THE PIANURA PADANA EMILIANA EARTHQUAKE

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

Behaviour of industrial buildings in the Pianura Padana Emiliana Earthquake

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

The seismic event which struck the Pianura Padana Emiliana at 04:03 (Local time) of May 20th, 2012 had magnitudes M_L = 5.9 (INGV estimation). The hypocenter of the event was only 6 km under the ground surface, and the epicenter was localized at 44.89° North and 11.12° East, between the towns of Mirandola, Finale Emilia, Poggio Rusco and Bondeno. Before and after the main event, several shocks of minor intensity occurred [1].

Almost all the municipalities hit by the 2012 earthquake were not classified as seismic areas before 2003. As a result, most of the existing structures had been designed without accounting for the seismic actions.

The Emilia plain is one of the most industrialized areas in Europe, with several factory and warehouse sheds, built in the last decades. They were often built up with a precast system, in which structural elements were made of precast reinforced concrete (r.c.), in simple or multi-storey buildings. The vertical structures consisted of squared pillars fixed at the base by grouted pocket foundations, with various connection systems for the beam location, but mainly forks at the top or corbels. For the single-storey configuration, the horizontal structures were composed of one or two-segment symmetrically sloped beams, plain covering. For the multi-storey configuration, the horizontal intermediate floor is generally realised with alveolar panels or tiles completed with r.c. cast. The upper covering system is realised with tiles of different shape, also made with pre-stressed r.c.. Beam-tile and beam-pillar connections are simply friction contacts. Another common typology of factory structure, surveyed during the post-seismic investigation, is made of mixed materials, made of pre-stressed concrete pillars, located in the central part of the building, and masonry walls along the perimeter.

- **Fernando Saitta, Giovanni Bongiovanni, Giacomo Buffarini, Paolo Clemente**
  ENEA, Technical Unit for Environmental Characterization, Prevention, and Recovery
- **Anna Marzo, Giuseppe Marghella, Maurizio Indirli, Alessandro Poggianti**
  ENEA, Technical Unit for Seismic Engineering
- **Alessandro Martelli**
  ENEA, Directorate-General

