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Damage and collapses in industrial precast buildings after the 2012 Emilia earthquake

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ABSTRACT

The present paper presents a complete and commented collection of cases of damage and collapse in reinforced concrete (RC) precast industrial buildings, observed by the authors during a series of field surveys after the 2012 Emilia earthquake in Northern Italy. They were selected among a total of about 2000 industrial RC precast buildings, whose structural characteristics and damage have been collected in a large database by the authors.

The main causes of the collapses were vulnerabilities related to the structural characteristics of Italian precast buildings not designed with seismic criteria. In particular, these structures were typically built as an assembly of monolithic elements (roof elements, main and secondary beams, columns) in statically determinate configurations. The most common failure causes identified were: the absence of mechanical connectors between precast monolithic elements, the interaction of structural elements with non-structural walls, the insufficient column bending capacity, the rotation of pocket foundations, the inadequacy of connections of external precast cladding walls to bearing elements (columns and beams), the overturning of racks in buildings used as warehouses or in automated storage facilities.

1. Introduction

A series of strong earthquakes struck the Emilia region, in Northern Italy, in May 2012. Two main earthquakes can be identified in the seismic sequence, with mainshocks featuring similar energies: the first event with moment magnitude, $M_w = 6.1$, struck on May 20th, while the second, with $M_w = 6.0$, on May 29th. The May 20th earthquake caused the collapse of several RC precast buildings in the industrial areas of S. Agostino, Bondeno, Finale Emilia, S. Felice sul Panaro, while the May 29th earthquake was particularly severe for industrial buildings in Mirandola, Cavezzo and Medolla. In the industrial areas close to the epicentres (less than 5 km), according to some estimates, more than 60% of RC precast buildings collapsed or were severely damaged [1]. Also other types of buildings, such as cast-in-place RC and masonry structures, were designed for non-seismic loads only and were significantly damaged. Historical city centres were also damaged, being built according to practical construction rules only (in the pre-code era).

No seismic design rules were mandatory in the area until the last decade, even if, in the past, the region had experienced earthquakes with similar magnitudes, such as the 1570–1574 Ferrara earthquake [2]. Only in 2003, an updated seismic hazard map for Italy classified the Emilia region as a low-to-moderate seismicity area [3]. That hazard map was formally adopted in 2003 [4], becoming mandatory for designers only in 2008 [5]. For these reasons, most of the industrial buildings in the area had been built without any seismic-design rule [6]. In particular, precast buildings were typically constructed as an assembly of monolithic elements (roofing elements, main and secondary beams, columns) in simply supported conditions, without mechanical connectors. Often, neoprene pads were used to allow end rotations in long span beams, thus further reducing friction resistance. According to Bellotti et al. [7] 85% of the precast buildings in the Emilia region were built without seismic design rules and more than 70% featured friction-based connections. Overviews on the main typologies of prefabricated structures used in Italy since the 70 s are provided by Bonfanti et al. [8] and Mandelli, Contegni et al. [9]. The most common precast industrial buildings in the area of interest were single-storey statically-determined frame structures with pocket foundations [10]. The seismic behaviour of these structures, as discussed by Bellotti et al. [7], is characterized by great flexibility and large displacements.

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Damage and collapses of precast buildings were observed by many authors after past earthquakes all over the world [11–17] and in Italy [18], but the extent and the severity of the collapses after the Emilia earthquakes are unprecedented in Italy. The first field reports on the Emilia earthquakes ([6,19–21]) showed that many collapses were caused by the lack of mechanical connectors between structural elements. In particular, Bournas et al. [21] reported that 25% of the damaged buildings that they analysed presented a partial or total collapse of the roofing elements, mainly due to the unseating of the main girders. Similarly, Liberatore et al. [20] observed the unseating of shed beams (used as roofing elements) in almost 30% of the 30 buildings that they analysed. Savoia et al. [19] highlighted the effects of the interaction with non-structural elements, like masonry or concrete panels, in particular when these latter were irregular.

The present paper comprises two parts. A discussion on the main features of the ground-motions recorded during the seismic sequence is presented first, highlighting those that might have been particularly critical for prefabricated structures. In particular, near-field effects such as pulse like behaviour and directionality are discussed with more details, since they were not analysed in the literature concerning the Emilia earthquakes. Then, the paper provides a complete and commended collection of damage cases and failure modes observed by the authors during the field surveys that took place in the zones struck by the earthquakes. The surveys in S. Felice sul Panaro and S. Agostino were carried out after the May 20th earthquake, while those in Mirandola, Cavezzo and Medolla after both mainshocks. The damaged or collapsed buildings illustrated in the paper were selected among a total of about 2000 industrial RC precast buildings, whose damage has been collected in a large database periodically updated [1,22]. In all the cases the main reasons of the collapses were identified in relation with the usual design criteria for non-seismic zones adopted in the region, which lead to structures with intrinsic vulnerabilities [7].

2. Features of the ground motions

The present section describes the main features of the strong ground-motions recorded during the seismic sequence. Various near-source effects such as high vertical accelerations and pulse-like features could be observed in some of the records and might have significantly contributed to the final damage scenario. In fact, near source ground-motions are in general more demanding on structures than far-field motions [23–26].

