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

Bruno Carpani, Maurizio Indirli, Giuseppe Marghella, Anna Marzo
ENEA, Technical Unit for Seismic Engineering

Alessandra Gugliandolo, Maria-Anna Segreto
ENEA, Technical Unit for Energy Efficiency

(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-

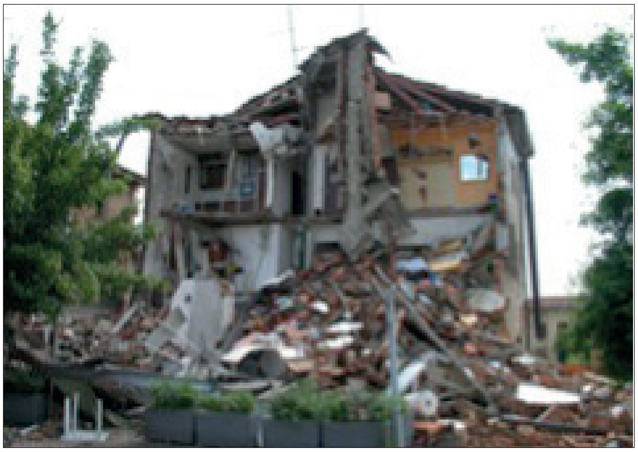


FIGURE 4 The front part of the building has completely collapsed; the damage grade is 5