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

Some relevant aspect of the seismic signals for industrial buildings

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

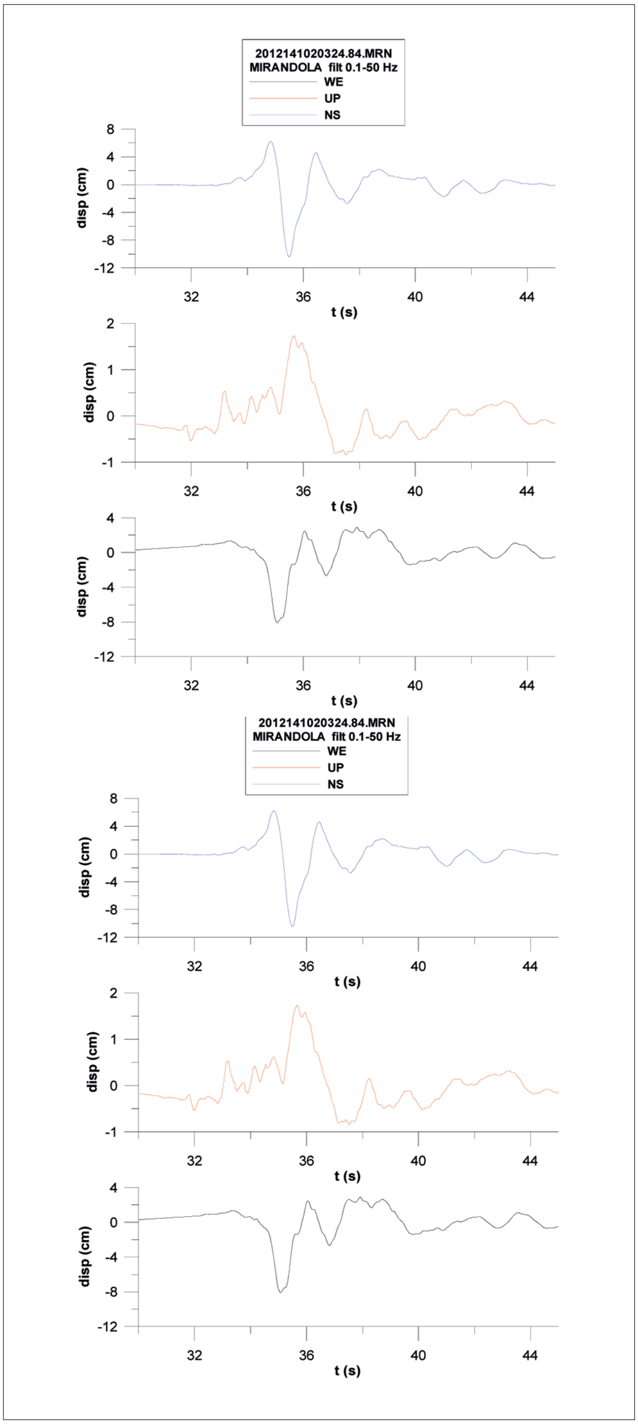

FIGURE 1 Displacement time-histories recorded at Mirandola (A) and Modena (B)
Source: ENEA elaboration of INGV data

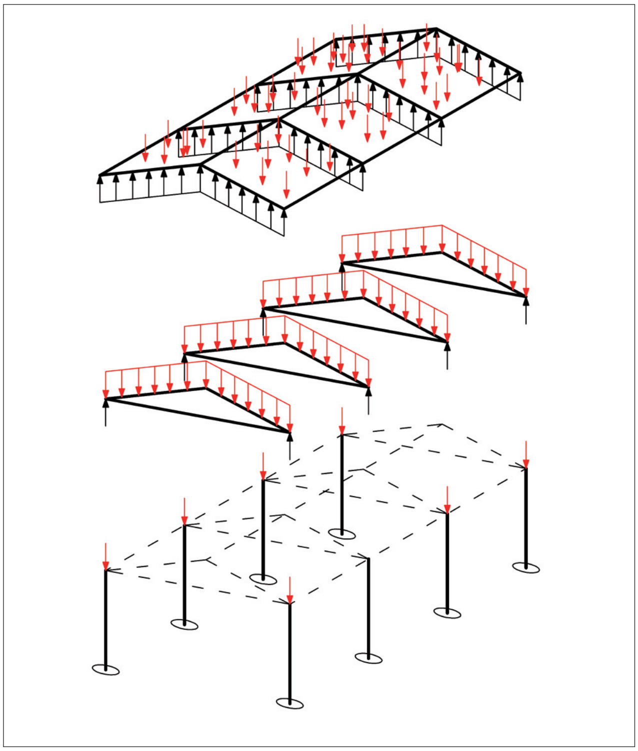

FIGURE 2 Structural conception of the industrial buildings
Source: ENEA

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

Structural conception and damage

A scheme of a typical one-story industrial building is outlined in Fig. 2, where the vertical load path from roof to foundation is clearly depicted. The critical points of the considered structures were the joints between the different elements, beams and columns, so much as the connections between the roof panels and the beams. Before showing some failure cases, structural peculiarities of precast buildings are summarised.
The main difference with in-situ cast concrete structures is given by the absence of continuity at nodes. Thus, different elements must be joined together to obtain the whole assemblage.
With reference to Fig. 3, in which a column-beam interface is represented schematically, various effects, such us shrinkage, thermal or external loads, can induce strains. The interface friction, at the mating surface, prevents movements, generating the friction force μR, where R is obviously the normal force to the surface, i.e., the vertical reaction.
The bending rotation of the beam creates a stress concentration at the top of the pillar, with possible spalling of the concrete (Fig. 4a). This suggests the interposition of a bearing pad (Fig. 4b). If a horizontal force overcomes the friction force, the beam can lose its bearing. A steel dowel or a reinforcing bar can prevent this kind of collapse (Fig. 5).

