Appendix A—Emilia Earthquake

In May 2012, two major earthquakes occurred in Northern Italy, causing 27 deaths and widespread damage. The most affected municipalities are 39. The provinces concerned are Modena, Ferrara and to a lesser extent Bologna, Mantova, Reggio Emilia and Rovigo. The epicenter located between the towns of Finale Emilia and San Felice sul Panaro (Modena) and Sermide (Mantova) (Fig. A. 1).

The maximum registered ground acceleration was about 0.31g and the magnitude Mw = 5, 9. [International Journal of Earthquake Engineering, 2–3 2012]

The earthquake has shown the structural weakness of the racks. During surveys different critical issues that contributes to total or partial collapse mechanisms have been observed:

Fig. A. 1 Earthquake epicenter

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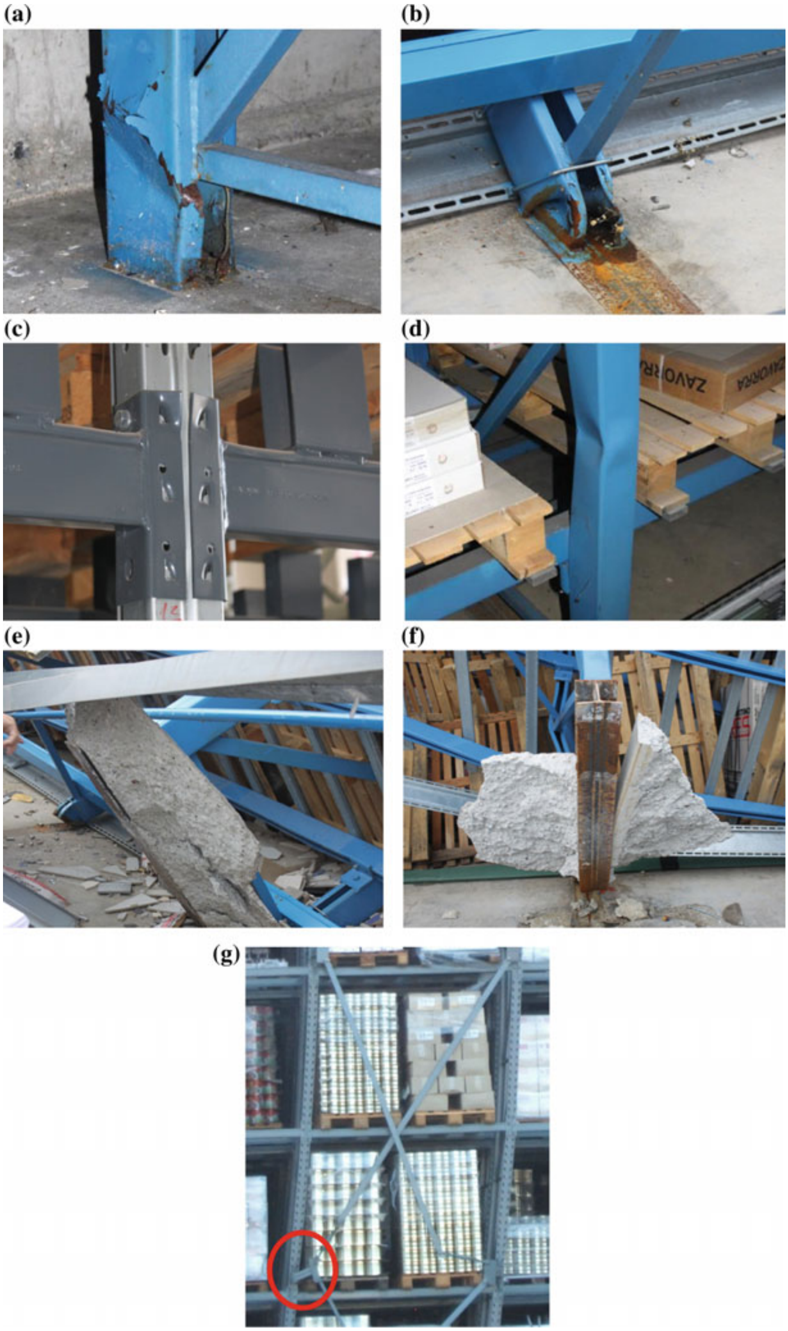

