Seismic damage assessment of school buildings after 2012 Emilia Romagna earthquake

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SUMMARY – *In the paper the usability checks performed on precast RC gyms and masonry school buildings, located in the Municipalities of San Pietro in Casale (BO), Bomporto (MO) and Bondeno (FE) after the seismic events occurred on 2012 May 20th and 29th, are reported and discussed. First, the main features of surveyed buildings have been identified. Later on, on the basis of the detected damages, their seismic deficiencies have been recognized. Finally, the indication of some appropriate simple interventions for retrofitting studied buildings has been given.*

Keywords: school building, Emilia Romagna earthquake, masonry structures, precast r.c. constructions, retrofitting interventions.

1. Introduction

After the 2002 Molise earthquake in Italy, where the collapse of the primary school "Francesco Iovine" in San Giuliano di Puglia caused the death of 27 children and one teacher, a large attention to the problem of the seismic vulnerability of schools has been deserved [Dolce, 2004]. The National Civil Protection Department immediately tried to understand the general causes of this problem and proposed the development of a new seismic zonation of the Italian territory and an updated seismic code. Five months after the earthquake, an Ordinance of the Prime Minister [OPCM 3274, 2003] stated that the seismic vulnerability of all public strategic buildings, including schools and hospitals, as well as the infrastructure in medium and high hazard areas, had to be evaluated within five years in order to setup a seismic rehabilitation programme. Nowadays, the provisions of the new technical Italian code, promulgated through a Ministerial Decree [M. D., 2008] explained in detail by means of an appropriate Circular [M. C., 2009] in February 2009, are the only normative reference to be used from 2009 July 1st both in the design of new structures and in the retrofitting of existing ones. So, a large investigation campaign on schools has been undertaken within the COST C26 Action "Urban Habitat Constructions under catastrophic Events"[2010], where a significant number of masonry and r.c. buildings have been seismically analysed and retrofitted under the design point of view [Formisano and Mazzolani, 2012]. Nevertheless, seismic checks of school buildings have not been still performed at large scale, as confirmed by large damages occurred into schools after 2009 L'Aquila earthquake [Salvatore *et al.*, 2009]. The same dramatic epilogue has been verified during the last Italian earthquake, occurred on May 20th and 29th within the Emilia Romagna Italian region.

In the following a synthetic report of survey checks performed at the beginning of June 2012 by the ReLUIS team n. 166, activated for supporting the zones damaged by the last Italian earthquake and coordinated by the Author, is presented.

Fifteen school buildings in San Pietro in Casale (BO), Bondeno (FE) and Bomporto (MO) have represented the case studies of the herein reported research and usability activities. So, in the following, results are presented into separate paragraphs for each of mentioned investigated Municipalities.

All investigated buildings, made of either reinforced concrete or masonry, have shown structural schemes and constructive details not aligned with provisions of the new seismic Italian code. For this reason, even if detected damages are limited, they should be retrofitted in order to resist future earthquakes.

2. Municipality of San Pietro in Casale (BO)

2.1. *"Maccaretolo" primary school*

The "Maccaretolo" primary school was built between 1919 and 1945 with a rectangular plan layout of about 500 m^2 developed on three levels (Fig. 1). The main vertical bearing structure is composed of 28 cm thick brick masonry walls surmounted by a pushing timber roof structure. Floors are made of timber beams covered by r.c. slab without tie-beams.

The building has shown few damages in the external part of the load bearing vertical structure. Instead, inside, at the first level, vertical cracks between masonry walls and internal ones, together with damages and failures of some ceiling panels, are noticed (Fig. 2).

On the façade, some horizontal cracks along the intersection zone between masonry wall and cornice roof have been recorded (Fig. 3).

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Fig. 1. *Front and back views of the "Maccaretolo" school building.*
Vista frontale e posteriore della scuola «Maccaretolo».