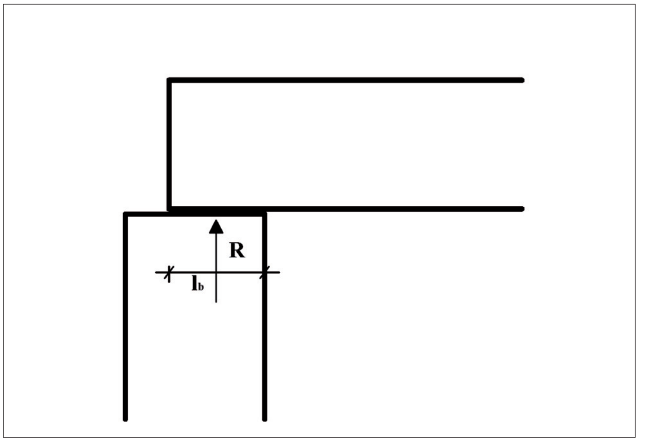

FIGURE 3 Schematic representation of the column-beam interface
Source: ENEA

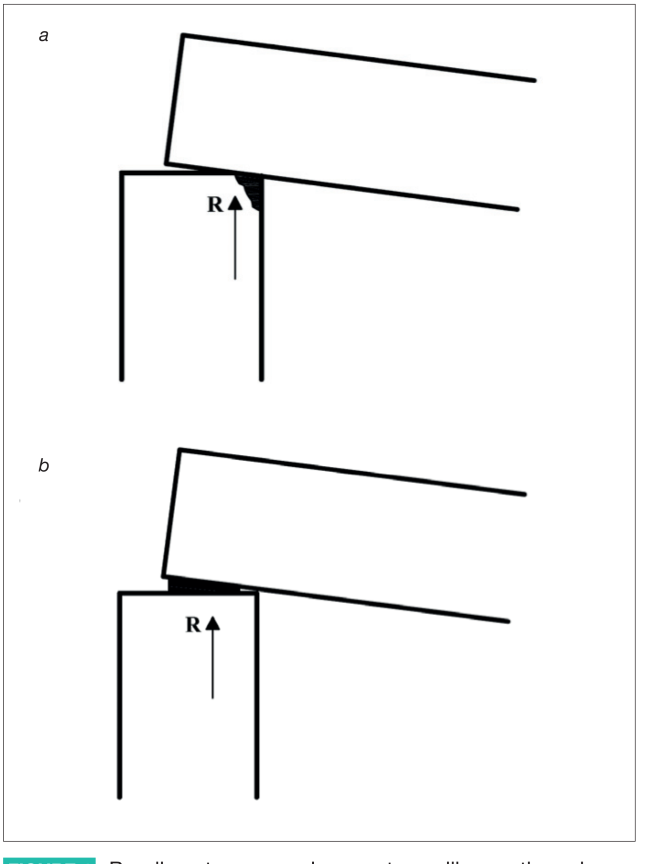

FIGURE 4 Bending stresses and concrete spalling on the column, avoided by means of the interposition of bearing pads
Source: ENEA