FIGURES 5-6 Details of RC elements

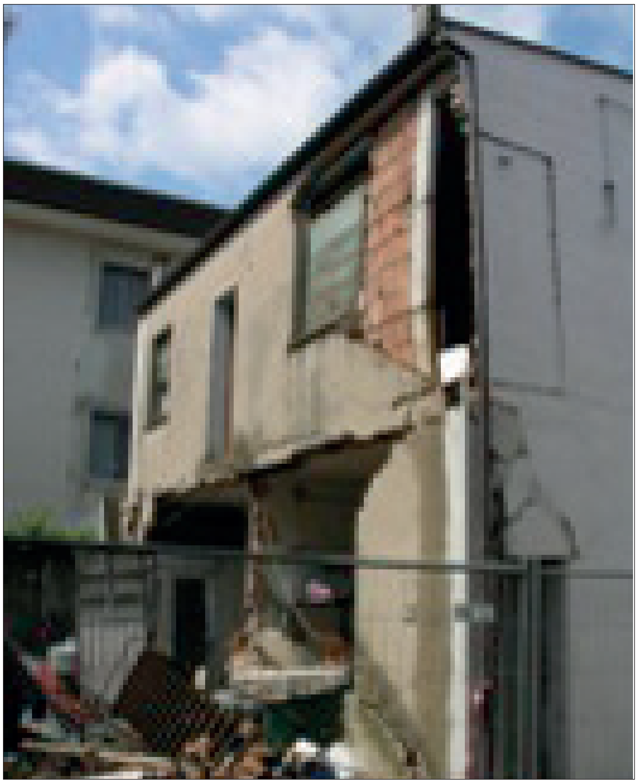


FIGURE 7 Serious failure of the walls, the damage is grade 4

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

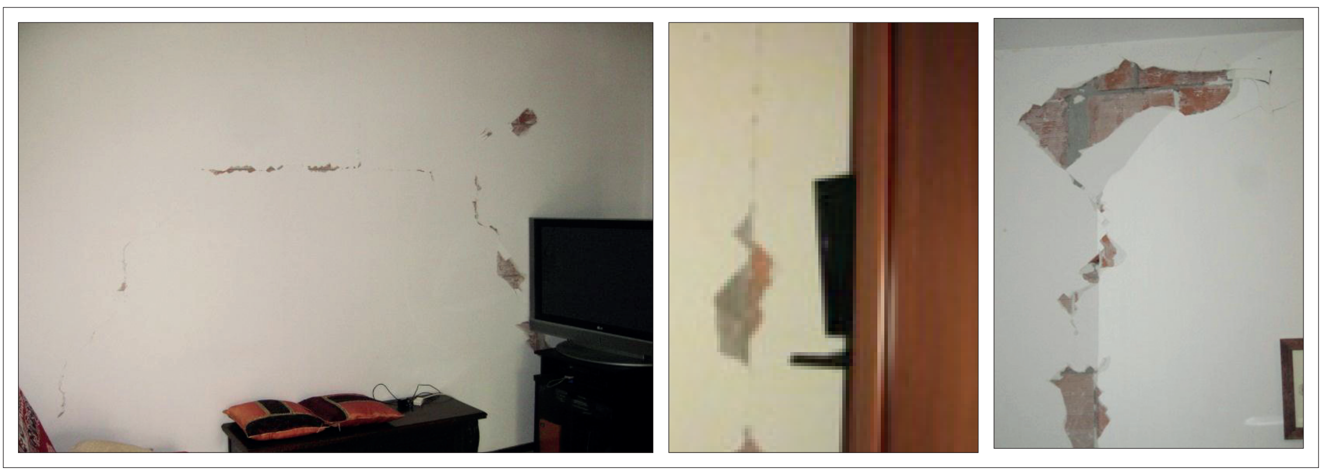
FIGURE 17 Damage to ground floor wall

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.

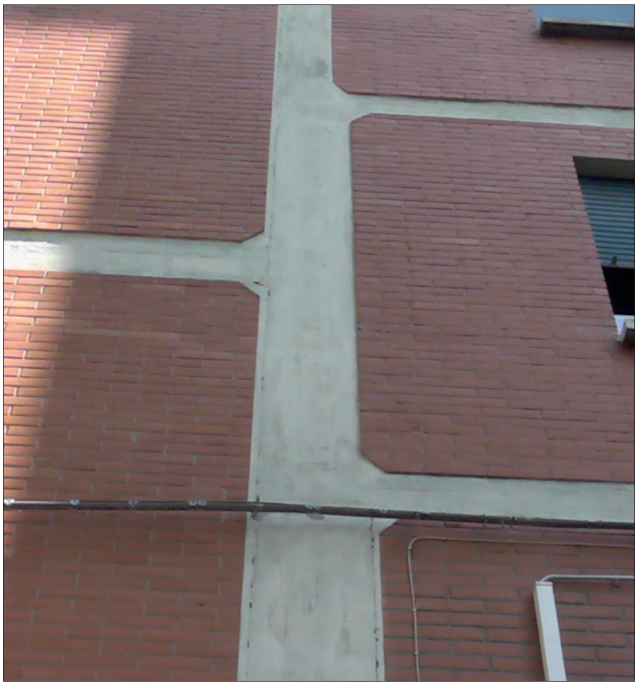


FIGURE 26 Separation between adjacent buildings

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.

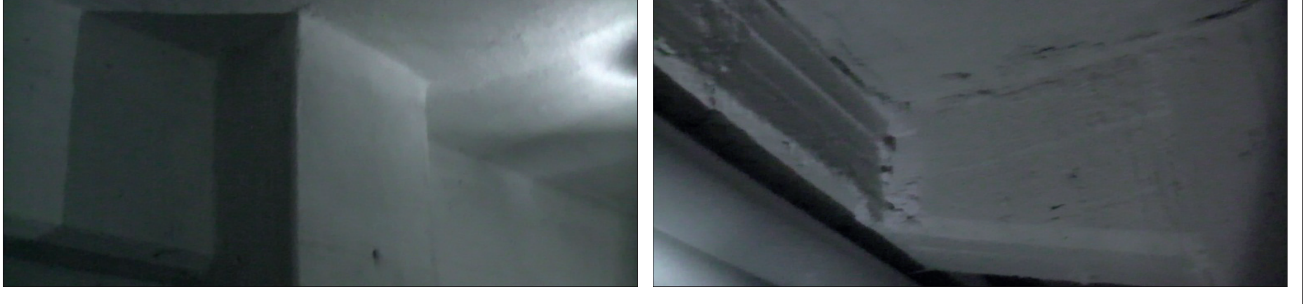
FIGURE 28 Separation between cladding and structure elements

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).