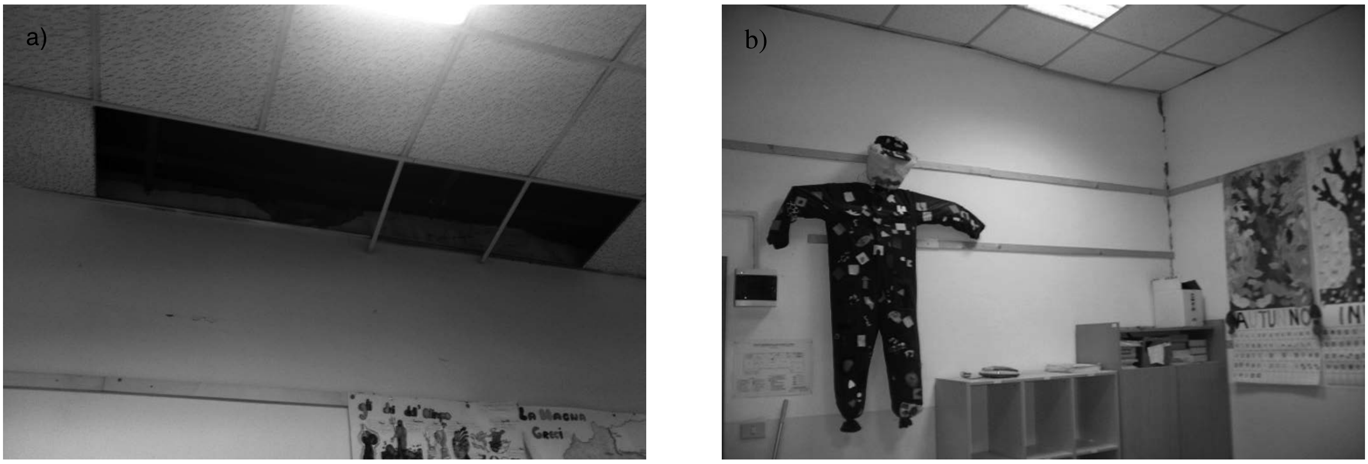


Fig. 2. *Failure of ceiling panels (a) and vertical crack between masonry wall and internal one (b).*
Crollo di pannelli del controsoffitto (a) e fessure verticali tra parete in muratura e divisorio interno (b).

Fig. 3. *Horizontal cracks along the roof cornice.*
Fessure orizzontali lungo il cornicione di copertura.

2.2. *"Bagnoli" secondary school*

The "Bagnoli" secondary school is composed of two buildings having rectangular shape and developed on five levels (Fig. 4). Such buildings, erected into different historic periods, are joined each other. In particular, the oldest building was built between 1972 and 1981, whereas the youngest one was fabricated in the last ten years.

Fig. 4. *Some views of the school building "Bagnoli".*
Viste esterne della scuola «Bagnoli».

Fig. 5. *Vertical crack corresponding to the joint zone (a) and a slight foundation subsidence at the building base (b).*
Fessure verticali in corrispondenza del giunto (a) e leggero cedimento della fondazione (b).

Both buildings have a structural scheme of r.c. frames with irregular meshes. Horizontal structures are made of mixed r.c. and hollow tile floors and a heavy not pushing roof.

A significant damage has been detected in the contact zone among buildings, since the "rules of art" have not been followed in the joint design and hammering of two structural parts have produced the detachment of large parts of plaster (Fig. 5a). One of the two buildings has shown a foundation relative displacement which has produced both displacement and rotation of the precast panel used to close the ventilation space around the building (Fig. 5b).

Inside the building, some damages in the staircase (Fig. 6a) and in a ground storey beam (Fig. 6b) have been detected, the latter showing few but diffused cracks due to vertical seismic accelerations. Other non-structural damages are cracks into plaster in the area close to the joint (Fig. 7a), as well as a horizontal crack on the pavement of a first level classroom. (Fig. 7b).

2.3. *"De Amicis" primary school*

The "De Amicis" primary school is composed of two buildings built in two different periods, namely before 1919 (Fig. 8a) and between 1945 and 1961 (Fig. 8b). Even if two structural bodies are connected each other through a steel footbridge at the first level, they can be considered as separate buildings.

The oldest construction, with a symmetric and irregular plan, has a masonry brick load bearing vertical structure (t = 28 cm) characterised by very slender piers. Roof and intermediate floors are composed of timber beams without r.c. or steel tie-beams.