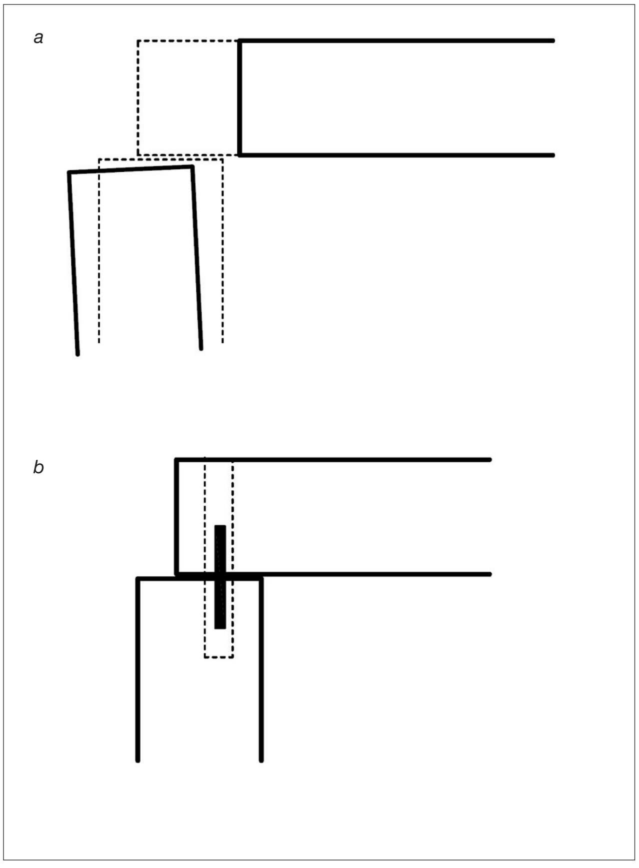

FIGURE 5 Possible relative displacement induced by external forces and insertion of a steel dowel to increase the shear resistance
Source: ENEA

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

The observed damage in industrial buildings was mainly due to the following reasons: loss of bearing, pillar damage, collapse of external cladding panels, instability of steel shelves. Figs. 6 and 7 show some examples of loss of bearing. In many cases, the length of the bearing was too short to allow the beam-support relative motion under the seismic action. Each portal, from a structural point of view, can be depicted schematically as in Fig. 8, where the static equilibrium exists only if the horizontal forces acting on the beam do not overcome the friction forces.
Some general considerations can be made for the in-plane behaviour of the roof. To guarantee a good transfer of the horizontal actions to the vertical elements, an effective structural design requires the presence of horizontal linking elements, in order to obtain a diaphragm behaviour with effective connections to the beams. It is worth noting that horizontal actions, albeit with minor intensity, are always present on a structure. These could be related to wind [4], lack of verticality of the structures – which can be assumed equal to 1.5% of vertical permanent loads – and temperature or shrinkage effects. The loss of bearing is indeed possible if a relative motion of the top of the pillars occurs.
A surprising case of undamaged factory is sketched in Fig. 9. It shows a similar construction system, but a significant difference in the constraint details, due to the shape

FIGURE 7 Longitudinal slipping of the roof beams
Source: ENEA

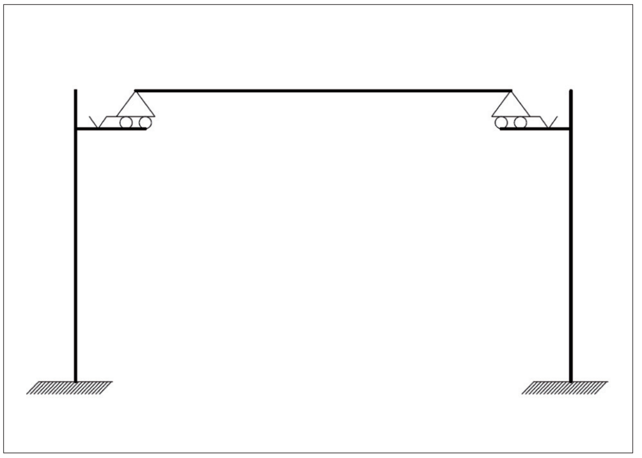

FIGURE 8 Scheme of the simply supported beams with friction
Source: ENEA

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

FIGURE 10 Lateral toppling of the beam
Source: ENEA

of the covering tiles, realising a tile/beam connection, effective in the seismic direction as a tying system.