Fig. A. 2 Critical issues observed on **a**, **b** base connection, **c** beam-to-upright connections, **d** upright, **e**, **f** base support, **g** bracing system

Fig. A. 3 Detail of anchored rack

- Plastic deformations of base connections (Fig. A. 2a, b) and beam end connectors (Fig. A. 2c)
- Local buckling of the uprights (Fig. A. 2d)
- Concrete failure of floor base anchoring (Fig. A. 2e, f)
- Failure of vertical bracing system connections (Fig. A. 2g).

These phenomena underline the importance of structural detailing. Most of the observed failure modes can be easily avoided with small improvement of connections that leads to great enhancement of structural performance.

Other issues linked to the racking systems highlighted by the earthquake are:

- Interaction with the main structure in case of collapse.

Often racking systems are anchored both to non structural (e.g. concrete cladding) or structural (e.g. concrete slabs and foundations) parts of the warehouse. Seismic actions will be transmitted mutually between the two structural systems (rack and warehouse) and can bring to unexpected consequences if not correctly taken into account during design (Fig. A. 3).

- Safety of workers.

The collapse of the rack and the falling/sliding of pallets can cause injuries or even death of the nearby workers. In fact The May 29th earthquake occurred during the daytime, when many people were working. As in the mainshock of May 20th, many of the causalities in the May 29th earthquake were workers inside huge warehouses and factories.

- Obstruction of escape routes (Fig. A. 4).

The fall from shelves and the damage of valuable Parmesan cheese inside storage warehouses, became the symbol of the economic loss related to Emilia Romagna Earthquake (Fig. A. 5).

The following picture shows the beginning of a global collapse mechanism of a fully loaded racking system. In this case part of the lateral walls and of the roof, in precast r.c. elements collapse during the earthquake. The fully loaded racking

Fig. A. 4 Serious calamity at the passage way

Fig. A. 5 Example of collapse with damage of parmesan cheese

system survived and was able to sustain the roof slabs that collapsed during the shock. Collapse of a warehouse where r.c. precast panels of the lateral cladding and of the roof collapsed while the steel rack survived, despite damages, and was able to sustain the roof (Fig. A. 6).

The recent experience of the earthquake in Emily Romagna with its casualties also indicates that the vertical component of the seismic action was larger than expected and should be taken into account ("the main reasons of the damage is the extremely high vertical ground shaking (of the order of 1.0g) in combination with the moderate horizontal motions" [Carydis P., Castiglioni C. A. et al., The Emilia Romagna, May 2012 earthquake sequence. The influence of the vertical earthquake component and related geoscientific and engineering aspects, International Journal of Earthquake Engineering, 2–3 2012, 31–57]).

Fig. A. 6 Onset of global collapse mechanism

Also some clad-rack warehouses were damaged by the earthquake. The clad-rack warehouses are complex storage systems in which the shelving facility is part of the building structure, thereby avoiding the need for the civil works of a conventional building. In clad rack warehouses, the shelving facility not only supports the load of the stored goods, but also the load of the roof and lateral cladding of the building, as well as external actions, such as wind, snow and eventually the earthquake. Most clad rack buildings are automatic systems (AS/RS) using robotic equipment for handling loads. In this case, the collapse of a warehouse or the falling of stored merchandise, is not a risk for the safety of workers, but can cause a large economical loss.

An example of the complexity of the behavior of this type of structures is the ceramic warehouse in Sant'Agostino. As shown in the Fig. A. 7, part of the structure totally collapsed while part of the same warehouse did not move.

Another aspect underlined by the image above is the layout of the stored pallets. As it is known, the distribution of masses along the height of the structure can highly influence the seismic response of the rack.

Fig. A. 7 Collapse of warehouse in Sant'Agostino