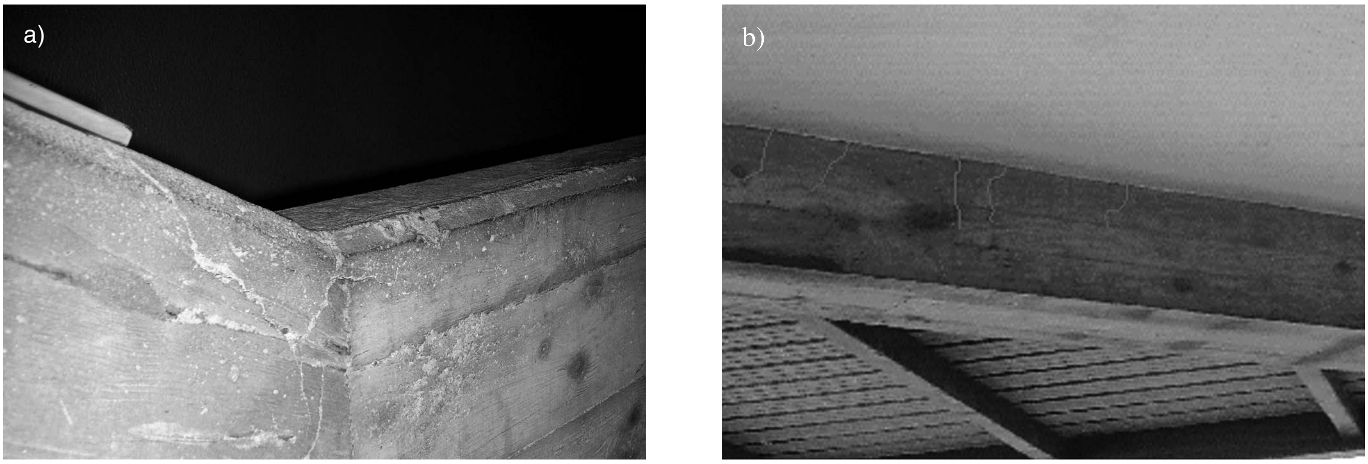


Fig. 6. *Cracks in the staircase beam (a) and in a ground storey beam external to the school (b).*
Fessure in una trave delle scale (a) e in una trave a piano terra esterna all'edificio (b)

Fig. 7. *Non structural damages: plaster cracks (a) and a pavement horizontal crack (b).*
Danni non strutturali: fessure nell'intonaco (a) e una fessura orizzontale nel pavimento (b).

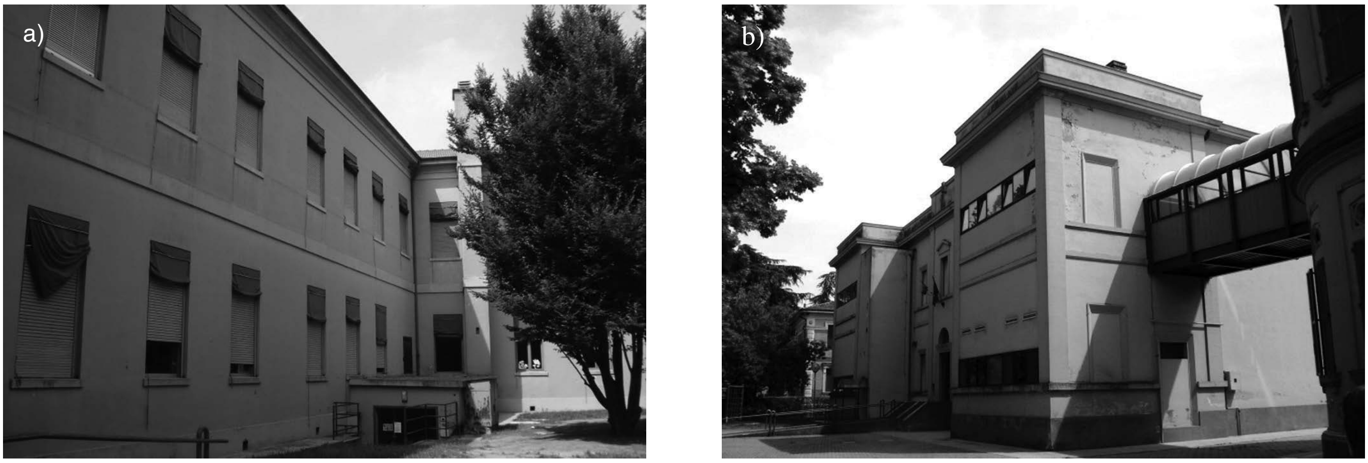


Fig. 8. *Back views of the ancient (a) and the new (b) parts of the "De Amicis" school buildings.*
Viste posteriori della parte antica (a) e della parte nuova (b) della scuola «De Amicis».