In some cases the beam toppled down laterally, as shown in Fig. 10, after the failure of the lateral restraint present at the top of the columns, unable to resist to horizontal actions. Clearly, the failure mechanism depended also on the prevalent direction of the seismic motion. Different types of damage to columns are shown in Fig. 11.

Several collapses were related with non structural elements. In particular, shelves were often present in warehouse sheds, constructed by an assemblage of steel elements; they carried huge gravity loads.

Under horizontal actions, such as those due to seismic excitations, these inadequately braced structures exhibited instability (Fig. 12a). When the shelves were part of the structure (Fig. 12b), the evaluation of second order effects in the design phase is certainly significant.

Another situation observed in many cases is related to the detachment of precast external walls, due to the absence of effective connections with the main structure (Fig. 13).

In particular, the claddings were often constituted by precast panels, attached to the façade and not contained by the main structural elements, i.e., beams and columns. The mechanical connections were based on the cohesion between concrete and steel, and/or on the shear resistance of the steel element. Depending on the mass of the panels and their

FIGURE 11 Damage to columns
Source: ENEA

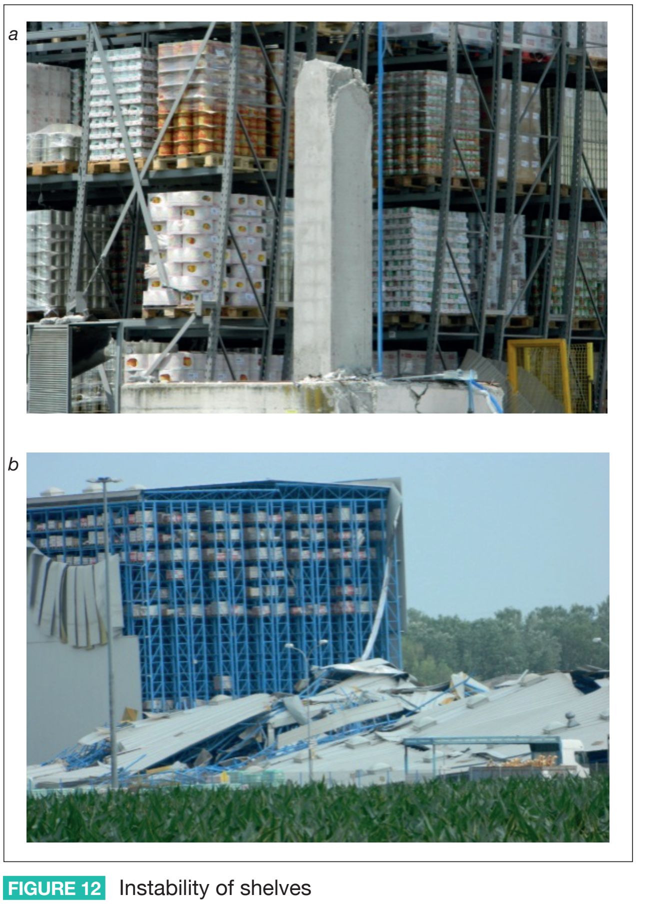

FIGURE 12 Instability of shelves
Source: ENEA

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

Italian codes at the construction age

Historical catalogues of the events in the area did not indicate relevant seismic phenomena in a radius of 30 km away from the epicentre. The most important earthquakes are resumed as follows:

- November 17th, 1570, with epicentre near Ferrara (30 km East from the recent shock), estimated magnitude M=5.5, macro-seismic intensity I_0=VIII;
- July 11th, 1987, between Bologna and Ferrara (20 km South), magnitude M=5.4,
- July 17th, 2011, in the Reggio Emilia District (20 km North-East), magnitude M=4.7.

