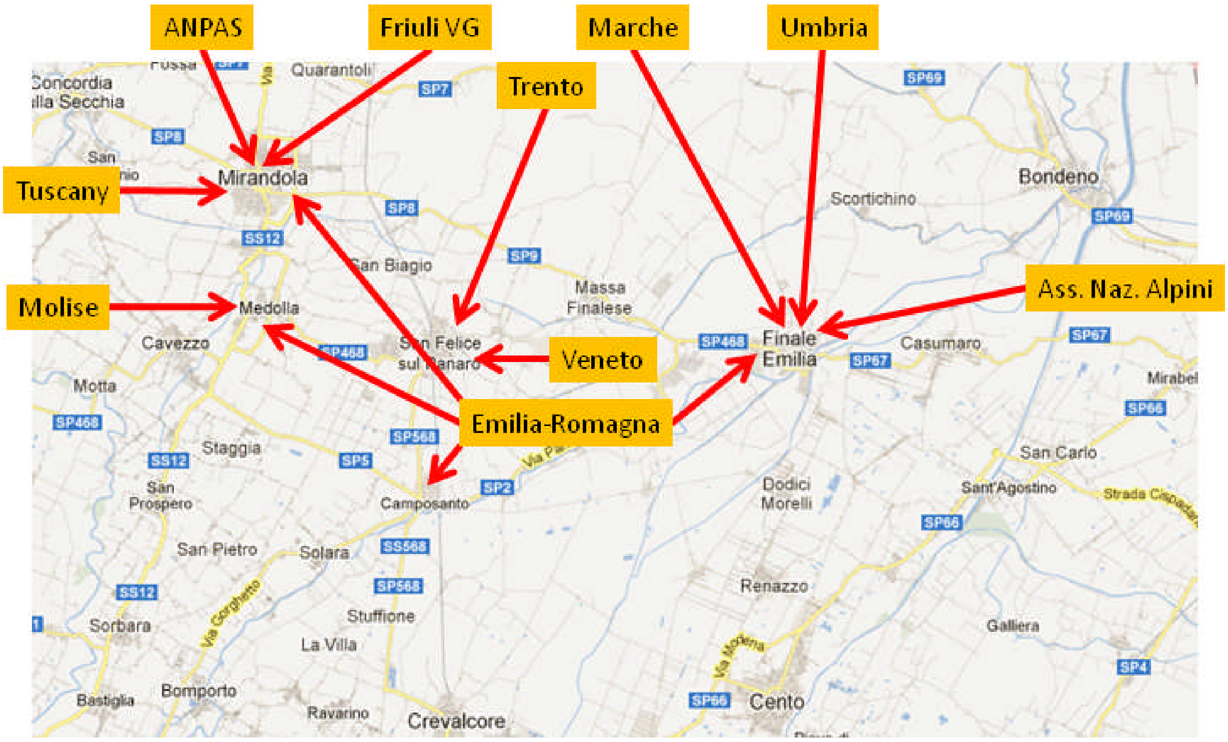


Figure 7.4. Division of competencies for tent camps after the 20th May earthquake.

The main affected towns, such as San Felice, Sant'Agostino and Finale Emilia rapidly became the locations of mixed operations centres (*Centri Operativi Misti*), using the Italian system of coordination in which resources are managed by sector according to support functions and are cascaded from national, through regional, levels to the larger and then smaller local settlements.

In 1998 legislation decentralised some civil protection functions from the Italian national government (and its representatives at the intermediate levels of government, the provincial prefects) to the regional governments, as coordinators of the provincial responses. This empowered the regional civil protection services and induced them to set up mobile relief columns that could be rapidly mobilised and sent to any part of the country (or abroad: the first use of these columns was in the mission to Albania during the Kosovo crisis of 1999). The principal use of these columns of vehicles and equipment is to provide shelter, medical care and technical assistance to populations displaced by disaster.

After the 29th May earthquake, relief columns were mobilised from the following regions: Lombardy, Emilia-Romagna, Umbria, Marche, Molise, Trento, Piedmont, Lazio, Friuli Venezia-Giulia and Abruzzo. Some of these regions mobilised double modules in order to set up two tent camps for displaced people. In addition, columns were mobilised by the Italian Red Cross and National Alpine Regiment Volunteer Group. The sequence of earthquake shocks continued in such a way to indicate that the emergency would not end soon.

