2.11 Post-event analysis of industrial structures behavior during L'Aquila earthquake

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2.11.1 Introduction

This contribution refers to both building-like and non-building-like industrial structures. Regarding the former type, L'Aquila earthquake represents the first case in Italy of a wide observation of their seismic response. Industrial buildings are often comprised of reinforced concrete precast elements. The earthquake has shown deficiencies related to inadequate design or construction criteria. In fact, insufficient separation distances between structures (causing pounding), insufficient size of saddles of precast beams and insufficient strength of non-structural infilling panels emerged. Moreover, localized failure of supports of horizontal elements due to insufficient size of saddles and too large concrete cover with respect to design specifications, were observed. Concerning non-building-like structures the investigations refer to the sili, for polypropylene stock, of Vibac in Bazzano close to Onna (AQ). These structures represent an interesting case-study of damages to steel constructions. Some of them experienced total collapse, others suffered local and global buckling. In particular three failure modes occurred: (1) crashing of the shell at the base (*elephant foot buckling*); (2) deformations due to instability; (3) pounding to close precast reinforced concrete structures.

2.11.2 Building-like industrial structures

Industrial buildings were built for many years as an assemblage of precast reinforced concrete elements. The April 2009 L'Aquila earthquake has struck, for the first time in Italy, industrial structures on a large scale. In fact, the Irpinia 1980 earthquake hit an area with few industrial sites; and similarly happened in the Umbria and Molise earthquakes, which moreover were felt within a limited area. On the other hand, the Friuli 1976 earthquake damaged industrial structures, but they were designed with no regard with respect to the seismic action; if any design rule was used, this however belonged to inadequate seismic codes. L'Aquila and its surroundings are instead undergoing a rather strong industrial development. Precast reinforced concrete buildings, with a column-beam structure, are the usual type in the industrial areas in Pile, Bazzano, Monticchio and Ocre (AQ). Buildings have generally one storey; two storeys are seldom observed, moreover only on a more limited area than the first storey. Beam supports on the columns may be of the saddle or bracket type. Deck beams are usually transversally aligned (with respect to the longer side of the structure plan) and they are I-shaped, with variable depth; longitudinal alignment and inversed T-shapes are less commonly observed. In the latter case, the shape is used to support the tiles. The roof is generally built with tiles π-shaped; less often U-shapes are observed. Skylights are sometimes present. Π-tiles are also used for the intermediate deck, when there is one. External partitions are either made with bricks, or with precast reinforced concrete shells, with no stiffeners. Structural nodes are those typical of the Italian constructions: beaker footing for the foundation to column nodes, simple support for the beam to column nodes (with neoprene bearings and steel pins). Tiles are generally directly resting on the beams, with neither horizontal restraint nor neoprene bearings. Pin connections are seldom present. Tiles may be connected each other with the upper reinforced concrete layer, or simply linked via steel restrainers (partly poured within the tiles concrete, partly welded with the next tile restrainer). Partition panels are either supported by the eaves beam or by the column, via links of many types. They are also sometimes supported by the deck tiles. A typical shell-eaves beam connection is via a steel plate partially put within the concrete shell during pouring. A bolt connects the plate and a steel angle, which is restrained to the eaves beam edge. The shell to column connection is often built with a steel plate within the column and a bayonet with bushing linked to the shell, via a long bolt. This technology is used also to connect the partitions to the deck tiles; the

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steel angles and bolts connection is less frequent. It is worth to note that structural shell buildings are much less common than beam-column buildings. A few precast industrial buildings were under completion on April 6^{th}, 2009, when the earthquake struck; so it was possible to verify the seismic behaviour of these structures under variable degrees of completion.

2.11.3 Damage and seismic performance analysis

The response of the structural elements of the industrial buildings to the April the 6^{th} 2009 earthquake was generally in accordance with their design level: no column collapsed, even though, in many cases a plastic hinge was observed, due to the high intensity of the seismic action (Fig. 1). In some cases such plastic hinge was not observed at the column base, i.e. at the column-foundation joint, but even one meter above, where the longitudinal reinforcement decreases. Furthermore no plastic hinge was observed in beams or tiles due to the increment of the vertical action. However, the damage of the precast industrial buildings should be well analysed; indeed, it was characterised by collapse of parts of the buildings, which, if the main-shock had happened during the working time instead of at 3 a.m., it would have caused victims. The static scheme of such structures is characterised by large deformability; consequently, the most of the observed damages of structural elements (made by reinforced concrete) depend on the relative displacements between the elements. Indeed, many cases of pounding between elements of the same structure were observed. Furthermore, pounding between adjacent buildings was frequent, in the case of both precast and cast in situ structures, due to the insufficiency of separation joints. In figure 2, taken by Giordano et al. (2009), the pounding between the tiles and the beam of an industrial precast building placed at Bazzano is shown.