On May 20th, 2012, a $M_w = 6.1$ [27] (epicentre at latitude = 44.89°N and longitude = 11.23°E) earthquake struck the area in the Po River Valley, north of the city of Modena, Italy. In the following 13 days, five $M_w > 5$ events occurred (see Fig. 1). Among these, the most intense was a $M_w = 6.0$ [27] earthquake on May 29th, with epicentre located about 12 km West of the first mainshock (latitude = 44.85°N and longitude = 11.09°E). This event can be considered as a second mainshock.

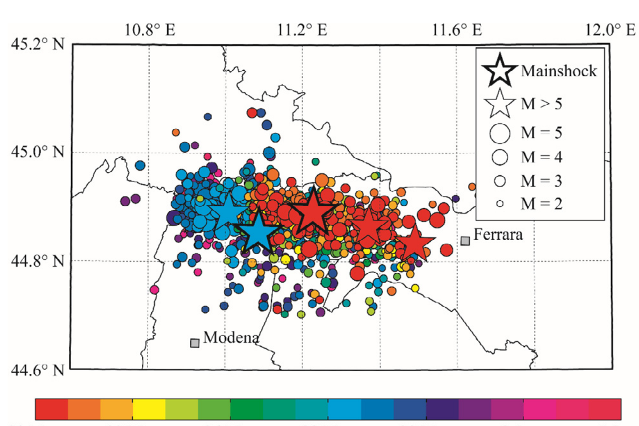

Fig. 1. Epicentres of the 2012 Emilia earthquake sequence. The colour scale indicates the earthquakes dates.

In the recent past, the same area was struck in 1996 by a $M_w = 5.4$ earthquake and by other smaller earthquakes in 1986 and 1967. The most destructive historical events were the November 15th, 1570, Ferrara earthquake, with an estimated $M_w = 5.48$, and the March 17th, 1574 event ($M_w = 4.7$), that produced damage in Finale Emilia [2,28].

The seismic-tectonic structure of the area is characterized by the northern Apennines frontal thrust systems, composed of a pile of North-East verging tectonic units as a consequence of the collision between the European plate and the Adria plate [29]. The geometry of the thrusts below the Po Valley has been studied by various authors [30,31]. Three major curved thrust fronts are identified, as depicted in Fig. 2: the Monferrato, the Emilia, and the Ferrara-Romagna Arcs. Active NE-SW shortening has been documented by various authors [32,33].

Several ground-motion recording stations of the Italian strong-motion network [34] recorded the ground-shaking during the 2012 earthquake sequence. Furthermore, after the first mainshock a number of temporary recording stations were installed (see Fig. 3). Site classification data are not available for all the recording stations but, to the authors knowledge, EC8 C class can be reasonably assumed in the whole area [35]. The ground-motion records analysed in the present paper were obtained from the ITACA database [36,37], which contains processed accelerograms mostly recorded in Italy [38].

During 2012 Emilia earthquakes, horizontal Peak Ground Accelerations (PGA_h) up to 259 cm/s^2 (May 20th, MRN station, epicentral distance $R_e = 12.3$ km) and 411 cm/s^2 (May 29th, MIR01 station, $R_e = 1.4$ km) were recorded. Horizontal pseudo-acceleration (PSA_h) response spectra, computed for the two horizontal components (East-West and North-South) of the ground-motions recorded by the stations closest to the epicentres, are depicted in Fig. 4. Fig. 4a shows that, during the May 20th earthquake, large pseudo-accelerations were recorded at the MRN station ($R_e = 12.3$ km) in the 0.5–1.0 s period range, possibly because of site-response and near-field effects, as discussed later. PSA_h response spectra reported in Fig. 4b for the May 29th event confirm large accelerations in the 0.5–1.0 s period range. Furthermore, the spectra for the North-South recordings at the MIR01 ($R_e = 1.4$ km) and MRN ($R_e = 4.1$ km) stations feature a peak at $T = 1.5$ s [7]. Also in this case, in addition to site effects, near-source effects have probably contributed to the definition of the spectral shape [39]. The possible effect of site response was suggested by Priolo, Romanelli et al. [40], who analysed eight different locations in the region struck by the earthquakes using the horizontal-to-vertical spectral ratio

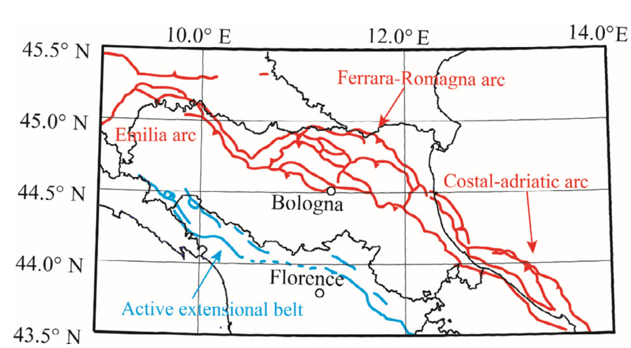

Fig. 2. Geological structures in the region struck by the Emilia earthquakes.