Vertical cracks into door architraves and diagonal cracks in the masonry spandrels above the same doors have been recorded inside and outside the building (Fig. 9). In addition, horizontal cracks between masonry walls and floors due to the deficient connection grade among them has been noticed.

Analogously, the youngest construction, with an irregular plan shape, has a main vertical structure of the same type of the other building.

Also in this case, slight damages consisting of cracks into architraves and masonry spandrels have been detected (Fig. 10a). Moreover, horizontal cracks between

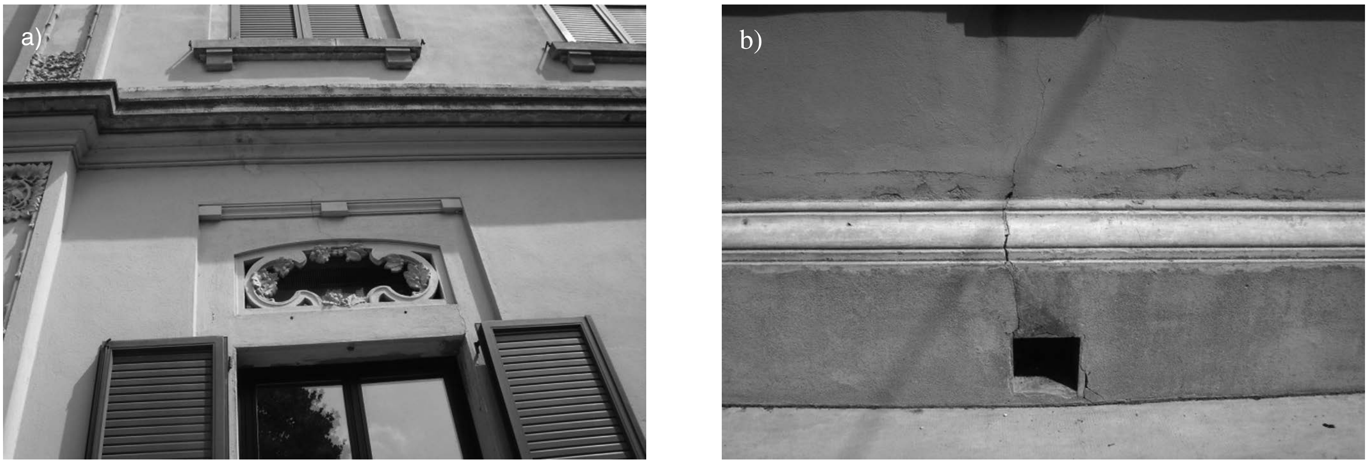


Fig. 9. *Vertical cracks into architrave (a) and at the building base (b).*
Fessure verticali nell'architrave (a) e alla base dell'edificio (b).

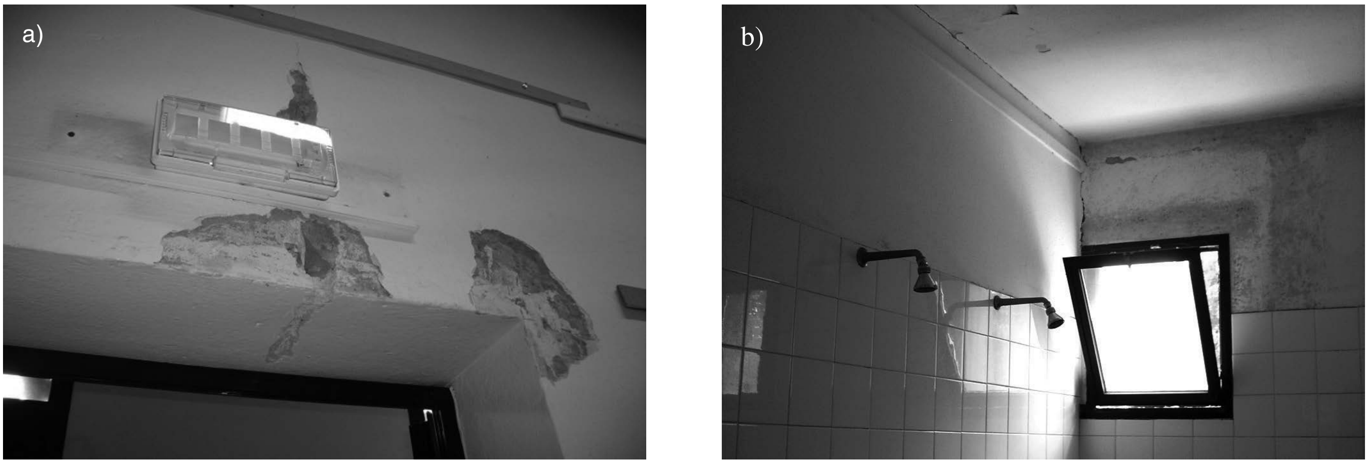


Fig. 10. *Architrave (a) and wall-floor (b) cracks.*
Fessure nell'architrave (a) ed all'attaco parte-solaio (b).

masonry walls and intermediate floors have been seen (Fig. 10b).