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

FIGURE 13 Detachment of the external wall
Source: ENEA

a

b

FIGURE 14 Solid brick cladding damage
Source: ENEA

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

Some examples of damage to industrial buildings after previous major earthquakes

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

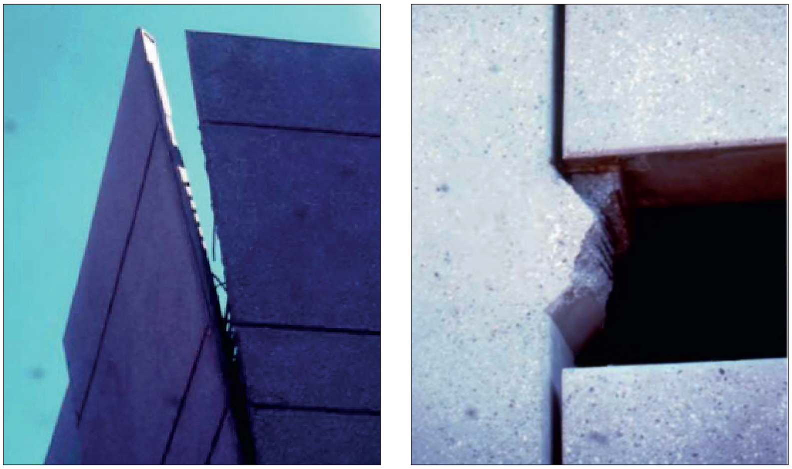
(a) (b)

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

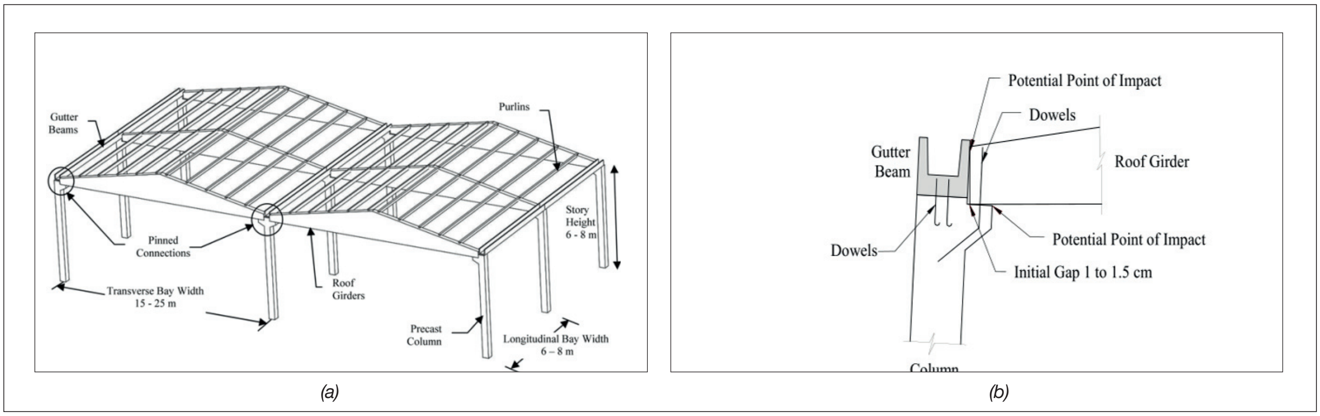

FIGURE 16 A Turkish typical configuration of one storey precast construction near Kocaeli and details [11-14]

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

hand, collapse and extensive damage was concentrated in pre-1981 r.c. and steel stock.
Some typical one-storey industrial pre-cast structures (Fig. 16), located in the epicentre area of the August 17th, 1999, Kokaeli earthquake (Turkey, M_w=7.4), didn't show good results, while others remained undamaged (Fig. 17) [10].
The collapse was mainly due to poor design, detailing, and construction, leading to the lack of diaphragm action caused by the inadequate connections (pinned or dowel, simple to realize by the prefabricators) between columns and beams. In addition, buildings under construction were susceptible to collapse when the roof girders rotated off their supports.

