Seismic risk assessment of an industrial plant struck by the Emilia 2012 earthquakes

Fabio Petruzzelli
AXA MATRIX Risk Consultants,
Milan, Italy
Email: fabio.petruzzelli@axa-matrixrc.com

Abstract: This paper presents the quantitative seismic loss assessment of an industrial plant and compares it to the real losses observed during the Emilia 2012 earthquakes. The analysis was performed by means of the FRAME software, which allows a rapid computation of seismic risk on probabilistic basis. The comparison between the estimated losses and the adjusted ones, although understandably questionable for the consistency of a probabilistic estimate of the loss observed in a single event, is believed to represent an opportunity for a critical analysis of strengths and limits of application of predictive estimations of earthquake-induced losses in the industrial field. Although some critical aspects related to the selection and the application of fragility and consequence functions exist, results show that loss estimates can be well correlated to the adjusted ones, thus encouraging the adoption of probabilistic approaches as a support for informed decision making.

Keywords: industrial facilities; earthquake losses; seismic risk assessment; precast structures; fragility curve.


Biographical notes: Fabio Petruzzelli is an earthquake risk specialist at AXA MATRIX Risk Consultants and a member of the Company’s “Center of Expertise for Earthquake and Tsunami”. His activity focuses on probabilistic seismic vulnerability assessment, development of software for earthquake loss assessment, and management of research agreements with academic partners. Before joining AXA MATRIX, he was a research fellow of the University of Naples Federico II, Italy, where he also received his PhD in Seismic Risk, and a freelance engineer, working in the field of the design of civil structures and infrastructures, reliability assessment of existing buildings and seismic retrofitting.


1 Introduction

The ultimate goal of risk assessment for industrial plants is to provide elements for a rational, transparent and proactive decision-making, as a fundamental part of the risk
management process, including the definition of acceptable risk levels and the implementation of mitigation strategies.

To this aim, probabilistic seismic risk assessment and Performance-Based Earthquake Engineering (PBEE; Cornell and Krawinkler, 2000) represent the state-of-the-art approaches for computing seismic risk on sound quantitative basis. Nevertheless, the use of qualitative risk estimates, based on macroseismic intensity or expert judgement, still represents the abiding philosophy in Insurance and Industrial Risk Management, due to the amount of resources, both financial and of time, generally available for the assessment. In fact, quantitative seismic risk assessment requires the explicit computation of the three main seismic risk components, namely the site hazard, that is the frequency and intensity of earthquakes; the vulnerability of structures, that is the susceptibility of the physical environment to be damaged by seismic events of a given intensity; and the exposure, accounting for the relevant economic consequences. In the practical application of such a framework to industrial plants, two major issues are related to the assessment of the vulnerability of structures or relevant non-structural components and to that of economic consequences.

In fact, dealing with a number of buildings usually ranging, depending on the size of the industrial plant, from tens to hundreds, a detailed assessment of seismic vulnerability is generally unfeasible both in terms of resources and possibility of investigating in-depth characteristics of the structures (Petruzzelli, 2013). On the other hand, relationships developed to assess vulnerability at a large scale (regional or national, typically used in the catastrophe modelling field, e.g. FEMA, 2001) are, in general, unable to capture the specificities of the individual buildings of a specific industrial plant. Although several efforts have been recently dedicated to the computation of seismic structural fragility for classes of buildings or to their systematic collection (e.g. Pitilakis et al., 2014; D’Ayala et al., 2014), very few studies have been dedicated to structures mostly recurring in industrial installations (e.g. Iervolino et al., 2004; Petruzzelli et al., 2012; Della Corte et al., 2013). A similar lack in literature exists for what concerns studies providing direct and indirect economic impacts of earthquakes in industry (e.g. Dowrick and Rhoades, 1995) or downtime estimates (e.g. Comerio, 2006).

On these premises, the main objective of this paper is to investigate the actual suitability of existing studies regarding structural fragility and economic consequences in providing loss estimates for industrial plants. In fact, the application of existing studies generally employed at the regional scale to an individual industrial plant is believed to represent a useful support for practitioners in forensic engineering, insurance and risk management, for their predictive or post-disaster loss estimations under limited resources.

To this aim, as a case study, an industrial facility affected by the Emilia 2012 earthquake has been analysed. The loss estimates computed in a PBEE approach through the FRAME software tool (Petruzzelli and Iervolino, 2014) have been compared to the real ones, as resulting from the claim and loss adjusting process.