3. **Municipality of Bomporto (MO)**

3.1. *"Menotti" primary school*

The school building "Menotti" is a building aggregate composed of three structural units schematically illustrated in Figure 11.

The oldest construction (Fig. 12a), built before 1919, has a load bearing vertical structure analogous to the one of other investigated schools and mixed steel beams – hollow tiles floors (Fig. 12b). Medium-heavy damages have been detected, they being represented by the floor-wall detachment due to the scarce link level among these parts (Fig. 13a), cracks into the vault key, horizontal cracks into floors and diagonal cracks into walls (Fig. 13b).

The central structural unit of the building block, built in 80's, has a r.c. vertical structure made of seismic resistant frames along its longitudinal direction (Fig. 14a).

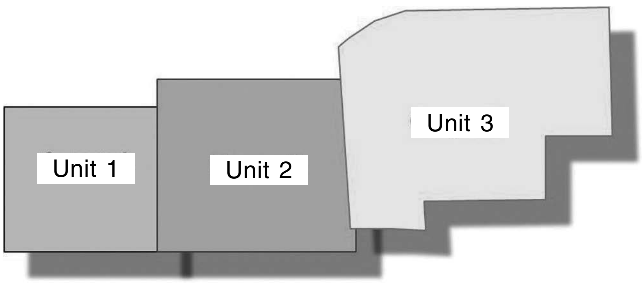


Fig. 11. *General scheme of the "Menotti" primary school structural units.*
Piano generale delle unità della scuola elementare «Menotti».

The building has suffered slight damages to non-structural parts, such as internal walls, plaster and ceiling panels (Fig. 14b). Even if a rather good building seismic response has been recorded, lack of transverse connections among frames makes the building very vulnerable towards earthquakes.

The last structural unit, erected in 90's to host the school refectory, has a r.c. structure with frames in one direction only (Fig. 15a). Damages to structural and non-structural components have not been recorded

Fig. 12. *Masonry structural unit of the school building "Menotti": external view (a) and internal corridor covered by a mixed steel beams-hollow tiles floor (b).*
Unità in muratura della scuola «Menotti»: vista esterna (a) e corridoio interno coperto da solaio misto in ferro e tavelloni (b).