Confirming the numerical studies (Magliulo et al., 2008; Capozzi et al., 2009) performed in the last years, the connections represented the weak parts in terms of seismic performance of both old and new precast buildings. Some buildings have shown damages at the beam-column connection: the only observed case of precast beams collapse was due to the damage of such connection and to the following support loss. Indeed, as shown by numerical analyses (Capozzi et al., 2009), the splitting of the joint bar cover happened where the thickness was minimum. In other frames of the same structure, it is also possible to observe the collapse of the beam due to support loss at the side without joint bar, caused by too large displacements, and the pounding between the beam and the column top fork (Fig. 3).

The phenomenon of the joint bar cover splitting can be also noted at the intermediate level of some two-storey precast buildings, where, as already written, the beam-column joint is on corbel. The same phenomenon has also characterised the collapse of some tiles. In this case, indeed, even where the joint had been fastened by a steel bar, the little thickness of the bar cover of the beam, also characterised by the lack of stirrups, collapsed, causing the tile support loss (Fig. 4a). Obviously, such support loss easily happened where the tile-beam connection was not fixed and/or there was no connection between tiles; particularly unlucky situations were characterised by buildings in phase of assembly, where the floor slab, joining the tiles, was not made yet.

However, the most important and spread damages of precast industrial buildings caused by the April the 6^{th} earthquake are those concerning the elements on the perimeter; indeed, the large damage of such elements, even though the structural typologies are different, associates precast buildings to the in situ cast ones. The top connection of the vertical panels to the side of the gutter beam, made by a profile drowned in the panel, bolt with nut and angle stirrup, in some cases gave way due to the angle stirrup breaking and/or to the bolt head going out from the profile (Fig. 4b). This last phenomenon also caused the collapse of panels connected to columns by a profile drowned in the column and bayonet with bushing joined to the panel by bolt; some of these last connections, instead, collapsed due to the bayonet breaking at bushing position. Some other failures where due to the going out of the whole profile from the panel where it was drowned. A better seismic response was shown by panels joined to the structure by angle stirrups and bolts. In the case of perimeter elements made by bricks, the seismic action determined their out of plane deformation, in many cases up to the expulsion of bricks and the consequent partial or total collapse of the perimeter element. Finally, among the carrying out mistakes, it is noteworthy, for precast structures, the local failure of the beam support. In figure 5, taken by Camata et al. (2009), a near collapse condition is shown,

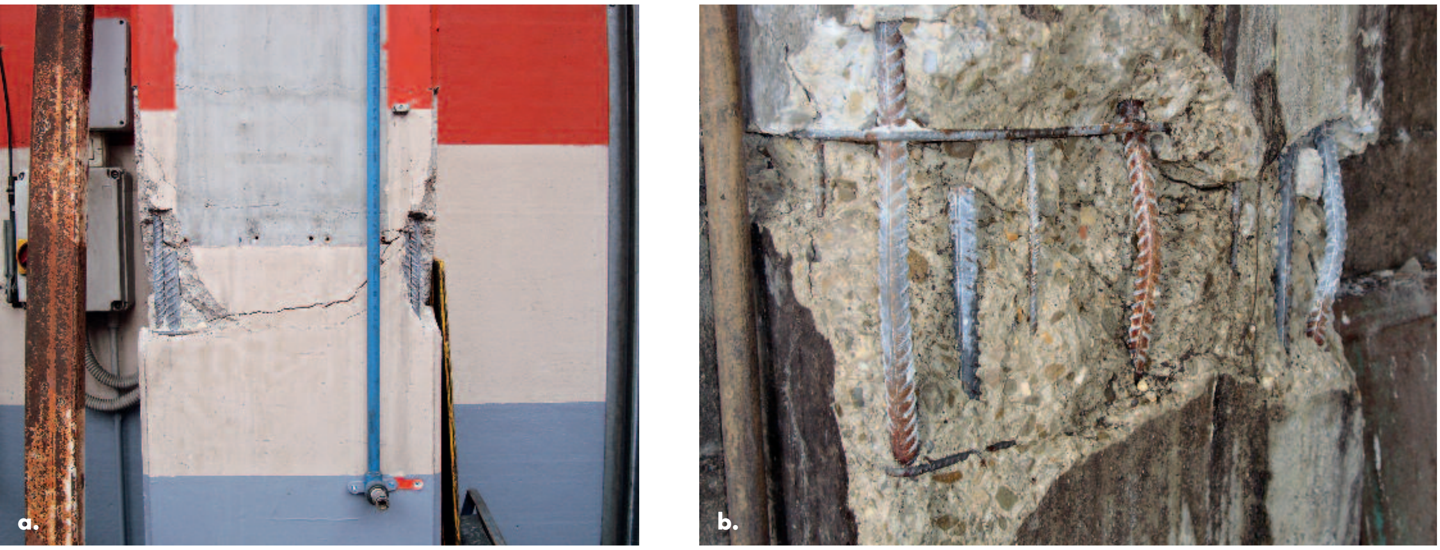

Fig. 1
Plastic hinge in columns of industrial buildings: (a) FIAT garage at Pile; (b) building used for bovine-breeding at Fossa.