2 The Emilia 2012 earthquake sequence

On 20 May 2012, at 04:03:53 a.m. (local time), the Emilia Romagna Region in Northern Italy was struck by a moment magnitude (Mw) 5.9 earthquake (Italian Institute for Geophysics and Volcanology (INGV) estimates. The epicentre was located between
Finale Emilia and San Felice sul Panaro (lat. 44.876; long. 11.282), about 36 km north of the city of Bologna and at a depth of 6.3 km. The event was followed by a dense seismic sequence affecting an area extending in the E-W direction for nearly 40 km, between the localities of Mirandola and Ferrara (Figure 1). This sequence culminated nine days after the mainshock, on 29 May 2012, at 09:00:03 a.m. (local time), into an Mw 5.8 (INGV) aftershock, causing additional damages, particularly to buildings already weakened by the first event. The epicentre was located in Medolla (lat. 44.814; long. 11.079) and the focal depth was about 10 km (Decanini et al., 2012). The whole seismic sequence, from 16 May up to 26 June 2012, featured seven events with Mw equal or higher than 5.0.

**Figure 1** Map of earthquake epicentres of the Emilia 2012 sequence (INGV, 2012a)

The maximum accelerations registered by the Italian National Accelerometric Network (MRN station, placed on ‘C’ type subsoil according to EC8; CEN, 2004) were, in the NS, EW and UP directions, respectively, equal to 0.264 g, 0.261 g and 0.310 g during the first event, and 0.224 g, 0.295 g and 0.889 g during the second. Spectral ordinates reached values larger than 1 g. Shakemaps providing PGA for the two events are shown in Figure 2.

### 2.1 Social and economic consequences

These earthquakes were structurally damaging over a wide area. Extensive damages were observed to historical masonry and precast industrial structures, while damages to infill and other non-structural elements mainly occurred for reinforced concrete civil structures (Parisi et al., 2012). The overall consequences of the Emilia earthquakes were 27 casualties, about 400 injured, 15,000 homeless and 13.2 billion Euros of property damage and business interruption (Italian Department for Civil Protection estimates). The reasons for such a large level of losses, if compared to the magnitude of the events, are to be firstly sought in the composition of the built environment of the area, that is largely participated by high-value cultural and historical heritages (Parisi and Augenti, 2013) and by a number of industrial facilities (Liberatore et al., 2013). In fact, the affected area is
one of the most industrialised Italian centres, in which 47,000 industrial activities and 187,000 workers produce, every year, the 2% of the Italian Gross Domestic Product (RER, 2012). The high damages observed can be also related to the subsoil composition of the Po river floodplain, made of soft alluvial soils, which caused the most of the seismic energy released by the earthquakes concentrated in the low frequency range (Lai et al., 2012). This caused large acceleration and displacement demands to structures characterised by low natural frequency of vibration, such as high-rise or large-spans, simply-supported precast buildings. On the other hand, the affected area was included in the national list of seismic zones only in 2003 and the New Italian Building Code (CS.LL.PP., 2008), enforcing seismic design for all the structures of the Italian territory, became mandatory for ordinary structures only from 1 July 2009 (Figure 3). As a consequence, the majority of the existing structures in the affected area were designed for gravity or wind loads only or, in the case of industrial buildings, for crane horizontal action.

**Figure 2** Shakemaps of PGA for Emilia 2012 earthquakes of 20 and 29 May 2012 (INGV, 2012b)
2.2 Damages to precast industrial buildings

Precast reinforced concrete structures represent about 9% of the building stock and the structural typology that suffered the most damage in the area hit by 2012 seismic events. In fact, as resulting from field surveys (Parisi et al., 2012; Magliulo et al., 2014), more than half of the existing precast structures suffered significant damages, ranging from the partial or total collapse to the failure of non-structural components, such as cladding panels, internal partitions, ceilings, storage racks or various equipment and stock contents.