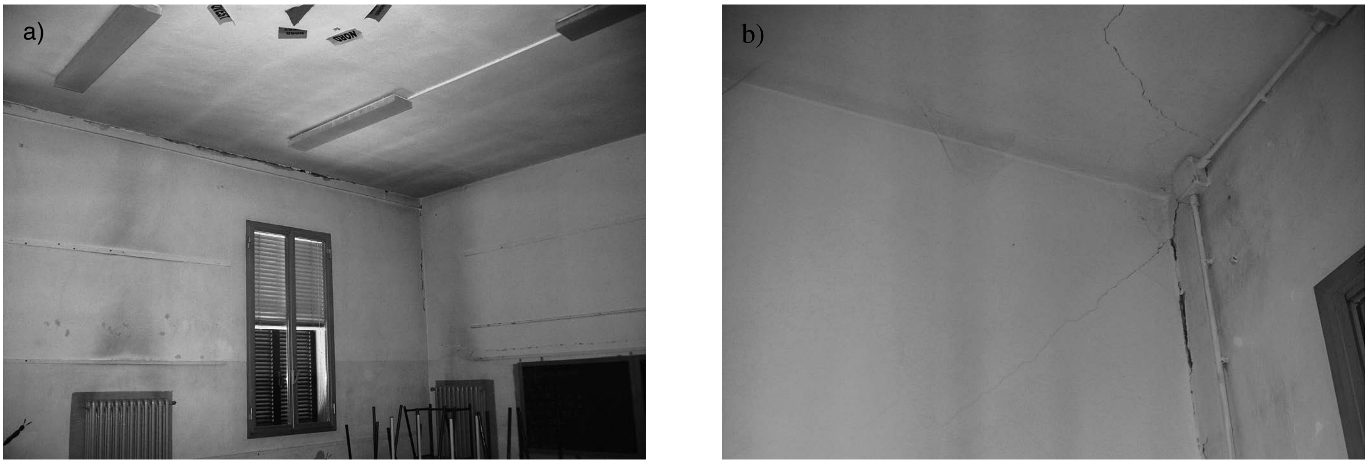


Fig. 13. *Masonry structural unit of the school building "Menotti": wall-floor horizontal crack (a) and diagonal cracks into wall and floor (b).*
Unità in muratura della scuola «Menotti»: fessure orizzontali muro-soffitto (a) e fessure diagonali in muro e soffitto (b).

Fig. 14. *The central r.c. structural unit of the school building "Menotti": external view (a) and ceiling damages (b).*
Unità in c.a. dell'edificio scolastico «Menotti»: vista esterna (a) e danni ai soffitti (b).

(Fig. 15b). Nevertheless, also in this case, absence of transverse connections among r.c. frames requires the seismic retrofitting of the school building according to the currently used code.

3.2. *Gym of the "Menotti" primary school*

This building is composed of a precast r.c. structure covered by glued lamber beams (Fig. 16), whose con-

Fig. 15. *The new r.c. structural unit of the "Menotti" school: external view (a) and refectory (b).*
La nuova unità in c.a. della scuola «Menotti»: vista esterna (a) e refettorio (b).

Fig. 16. *External (a) and internal (b) view of the "Menotti" gym building.*
Viste della palestra della scuola «Menotti»: (a) esterna, (b) interna.

nection type with columns below has not been evaluated.

The building has not shown damages to load-bearing vertical structures, whereas precast cladding panels have overturned externally to the building, their connection with columns being completely compromised. In addition, some damages to ceiling, consisting of failure of some panels, have been detected.

3.3. *"Sorelle Luppi" primary school*

The primary school "Sorelle Luppi" has been built before 1919 and, due to valuable architectural features, is now under the control of the Superintendence of Architectural Heritage (Fig. 17). The main vertical structure is made of masonry brick walls with deformable timber floors without steel chains and r.c. tie-beams.

In the building few damages among walls and not significant floor-wall cracks have been recorded. Diagonal cracks into masonry piers and horizontal cracks in vaults are very diffused (Fig. 18).

4. **Municipality of Bondeno (FE)**

4.1. *"Battisti" primary school*

The primary school "Battisti" is a very imposing construction erected in the fascist epoch (Fig. 19a). Having a significant architectural merit, the building has the vertical structure made of two heads masonry brick walls with a thickness of about 28 cm.

The building is composed of a unique construction having a symmetric and irregular plan scheme.

Slight structural damages, namely vertical cracks in door and window architraves (Fig. 19b), horizontal cracks at the floor-wall intersections and diagonal and vertical cracks into masonry walls (Fig. 20), have been noticed. However, a very heavy damage has been detected at the intersection of two masonry walls, which were completely separated (Fig. 21a).

About non-structural components, a medium-heavy crack in the intersection zone between the facade and a masonry chimney has been noticed (Fig. 21b). Also, significant damages into ceiling have been observed, they producing the collapse of some covering panels.