caused by the large column cover due to the fire protection provisions; indeed, due to such provisions, a volume of concrete without reinforcement works as beam support.

2.11.4 Non-building-like structures: the case study of the Sili Vibac in Bazzano.

The sili of the Vibac multinational (a chemical company which produces plastic films), located in Bazzano, close to Onna (Fig. 6) represent an exceptional case of damage to steel constructions. They also represent an emblematic case of damage induced by the earthquake of April 6th. The sili are used for the storage of polypropylene pearls and they were full when earthquake struck (EERI, 2009). Some sili collapsed, some other remained standing even though strongly deformed, both locally at some rings and diffusely (Fig. 7).

A more close visual inspection indicated that the collapses occurred for overturning due to the crushing of the base rings and the hopper. Moreover, along the sili height, deformations induced by buckling phenomena of the wall panels are apparent. In some cases an effect of pounding on the adjacent precast reinforced concrete constructions took place, the latter have achieved the partial failure of the curtain walls, which have induced strong deformations of the shells of the sili. Such type of damages are a clear effect of the earthquake vertical component, whose importance they highlighted (Fig. 7).

The Vibac sili have a metallic structure. Generally for their conception sili have a very low structural weight, normally significantly lower than the weight of the contained material. Such a characteristic implies a very slender structure. It is evident that such structures are sensitive to both local and global buckling phenomena. In fact the most common failure mode is the instability of the wall panels due to the effects of the axial force in compression. Such actions are due to the friction between the silage material and the walls. The horizontal radial pressure, acting on the cylinder surface from the silage material, has a stabilizing effect against the buckling of the silos' walls, giving rise to a tension stress field of membrane type. The distribution and intensity of the internal forces in every constituting part of the silos, the cylinder and the hopper, are strongly influenced by the material extraction behaviour,

Fig. 2
Effects of pounding between the cover tiles and the beam (Giordano et al. 2009).

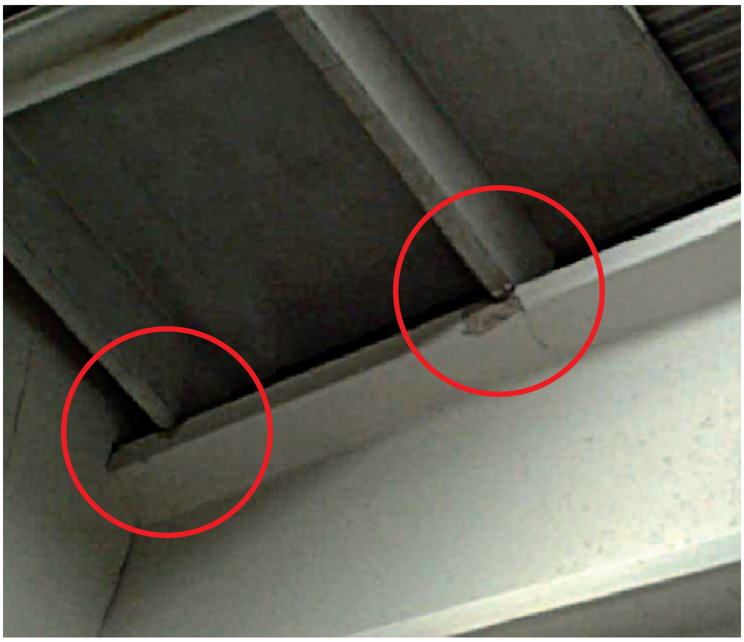

Fig. 3
Collapse of beams due to loss support of a building at Fossa used for bovine-breeding.