The most common precast structures in the affected area are frame structures, consisting of socket footing foundations in which precast columns are placed, supporting pre-stressed precast beams with different shapes. These structures are usually completed by roof elements with various geometry and precast panels, either inserted between columns or placed externally to these. Comprehensibly, the seismic performance of such structures is largely influenced by the quality of the connections between structural elements (Magliulo et al., 2014). Most of the damaged precast structures featured friction connections between horizontal elements (beams and roof elements) or between horizontal (beam) and vertical (columns) members. In fact, according to the Ministry Decree of 1987 (DM 3/12/1987, 1987) the use of mechanical connections was mandatory for structures located in seismic-prone areas only.

As a consequence, the most common structural failure modes observed were the loss of support of both roof elements from beams and beams from columns, due to excessive displacement demands at relatively large periods and inadequate strength ensured by
friction mechanism (Figure 4 (a)). As demonstrated by Magliulo et al. (2014) the inadequacy of friction connections in withstanding the earthquake-induced lateral force was exacerbated by the adoption of code-based friction coefficients for most common beam-to-column connections (Circ. M. LL.PP, 1965) largely overestimated with respect to experimental values. Some structural collapses were also observed even in the case of mechanical connections made by dowels pinning horizontal to vertical elements, due to inadequate design (Figure 4 (b)).

Further structural damages were due to the loss of verticality of columns, as a consequence of the rotation of the socket foundation (Figure 4 (d)), plastic hinge development (Figure 4 (e)) or shear failure at column base sections (Figure 4 (f)). Besides, shear failure in short columns due to interactions with masonry infill and failure of cladding panels due to inadequate panel-to-structure connections (Figure 4 (c)) were observed.

**Figure 4** Damage to precast industrial buildings: (a) loss of support in the beam-to-column friction connection; (b) failure of mechanical connection; (c) failure of vertical cladding panels; (d) loss of verticality due to foundation rotation; (e) plastic hinge development; and (f) shear failure due to lack of a horizontal reinforcement (courtesy of ReL UIS, www.reluis.it; Parisi et al., 2012)

The above represents a clear example of the current seismic vulnerability of the Italian building stock, and of the impact of the enforcement of code regulations on the actual seismic performance of structures. Since 2008, Italian seismic regulations (CS.LL.PP., 2008) dedicated more attention to the seismic design of precast structures, acknowledging several prescriptions included in EC8. For instance, connections between structural elements have to be designed without taking into account the friction strength and a 50% increase in the design seismic force must be considered if some specific requirements concerning the strength and ductility of connections are not followed.
3 Case study plant

The case study analysed in this paper is an industrial plant dedicated to the production of medical devices, located in Mirandola (MO), respectively, at 17 km and 8 km from the epicentres of the two earthquakes. These events caused major structural and non-structural damages, leading to significant direct economic losses to property, downtime and consequent business interruption.

As summarised in Table 1, the plant was composed by 17 buildings, the oldest of which was designed in 1966. All the buildings were precast reinforced concrete (RC) frames, except two cast-in-place RC buildings for offices (Building 1) and storage (Building 11). It is worth noting that only one building, completed in 2011, was designed to withstand the horizontal seismic action according to the current Italian seismic code (CS.LL.PP., 2008).