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

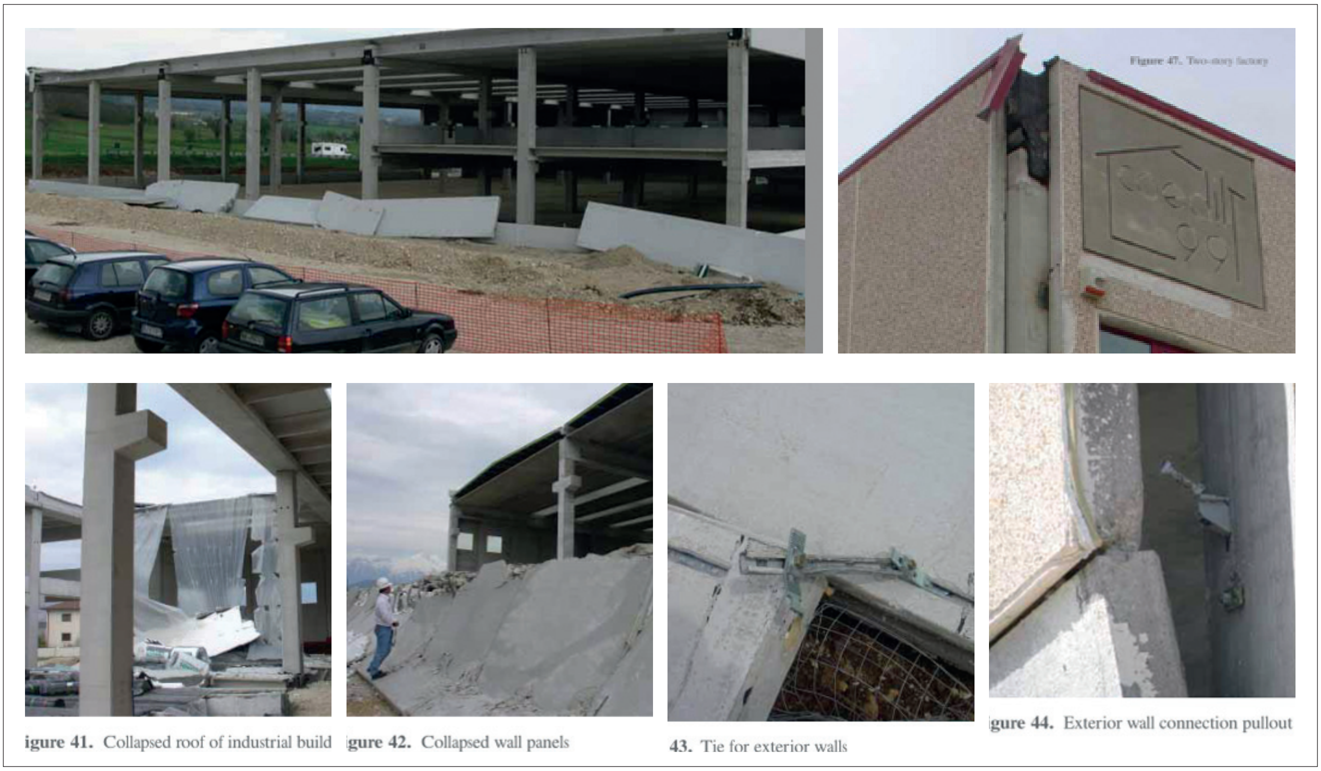

FIGURE 19 Collapse due to lack of adequate anchoring in p/p. r.c. structures in L'Aquila [17]

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

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

Conclusions

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

references

[1] Clemente P., Forni M., Martelli A. (2012), Introduction, *Energia Ambiente e Innovazione,* Vol. 4-5, Parte II, ENEA, Roma.

[2] Italian Ministry of Infrastructure (2008), Nuove norme tecniche per le costruzioni, D.M. of January 14th, 2008, *Gazzetta Ufficiale n. 29, Supplemento Ordinario 30,* February 4th, 2008, (in Italian).