Fig. 4
(a) Tiles collapse due to cover splitting and support loss of a FIAT garage at Pile. (b) Collapse of perimeter panels due to the breaking of the angle stirrup or to the bolt head going out from the profile in a building used as material and machine deposit at Bazzano.

which in turn depends on the shape of the silo. The Vibac sili have an elongated shape typically used for the storage of plastic material. Therefore the predominant extraction mode is of the so called "mass" type, having the characteristic that the first material coming out is the one inserted as first in the silos, all the material mass is in movement at the leakage. In case of sili with a stocky shape, the extraction behaviour of "funnel" type prevails, it has the characteristic that a central tube forms in the material mass, which is sucked by the hopper. Such a "tube" is fed by the silage material all along the height, the part of material external to the tube rests during the leakage. In particular, in elongated sili, when completely full, along the height of the cylinder, from the higher ring bands the radial pressure grows towards the base up to assume a constant value, then at the section variation, it reduces from the ring where the hopper is installed, and high stress levels arise. Obviously in case of empty or partially full silos the behaviour is different, the stabilizing effect of the radial pressure is lost in the empty part with a consequent abrupt variation of the critical stress. Pressure variations inside the silos depend also by the leakage of the material through the hopper, which causes a backwash effect and thus depressions. In order to control and regulate such an effect, sili are provided with pressure valves. Given that it is plausible that on one side the effect of the seismic vertical component provoked a sharp and important increment of the actions in compres-

Fig. 5
Local failure of the beam support.

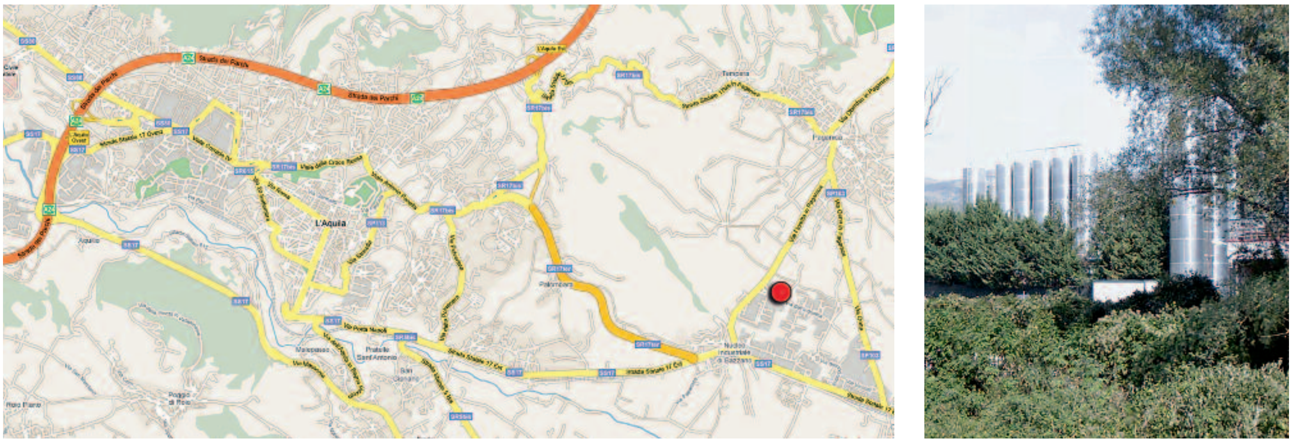

Fig. 6
(a) Localization of the plant VIBAC in the Bazzano municipality (AQ).
(b) Sili before the earthquake.

sion in the sili walls, causing buckling, the contemporary seismic action in all the components accentuated the effect of possible asymmetrical distributions of pressure, due either to structural eccentricities, or to the silos filling method, or to the anisotropy of the silage material, causing a reduction of the stabilizing effect of the radial pressures themselves. Furthermore, buckling could also occur due to constructional imperfections at the joints between the coating ring bands of the silos, where joints in any case represent a discontinuity in the flow of longitudinal stress in compression, with high concentrated stress. The above mentioned considerations fully justify the collapse behaviour observed during the April 6th L'Aquila earthquake.

2.11.5 Conclusions

Most of the buildings which experienced the April 6th 2009 L'Aquila earthquake are one-storey precast reinforced concrete structures. The observed damages are mostly related to their flexibility and to the inadequate performance of connections, especially for the case of infilling panels. In fact, pounding occurred; in some cases the beams lost their support, in other cases the bolts and steel connections of panels failed. The large number of these observations suggests that more attention must be devoted towards the connection detailing for these structures.

Concerning non-building-like structures, the case of the sili of Vibac in Bazzano highlights that design of these structures is poor with respect to earthquake resistance. In fact, it is necessary to control the risk of damaging these structures and the likelihood that an earthquake event may trigger industrial accident. In fact, in the case of sili containing hazardous material, this may greatly increase the earthquake risk.

Finally, the observed damages in industrial structures, building-like and non-building-like, may have been affected by the near-source fea-

Fig. 7
Pictures of the sili after the seism. Photo by G. Verderame, ISPRA, F.M. Mazzolani.

tures of the earthquake, including the intensive vertical component. Therefore, a revision and upgrade of seismic code provisions to account for the near-source effect seems to be required.

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