Table 1

<table>
<thead>
<tr>
<th>Building</th>
<th>Constr. material</th>
<th>Design year</th>
<th>$V_{STR}$ [EUR]</th>
<th>$V_{M&amp;E}$ [EUR]</th>
<th>$V_{STK}$ [EUR]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – Offices</td>
<td>Cast-in-place RC</td>
<td>1990</td>
<td>2,040,000</td>
<td>200,000</td>
<td>0</td>
</tr>
<tr>
<td>2 – Production</td>
<td>Precast RC</td>
<td>1983</td>
<td>4,500,000</td>
<td>21,000,000</td>
<td>700,000</td>
</tr>
<tr>
<td>3 – Production</td>
<td>Precast RC</td>
<td>1983</td>
<td>1,440,000</td>
<td>9,000,000</td>
<td>300,000</td>
</tr>
<tr>
<td>4 – Production</td>
<td>Precast RC</td>
<td>1990</td>
<td>1,300,000</td>
<td>8,000,000</td>
<td>300,000</td>
</tr>
<tr>
<td>5 – Warehouse</td>
<td>Precast RC</td>
<td>2011</td>
<td>3,400,000</td>
<td>300,000</td>
<td>2,300,000</td>
</tr>
<tr>
<td>6 – Production/warehouse</td>
<td>Precast RC</td>
<td>1977</td>
<td>4,000,000</td>
<td>2,500,000</td>
<td>1,900,000</td>
</tr>
<tr>
<td>7 – Production/warehouse</td>
<td>Precast RC</td>
<td>2002</td>
<td>2,600,000</td>
<td>1,500,000</td>
<td>700,000</td>
</tr>
<tr>
<td>8 – Warehouse</td>
<td>Precast RC</td>
<td>1982</td>
<td>1,800,000</td>
<td>150,000</td>
<td>2,500,000</td>
</tr>
<tr>
<td>9 – Warehouse</td>
<td>Precast RC</td>
<td>2003</td>
<td>3,100,000</td>
<td>300,000</td>
<td>11,000,000</td>
</tr>
<tr>
<td>10 – Warehouse</td>
<td>Precast RC</td>
<td>1993</td>
<td>890,000</td>
<td>1,150,000</td>
<td>5,000,000</td>
</tr>
<tr>
<td>11 – Production</td>
<td>Cast-in-place RC</td>
<td>1966</td>
<td>700,000</td>
<td>2,660,000</td>
<td>250,000</td>
</tr>
<tr>
<td>12 – Warehouse</td>
<td>Precast RC</td>
<td>1972</td>
<td>2,100,000</td>
<td>100,000</td>
<td>1,200,000</td>
</tr>
<tr>
<td>13 – Warehouse</td>
<td>Precast RC</td>
<td>1960</td>
<td>1,100,000</td>
<td>100,000</td>
<td>700,000</td>
</tr>
<tr>
<td>14 – Offices</td>
<td>Cast-in-place RC</td>
<td>2000</td>
<td>250,000</td>
<td>50,000</td>
<td>0</td>
</tr>
<tr>
<td>15 – Utilities</td>
<td>Cast-in-place RC</td>
<td>1983</td>
<td>300,000</td>
<td>200,000</td>
<td>0</td>
</tr>
<tr>
<td>16 – Offices</td>
<td>Precast RC</td>
<td>2001</td>
<td>360,000</td>
<td>20,000</td>
<td>0</td>
</tr>
<tr>
<td>17 – Warehouse</td>
<td>Cast-in-place RC</td>
<td>2000</td>
<td>120,000</td>
<td>70,000</td>
<td>850,000</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>30,000,000</td>
<td>47,300,000</td>
<td>27,700,000</td>
</tr>
</tbody>
</table>

Values of buildings and contents were estimated on the basis of a construction cost per unit area ranging between 600 and 800 euros (depending on structural characteristics), and adjusted according to indications provided by the plant management. The total property value of the plant was estimated in 105 million euros, distributed as follows: 30 million for structures ($V_{STR}$), 47.3 million for machineries and equipment ($V_{M&E}$) and 27.7 for stock contents ($V_{STK}$).

Owing to the homogenous structural typology, the value of structures (STR) mainly depends on the geometric dimensions of the building. Conversely, the value of other components (M&E and STK) is well correlated with the type and extension of activities
Seismic risk assessment of an industrial plant

3.1 Damages on the plant

In the aftermath of the second seismic event (29 May 2012), the plant was visually surveyed with the aim of collecting a detailed description and photographic documentation of the damage, as well as retrieving available design documents. Besides, building structural taxonomy information was retrieved via visual inspection, including but not limited to: number of floors, height, plan and elevation dimensions, construction material, lateral load resisting system, detailing of connection between structural elements, roof characteristics and eventual irregularities.

Figure 5 shows a sketch of the plant layout, with indication of the usability judgement and damage observed in the aftermath of the second seismic event. It can be noticed that only four of 17 buildings could be immediately reoccupied, while three suffered severe structural damages with partial or total collapse. The damage observed in the remaining structures ranged between slight and moderate.

The resumption of the normal work activity was progressively achieved in different buildings depending on their damage and the eventual retrofitting intervention required to meet code requirements. The full production capacity was restored four months after the events and amount of sales budgeted in 2012 was achieved after six months. It is worth noting that assessment of the indirect damages due to Business Interruption (BI) is beyond the purposes of this study.
Table 2 summarises the Property Damage (PD) to structures (STR) after the loss adjustment process. This is believed to be a much more realistic representation of the real losses with respect to the claim, which is a request of compensation to the Insurer. Values reported in Table 2 include costs related to reconstruction, demolitions, debris removal and expenses to adhere to new seismic regulations, i.e. retrofitting interventions required to achieve at least the 60% of the seismic capacity of a new building, designed according to current Italian seismic code. It is worth noting that the claim and loss adjustment process aim at quantifying the resources required to recover the damage and to restore the situation existing before the adverse event. Therefore, eventual costs for improving the seismic capacity of structures besides eventual code requirements are not taken into account. No claim was presented for Buildings 13–17, therefore they will be not analysed in the following. The total value of the adjusted loss to structures (STR) was equal to 21% of the total value of structures.