[3] Paolini S., Martini G., Carpani B., Forni M., Bongiovanni G., Clemente P., Rinaldis D., Verrubbi V. (2012), "The may 2012 seismic sequence in Pianura Padana Emiliana: Hazard, Historical seismicity and preliminary analysis of accelerometric records", *Energia Ambiente e Innovazione,* ENEA, No. 5, 2012 .

[4] Elliott K.S. (2002). *Precast Concrete Structures*. Butterworth-Heinemann, Oxford, UK, 2002.

[5] Italian Ministry of Public Works (1987), Norme Tecniche per la progettazione, esecuzione e collaudo delle costruzioni prefabbricate, D.M. of December 3rd, 1987, *Gazzetta Ufficiale n. 106, Supplemento Ordinario*, May 7th, 1988, (in Italian).

[6] EERI (1994). Northridge Earthquake January 17, 1994, *EERI Preliminary Reconnaissance Report,* Earthquake Engineering Research Institute, 104 p.

[7] Bonacina G., Indirli M., Negro P. (1994), The January 17, 1994 Northridge Earthquake, Report to EEFIT, in The Northridge California Earthquake of 17 January 1994, a Field Report by EEFIT, A. Blakeborough, P.A. Merriman, M.S. Williams (eds.).

[8] Various Authors (1995). *Il terremoto di Kobe del 17 gennaio 1995, Report,* Presidenza del Consiglio dei Ministri, Dipartimento per la Protezione Civile, Dipartimento per i Servizi Tecnici Nazionali, Istituto Poligrafico e Zecca dello Stato, Roma (in Italian).

[9] Muguruma H., Nishiyama M., Watanabe F. (1995). Lessons learned from Kobe earthquake, A Japanese perspective, *PCI Journal,* V40, N4, July/August, pp. 28-42, 1995.

[10] EERI (2000). Kocaeli, Turkey, Earthquake of August 17, EERI Reconnaissance Report, *Earthquake Spectra*, Supplement to Vol. 16.

[11] Senel S.M., and Kayhan A.H. (2010). Fragility based damage assesment in existing precast industrial buildings: A case study for Turkey, *J. Structural Engineering and Mechanics*, Vol. 34, No. 1 (2010) 39-60.

[12] Saatcioglu M., Mitchell D., Tinawi R., Gardner N. J., Gillies A.G., Ghobarah A., Anderson D.L., and Lau D. (2001). The August 17, 1999, Kocaeli (Turkey) earthquake-damage to structures. *Canadian Journal of Civil Engineering*, 28(4): 715–737 (2001).

[13] Posada M., Wood S.L. (2002). Seismic performance of precast industrial buildings in Turkey, *Proc. of the 7th U.S. National Conference on Earthquake Engineering, July 21-25, 2002*, Boston (USA), EERI publications.

[14] Doneux C., Hausoul N., Plumier A., 2006. Deliverable 55 "Analysis of 3 precast RC structures with dissipative connections", LESSLOSS Sub-Project 7 – Techniques and methods for vulnerability reduction, LESSLOSS Final Workshop "Risk Mitigation for Earthquakes and Landslides", Integrated Project, Priority 1.1.6.3 Global Change and Ecosystems, European Integrated Project GOCE-CT-2003-505488, 19-20 July 2007, Hotel Villa Carlotta, Belgirate (VB), Lago Maggiore, Italy.

[15] Zhaoa B., Taucera F., Rossetto T., 2009, Field investigation on the performance of building structures during the 12 May 2008 Wenchuan earthquake in China, *Engineering Structures*, 31 (2009) 1707–1723.

[16] ENEA Report, 2009. Energia, Ambiente e Innovazione (Energy, Environment, Innovation). http://old.enea.it/produzione_scientifica/EAI/2009/Index_Maggio-Giugno09.html

[17] Various Authors (2009), M6.3 L'Aquila, *Italy, Earthquake Investigation Report, Global Risk*, Myiamoto, 2009.