In the first days after the second earthquake, 15,000 displaced people were being assisted by civil protection organisations, which had set up 37 tent camps (locations of the first 24 are shown in Figure 7.5) and accommodated people in 37 other structures and 15 hotels.

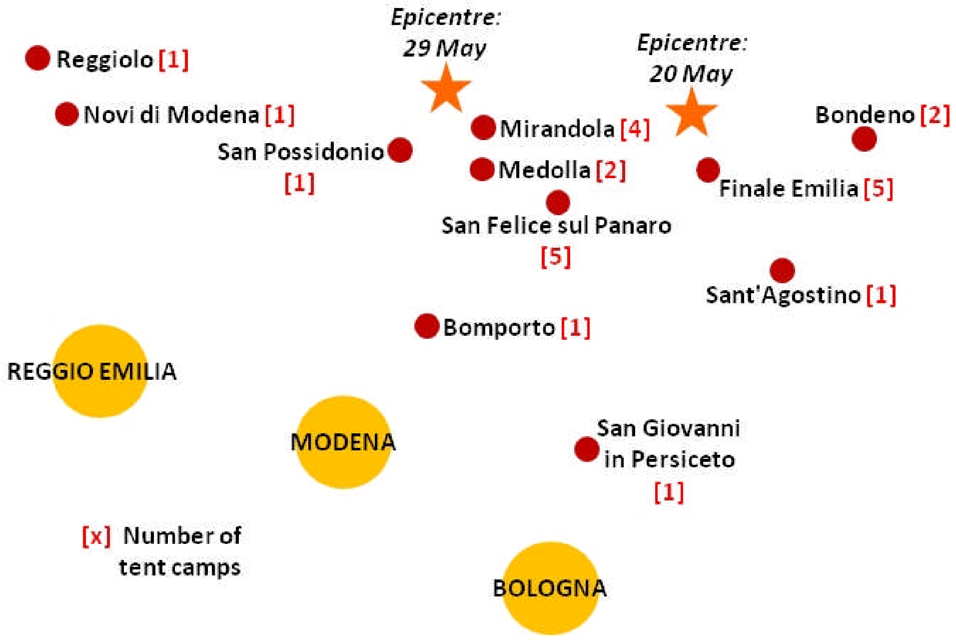


Figure 7.5. Location of tent camps open on 31 May 2012.

One of the competencies managed by the national Department of Civil Protection is to coordinate technical assessments of the stability and habitability of residential buildings. Technicians from various regions conducted this time consuming operation. The greatest need was found to be in Mirandola, Finale e Sant'Agostino, hence in the areas of greatest damage and most significant liquefaction. Meanwhile, in nine days, firemen had conducted 7,500 building inspections, many accompanied by buttressing or dismantling of architectural details.

One final management question concerns looting. Numerous enquiries into the sociology of disaster indicate that looting and other forms of criminal or antisocial behaviour are rare after disaster and are often exaggerated by the mass media. In the days following the earthquakes in Emilia, much was made in the Italian press of apparent episodes of looting. It was suggested that criminal elements were disguising themselves as civil protection workers and ordering people out of their homes so that they could break in and steal things. It seems probable that the crisis in Emilia did attract criminal elements, and some were arrested. Although it is difficult to arrive at a robust conclusion about this, cutting through the exaggeration and hyperbole in the press, it seems that 10-12 people may have been involved. Episodes, and subsequent arrests, were, as usual, given very high profile.

7.3 Economic impact

On 27 May at Bonderno (Ferrara) a 45-metre-high factory chimney was safely demolished by military engineers. Firemen worked throughout the affected area to remove precarious architectural elements and buttress buildings. Lastly, in Ferrara 500 prisoners were evacuated for precautionary reasons.

In net contrast to the earthquake of 6 April 2009 at L'Aquila, in Emilia, much greater emphasis was placed upon remediating the economic situation. Some 500 factories were damaged and access was banned to 3,000 others. In what was probably the worst case, Mirandola (Province of Modena), where four deaths occurred in factories, the Mayor signed an ordinance to interdict the entire industrial area pending evaluation of the seismic safety of buildings. Throughout the affected area, at least 15,000 workers were laid off or lost their jobs. Of these, 5,000 were from the engineering sector, 4,000 from food production, 4,000 from biomedical production, and 2,000 in ceramics. This part of Italy has about 60,000 firms and produces about 1 per cent of national GDP and 10 per cent of the GDP of Emilia-Romagna Region. It is considered crucial to economic recovery from the prevailing recession, especially as many firms are technologically advanced and make high-value products for export.