Table 2  Adjusted loss to structures (STR) of each building of the plant

<table>
<thead>
<tr>
<th>Building</th>
<th>Observed loss to structures (STR), as resulting from adjustment</th>
<th>EUR</th>
<th>% of building value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – Offices</td>
<td></td>
<td>737,199</td>
<td>36</td>
</tr>
<tr>
<td>2 – Production</td>
<td></td>
<td>2,932,831</td>
<td>65</td>
</tr>
<tr>
<td>3 – Production</td>
<td></td>
<td>107,230</td>
<td>7</td>
</tr>
<tr>
<td>4 – Production</td>
<td></td>
<td>107,230</td>
<td>8</td>
</tr>
<tr>
<td>5 – Warehouse</td>
<td></td>
<td>157,331</td>
<td>5</td>
</tr>
<tr>
<td>6 – Production/warehouse</td>
<td></td>
<td>680,199</td>
<td>17</td>
</tr>
<tr>
<td>7 – Production/warehouse</td>
<td></td>
<td>113,336</td>
<td>4</td>
</tr>
<tr>
<td>8 – Warehouse</td>
<td></td>
<td>122,839</td>
<td>7</td>
</tr>
<tr>
<td>9 – Warehouse</td>
<td></td>
<td>336,460</td>
<td>11</td>
</tr>
<tr>
<td>10 – Warehouse</td>
<td></td>
<td>332,988</td>
<td>37</td>
</tr>
<tr>
<td>11 – Production</td>
<td></td>
<td>191,913</td>
<td>27</td>
</tr>
<tr>
<td>12 – Warehouse</td>
<td></td>
<td>406,211</td>
<td>19</td>
</tr>
<tr>
<td>13 – Warehouse</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>14 – Offices</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>15 – Utilities</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>16 – Offices</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>17 – Warehouse</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>6,225,766</td>
<td>21</td>
</tr>
</tbody>
</table>

Concerning Machinery and Equipment (M&E) and Stock (STK), an adjusted value of loss was not available; therefore, reference has been made to the overall claim submitted to the Insurer (Table 3).
Among the structures which suffered heavy structural damages, Building 2 is the one for which the largest loss was observed. It was a two-storey precast frame with vertical irregularities due to the presence of mezzanine floors and some adjacent structures. From a structural point of view, the building suffered the collapse of exterior precast cladding panels, due to a lack of adequate structural details on their connections to the structure, and the diffuse shear failure of columns base sections of the second floor. Furthermore, an extensive damage was observed for large part of the high-value equipment located at the ground level, i.e. clean rooms and oxygenators with poor mechanical anchoring to their foundation. In particular, clean rooms resulted to be particularly vulnerable to the seismic action and earthquake-induced displacements. In fact, the cracking of clean rooms’ partitions and the consequent fall of plaster, as well as the failure of ceil-mounted equipment, caused significant damages to room’s content and the need to restore controlled environment before restarting the production. The decision regarding this building was to completely demolish the second floor and repair the remaining part. This explains the overall loss figure, exceeding the 65% of the total structure value.

Building 6 was a part of a larger building dedicated to production, originally designed in 1977 and subsequently expanded in 2002 (Building 7). It was a single-storey precast RC building which suffered the loss of verticality of columns and the loss of support of the beam due to inadequate mechanical connection. From a structural engineering point of view, the damage is a partial collapse of the structure, nevertheless the adjustment considered only repairing interventions limited to the area interested by the damage, with a consequent loss equal to 17% of total structure value.

Similarly to the previous, Building 10 was a single-storey precast building which was severely damaged by the earthquakes. In fact, the failure of horizontal precast cladding panels and a significant loss of verticality of columns were observed. Although the loss adjustment resulted in a quantification of repairing actions (in the measure of 37% of total value), it was decided to completely demolish the building.