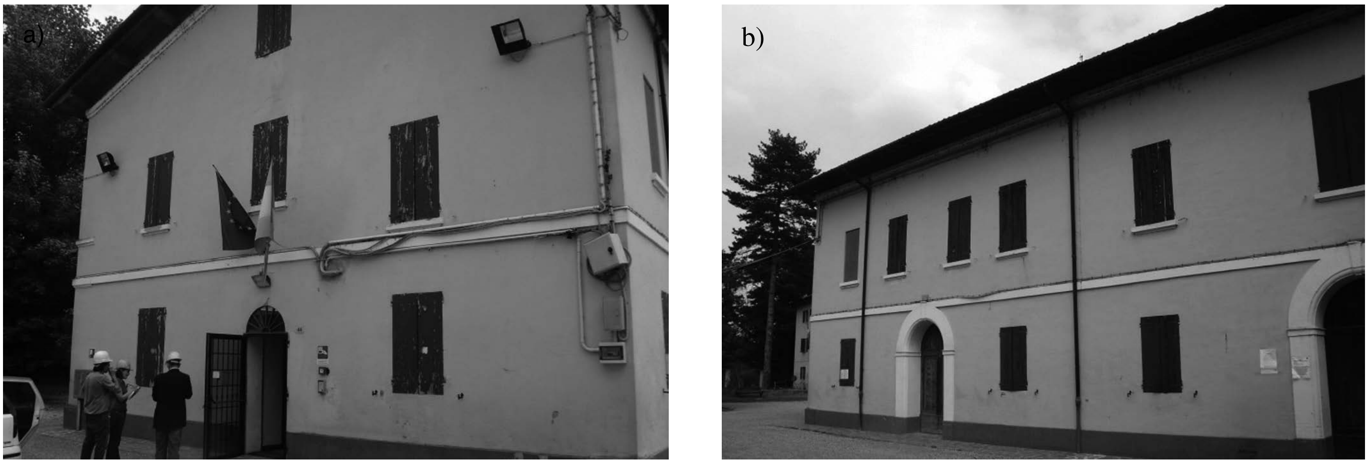


Fig. 17. *Front (a) and back (b) views of the "Sorelle Luppi" school building.*
Fronte (a) e retro (b) dell'edificio scolastico «Sorelle Luppi».

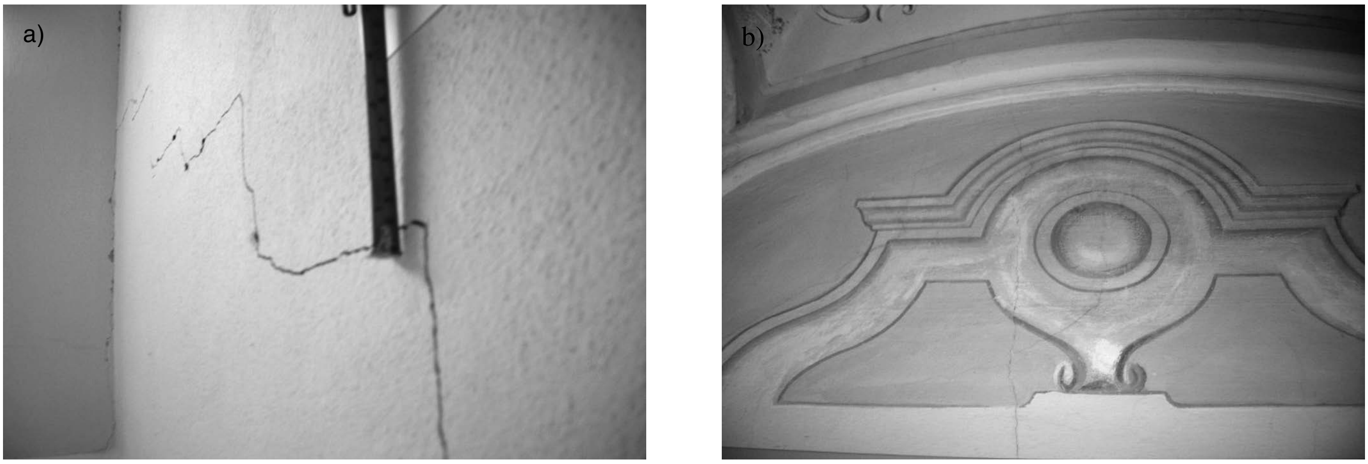


Fig. 18. *Details of some cracks detected in the "Sorelle Luppi" school building.*
Dettagli di fessure osservate nella scuola «Sorelle Luppi».

Fig. 19. *The primary school "Battisti": external view (a) and architrave cracks (b).*
La scuola elementare «Battisti»: vista esterna (a) e fessure in un architrave (b).

4.2. *"Margherita" children school*

The "Margherita" building block is composed of two one-storey buildings, erected in two different periods and connected each other by means of a central passage (Figs. 22 and 23).

The oldest building has been built in 80's and is used to host the nursery (Fig. 24a). It has a structure made

Fig. 20. *Vertical cracks in masonry piers of the primary school "Battisti".*
Fessure verticali in maschi murari della scuola elementare «Battisti».