Food production is one of the mainstays of the regional economy in Emilia-Romagna. It is estimated that 633,700 wheels of Parmigiano Reggiano and Grana Padano cheese were damaged by falling off factory shelves where they were maturing. The cost of the damage is estimated at €150 million. Moreover, problems were experienced with providing feedstock to about 20 per cent of the region's cows. In addition, damage occurred to a significant number of farms throughout the affected area.

The Italian government responded rapidly to the economic crisis caused by the earthquakes by planning fiscal measures and a reconstruction fund. It appears that the prime source of this is a rise in automotive fuel prices at the pumps. This approach was also used to fund the recovery from the 1980 Irpinia-Basilicata earthquake, albeit rather more reluctantly in view of the negative political repercussions. Other measures used included payment and tax holidays and suspension of evictions for non-payment of rent or mortgage instalments. Measures were also announced by banks, but there was some concern about whether these were effective or merely a form of increasing revenue.

7.4 Concluding Remarks

In synthesis, despite the relatively high levels of destruction and disruption, the Emilia earthquakes were small and geographically circumscribed enough not to present exceptional challenges to the Italian civil protection system or the national economy. The same management strategies were used as in the L'Aquila earthquake of 6th April 2009; namely, to cordon off the centres of damaged towns and maintain a guard on them. Residents and others were allowed inside the cordon only when accompanied by fire department personnel, and when wearing protective helmets. Overall, resources were perfectly sufficient to manage needs generated by the emergency, which were mainly the accommodation of people rendered temporarily homeless, the maintenance of cordons around damaged areas of urban fabric, the inspection of damage and the emplacement of preliminary buttressing.

As in the case of both L'Aquila and the 1997 Umbria-Marche (Colfiorito) seismic disasters, the emergency managers had to deal with an earthquake swarm in which the sequence could not be defined in advance, either in terms of its duration or the timing of its greatest impacts. In all three cases the damage to historical-artistic heritage was severe and the effects were distributed across a sizeable tract of the Italian landscape.

In the early stages of the Emilian emergency, transitional shelter was not an issue (it was one that dominated the response to the L'Aquila and Umbria-Marche earthquakes).

One of the most dramatic differences between the Emilian earthquakes and the seismic disasters that preceded them in Italy is the renewed emphasis on the preservation or regeneration of industry and employment. This situation reflects, first, the strategic importance of the affected area in terms of national productive capacity; secondly, the need to revive the Italian economy in the face of recession; and thirdly, the more businesslike, less paternalistic, attitude of Mario Monti's 'technocratic' interim government. It remains to be seen how much of the new approach "trickles down" to the rather neglected province of L'Aquila: in past situations, notably after the Belice Valley (Western Sicily) earthquake of 1968, the area eventually benefitted from provisions made for subsequent disasters.

8.0 SUMMARY

This report presents an overview of the 29th May 2012 Emilia Romagna earthquake, the damage it caused, geotechnical features and disaster management issues made by a team from UCL EPICentre.

Both the 20th and 29th May 2012 earthquakes are characterised by heavy damage and collapse to historical structures and industrial facilities. The latter damage can be attributed to distinct structure types (pre-cast reinforced concrete warehouses) that were not designed for seismic loads and had deficient connections between columns and their sustained beams/roof systems. It is observed that the failure of these buildings, combined with the time of occurrence of the earthquake, meant that they were the largest contributors to the death toll sustained. The closure of industrial facilities also has meant a relatively large economic impact of these moderate size earthquakes.

In the early stages of the aftermath of the Emilian earthquakes, there was much discussion of the need for inspection of the seismic resistance of factories and workplaces. There was also a proposal for a 15-year plan for disaster risk reduction. At the time of writing it remains to be seen how much of this survives the end of the emergency phase. DRR planning is likely to be critically dependent on how strategic priorities are set and the means by which vulnerability is assessed: in neither case does Italy have a good track record so far. Regarding factories, the loss of 13 lives in factories in a second earthquake, shortly after the first one had killed four workers, should be cause for profound reflection about the rules for safety in the workplace.

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