Among structures which were moderately damaged, Building 1 (mid-rise RC frame) suffered extensive non-structural damages due to the failure of exterior cladding and interior furniture; Buildings 11 and 12 experienced some plastic hinge formation at the base plate of columns and non-structural damages to partitions, misalignment of machineries and storage rack failure. These structures were refurbished and their occupancy was maintained.

All the other buildings behaved relatively well, as limited damages were observed. For instance, in Building 9, where 42% of the whole storage plant value was located, the good structural characteristics and proper detailing caused a very limited damage, consisting in slight non-structural damages (very limited loss of content from industrial storage racks). In fact, although not designed for seismic action, the building was characterised by mechanical connections between structural elements and adequate structural dimensions and reinforcement ratios.
4 Analysis

The case study plant was analysed through the FRAME software tool (Petruzzelli and Iervolino, 2014), allowing a rapid computation of seismic risk, either in terms of annual expected loss or conditional expected loss, given the occurrence of a scenario Intensity Measure (IM).

4.1 Methodology

In this study conditional loss expectancies have been computed given the occurrence of a PGA equal to 0.3 g, that is the maximum value observed at the site, as per INGV shakemaps (Figure 2):

$$E[L|IM] = \sum_i E[L|DS_i] \cdot P[ds = DS_i|IM]$$

In the previous equation, $P[ds = DS_i|IM]$ is the conditional probability that the structure is in the $i$-th damage state, $DS_i$, given the scenario intensity measure. The latter can be computed from the fragility function set employed to model the seismic vulnerability, by simply subtracting the conditional probabilities of exceeding two consecutive damage states (Figure 6).

**Figure 6** (a) Fragility functions providing the conditional probability of exceeding different structural damage states, given the scenario earthquake intensity measure, IM; and (b) distribution of conditional probabilities that the structure is in the $i$-th damage condition, given the scenario IM.

The term $E[L|DS_i]$ represents the so-called consequence function, allowing to translate the probability of observing different damage conditions (from no damage to the complete collapse) into decision variables of interest, such as repair and replacement costs, casualties, downtime, and other relevant impacts (Mitrani-Reiser, 2007). In this case, the consequence function provides the expected value of the loss, $L$, given the Damage State, $DS_i$.

Owing to the difficulties in retrieving information regarding building contents, it was decided to link the damage to non-structural components and stock to that of the structure, rather than employing fragility functions for each relevant non-structural element (e.g. Aslani and Miranda, 2005; FEMA, 2012).
The $E[L|DS_i]$ term was computed for each component of the value ($V_{STR}$, $V_{M&E}$ and $V_{STK}$) as the product of the value and the fraction that is expected to be lost, also known as damage ratio, $DR$.

\[
E[L|DS_i] = V_{STR} \cdot E[DR_{STR}|DS_i] + V_{M&E} \cdot E[DR_{M&E}|DS_i] + V_{STK} \cdot E[DR_{STK}|DS_i]
\]  

(2)

Expected values of damage ratios for the structure, $E[DR_{STR}|DS_i]$, were obtained from HAZUS (FEMA, 2001), while those for machineries and equipment ($E[DR_{M&E}|DS_i]$) and stock ($E[DR_{STK}|DS_i]$) were obtained from the study by Dowrick and Rhoades (1995). The latter provides damages occurred in past seismic events to typical industrial equipment and stock. Accordingly, the machinery and equipment was classified as ‘robust’, ‘medium’ or ‘fragile’, depending on its susceptibility to the structural damage and the consequence function for stock was defined on the basis of the main building occupancy (‘industrial’ or ‘offices’).

Concerning the selection of structural fragility functions, the FRAME software inventories existing studies according to a structural taxonomy derived from that developed in the Syner-G (Pitilakis et al., 2014) and GEM (D’Ayala et al., 2014) projects. The latter was expanded to describe most common structural typologies in industrial field, such as precast RC structures or steel industrial buildings. Concerning industrial precast RC structures, the FRAME software includes the following studies: Bolognini et al. (2008) and Casotto et al. (2015), dedicated to Italian structures, and Senel and Kayhan (2010), regarding Turkish buildings.