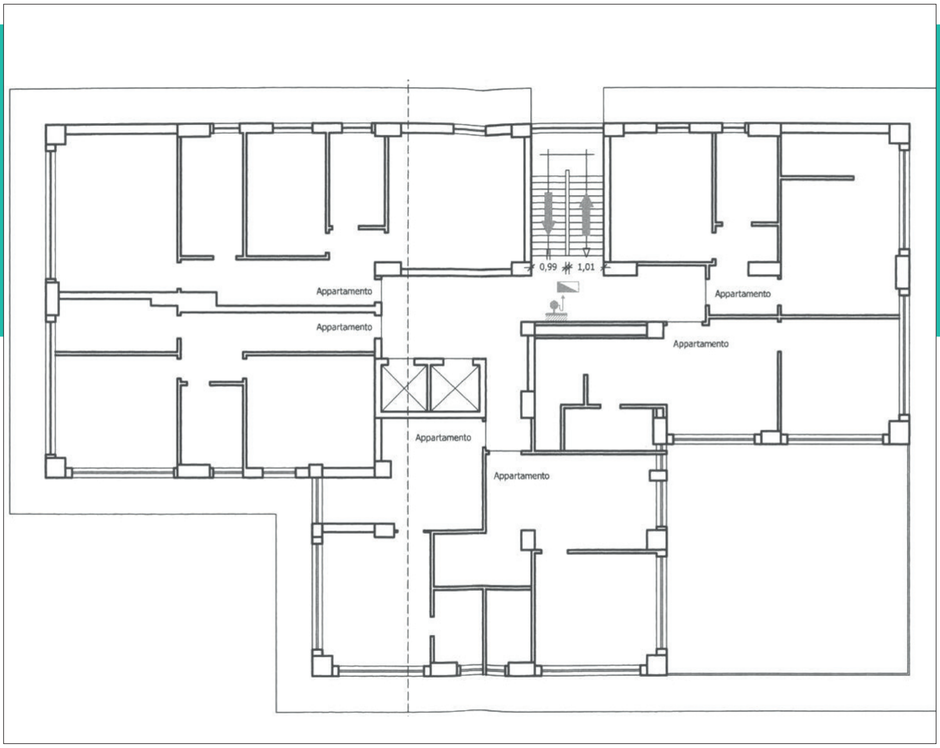


FIGURE 31
In plan distribution: first floor

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

(a) (b)

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

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

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.

references

[1] Arcoraci L., Berardi M., Bernardini F., Brizuela B., Caracciolo C.H., Castellano C., Castelli V., Cavaliere A., Del Mese S., Ercolani E., Graziani L., Maramai A., Massucci A., Rossi A., Sbarra M., Tertulliani A., Vecchi M., Vecchi S. (2012). Rapporto macrosismico sui terremoti del 20 (ML 5,9) e del 29 maggio 2012 (ML 5,8 e 5,3) nella pianura padano-emiliana, Report INGV.

[2] AeDES (2000). Agibilità e danno nell'emergenza sismica, First Level form for safety assessment, damage investigation, prompt intervention for ordinary buildings in the post-earthquake emergency [in Italian]. Civil Defense Department, Rome, Italy. http://www.protezionecivile.it/cms/attach/ editor/schedadanni.pdf.

[3] Arcoraci L. et alii 2012b, Rapporto Macrosismico sui terremoti del 20 (ML 5.9) e del 29 maggio 2012 (ML 5.8 e 5.3) nella Pianura Padano-Emiliana, in http://quest.ingv.it/images/quest/QUEST_Emilia2012_RapportoFinale.pdf

[4] Italian Ministry of Public Works (1987). Decree of November 20th, 1987. Norme Tecniche per la progettazione, esecuzione e collaudo degli edifici in muratura e per il loro consolidamento (Technical Code for design, realization, testing and strengthening of masonry construction) [in Italian], Gazzetta Ufficiale n. 285, Supplemento Ordinario, December 5th, 1987.