The first two studies classify the Italian precast industrial building stock in four main classes, as indicated by Calvi et al. (2009):

- Type 1: one-storey parallel portals, with columns fixed at the base, saddle double T-shaped beams and double tee slabs;
- Type 2: one-storey parallel portals, with columns fixed at the base, double T-shaped main beams and large span roof elements with double tee slabs;
- Type 3: one-storey parallel portals, with columns fixed at the base, Truss beams and pre-stressed thin slabs; and
- Type 4: two-storey frames, with continuous columns fixed at the base and pinned beams and double tee slabs.

Fragility functions are provided for two limit states (yielding and collapse) and different levels of seismic design action (‘pre-code’, ‘low-code’, ‘moderate-code’). It is worth noticing that the study by Casotto et al. (2015) only analyses the first two structural typologies of the previous list.

On the basis of the data surveyed on field, fragility functions better adapting to the actual structural characteristics were associated to each building of the plant. Similarly, content and stock classes were defined on the basis of occupancy and prevalent equipment. It is worth noting that the structural scheme was considered as the main parameter in the selection of fragility functions, while the design seismic action was adapted in order to take into account structural regularity, design specifications and detailing (e.g. reinforcement ratios retrieved from design documents). In fact, almost all the structures of the plant were designed without considering any seismic action and the use of ‘pre-code’ functions would have led to an unrealistic overestimation of losses.
For what concerns cast-in-place RC structures, median fragility functions computed through FRAME software from European RC Moment Resisting Frames (MRFs), not designed for seismic action (NC), were employed. In particular, median fragility functions for mid-rise buildings (MR) were applied to Building 1, while that for low-rise structures (LR) was considered for Building 11. This choice was motivated by the lack in information regarding the structures, besides rise, structural scheme and seismic design action.

Table 4 summarises the main assumptions made in the assessment and the estimated loss expectancy.

<table>
<thead>
<tr>
<th>ID</th>
<th>Fragility function</th>
<th>M&amp;E class</th>
<th>STK class</th>
<th>Loss estimates [EUR]</th>
</tr>
</thead>
<tbody>
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<td>STR</td>
<td>M&amp;E</td>
<td>STK</td>
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4.2 Results

As a first result of the analysis, the estimated total loss expectancy, given the occurrence of the earthquake scenario, is 20.035 mln euros (19% of total plant value), against an observed loss of about 15.835 mln euros (15% of total plant value). More specifically, the total loss to STR, M&E and STK is, respectively, 21%, 24% and 9% of total component value, while the observed ones are, respectively, 21%, 16% and 8%. While the overall loss estimates obtained for STR and STK are quite satisfactory, the expected loss to M&E suggests the opportunity of explicitly considering fragility functions of equipment (e.g. FEMA, 2012), especially if characterised by high value (as in the case of Building 2).

In order to investigate the distribution of estimated losses throughout the plant and the relative impact of each building on different loss components, loss estimates are shown in Figure 7 as fractions of the total value of the specific component at risk.
With specific reference to the component related to the value of the structures, the high vulnerability of Buildings 2 and 6 resulted in a cumulative expected loss of about 10% of the total value of structures. In addition, the high susceptibility to damage of non-structural elements and equipment in Building 2, mainly made up of clean rooms and oxygenators, together with their high value, leads to an expected loss estimate equal to the 18% of the total equipment value of the plant. Conversely, the expected loss for Buildings 5, 9 and 10 is relatively low, because of a structural scheme devoid of significant irregularities, a relatively recent design, and an adequate structural dimensioning.

The case study represents a clear example of inadequate distribution of assets and values with respect to the seismic vulnerability of structures. In fact, with rare exceptions (e.g. Buildings 3, 4 and 9), most of the machinery essential to the production or of greater value were placed in the most vulnerable buildings. This caused, on the one hand, most of the direct damage and downtime and, on the other, suggests that a rational relocation of operations and production following seismic loss assessment could be one suitable strategy for the reduction of earthquake impacts in industry. It is worth noting that the 4% of plant stock loss is estimated in Building 9. This is caused by a very low seismic vulnerability of the structure, as the building housed 11 mln euros of stock, corresponding to about 40% of plant value.

A structure-by-structure comparison of the estimated conditional expected loss and that resulting from the loss-adjustment process is reported in Figure 8. This comparison was carried out with reference to the STR component only, due to the unavailability of the other components of the loss agreed between the parties. Results are expressed in terms of loss (estimated and adjusted) to building total value ratio.
As a general result, the loss estimates appear to be consistent and sufficiently well correlated to the adjusted loss, yet some discrepancies exist. More specifically, a tendency in overestimating the actual loss emerges, which appears to be more evident for structures which suffered slight damages (Buildings 3, 4 and 7). This is due to several factors, such as: (i) the probabilistic nature of the assessment, providing the expected value of the loss; (ii) the conventional definition of damage states; and (iii) the adoption of specific fragility and consequence functions. While the first two points of the previous list are intrinsic in the pursued approach, the last one is strictly related to the epistemic uncertainty in the inspection of the structure and collection of building taxonomy, as well as the availability of studies able to adequately describe the structural and non-structural building characteristics.

For the same reasons, buildings which suffered moderate to severe damages (Buildings 2, 10, 11 and 12) show an opposite trend compared to that described above, that is an underestimation of the expected loss with respect to those observed.

In particular, for what concerns Building 2, the fragility study employed (Bolognini et al., 2008; type 4 structural scheme) was that providing the largest failure probabilities among those available in FRAME software with structural schemes similar to the real one. Indeed, this lack in fragility studies for multi-storey precast RC structures limited the possibility of reproducing the actual loss.

One exception to the above is represented by Building 6, for which the expected loss is significantly larger than the adjusted one (32% against 17%) even though structural collapse occurred. This is believed to be due to a relatively low value of the adjusted loss, corresponding to the repair of a partial collapse occurred in a limited portion of the building, instead of its complete reconstruction.
5 Conclusions

In this study a plant struck by the Emilia 2012 earthquakes was analysed, with the aim of comparing the direct losses obtained through quantitative seismic risk assessment to those provided by the claim and adjustment process. The earthquakes were particularly damaging for the plant, due to the high vulnerability of buildings (mainly cast-in-place and precast reinforced concrete structures) and equipment (mainly clean rooms, oxygenators and other fragile contents). The assessment of the expected losses was performed considering the maximum acceleration felt at the site during the earthquake sequence and accounting for structural and non-structural damages. The latter were assessed through the use of consequence functions retrieved from the literature, providing the expected damage to non-structural components and contents as a function of the structural damage state.

The most critical aspect of the whole assessment is related, from the one hand, to the collection of a sufficiently accurate structural taxonomy (through visual inspection and/or analysis of design documents) and, on the other hand, to the availability of fragility functions suitable to the structure under investigation. In fact, the existing studies are generally applied at the regional scale, rather than at the scale of individual industrial installations. More specifically, studies providing fragility functions for Italian precast RC structures define homogeneous building classes on the basis of structural scheme and seismic design level. To adequately capture the specificities of each precast building of the case study, such as actual member sizes and reinforcement detailing, it was necessary to select fragility functions neglecting the indication regarding the seismic design level. In fact, all the buildings of the plant except one were designed without considering any seismic action. Therefore, the use of fragility functions developed for ‘pre-code’ structures only would have led to unrealistically overestimated losses.

On the overall, the obtained loss estimates resulted to be well-correlated to the actual damage. In particular, the total loss expectancy to structures is very close to the adjusted loss (both can be rounded to 21% of total structure value). Similarly, the total loss expectancy to stock is 9% of the total value, while the claim totalled 8%. Slightly larger differences can be observed for machinery and equipment, for which the estimated loss is 24% of total value, against 16% based on the claim, remarking the opportunity of employing fragility functions for individual components in case of high-value equipment.

Understandably, a building-by-building comparison shows that the conditional expected losses are larger than real ones, for structures which showed a partial or total collapse and, conversely, lower for structures which suffered slight damages.

These discrepancies are to be regarded, on the one hand, as typical of a probabilistic approach, and, on the other hand, are believed to be intrinsically related to the level of knowledge that can be achieved about structural and non-structural features, as well as to the availability of suitable studies regarding structural fragility and consequence functions.

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References


Circ. M. LL.PP. (1965) Circolare del Ministero dei Lavori Pubblici n.1422 del 6 febbraio 1965, Istruzioni per il rilascio della dichiarazione di idoneità tecnica dei sistemi costruttivi e strutture portanti prevista negli art. 1 e 2 della Legge 5 novembre 1964, n. 1244 con particolare riferimento alle strutture prefabricate, G.U. della Repubblica Italiana. [In Italian]