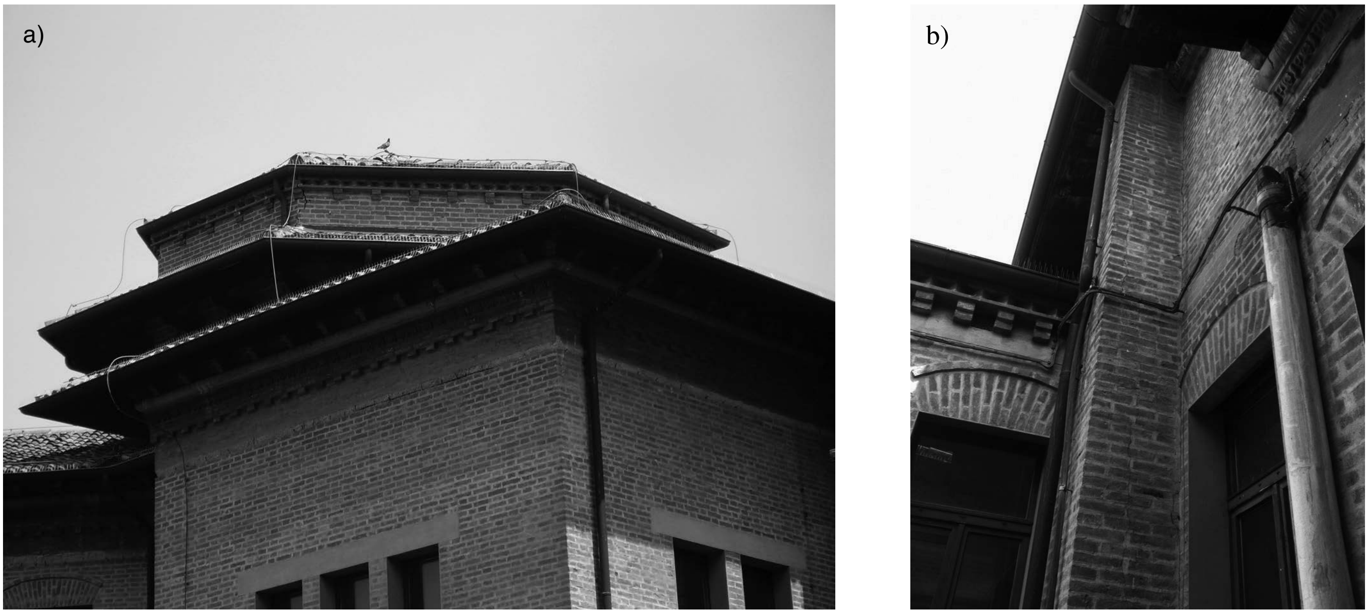


Fig. 21. *A very large crack between two masonry walls (a) and a vertical crack between the chimney and the façade (b) of the primary school "Battisti".*
Scuola elementare «Battisti»: una fessura molto larga tra due pareti in muratura (a) ed una fessura verticale tra canna fumaria e facciata (b).

of precast r.c. panels which has shown light and diffused damages after earthquake. In particular, horizontal cracks in masonry walls (Fig. 24b) and vertical cracks at the interaction zones among walls and between walls and floors (Fig. 25) have been recorded.

The second building of the block, erected in the last decade, has a vertical structure made of r.c. frames. It has exhibited a satisfactory seismic response, since no significant damage has been observed after earthquake (Fig. 26).

4.3. *"Bonati" secondary school*

The secondary school "Bonati" (Fig. 27) is a r.c. building built after 2005. Connected to an adjacent gym building (Fig. 28a), the school building is strongly irregular in plan, so to be subdivided into six structural units opportunely joined each other (Fig. 28b). Nevertheless, since structural joints have not been made following the "rule of art", that is leaving an appropriate

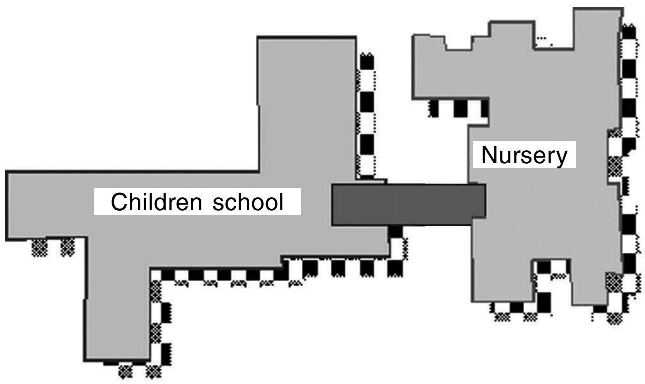


Fig. 22. *Schematic view of the "Margherita" building block.*
Vista schematica dell'edificio «Margherita».

Fig. 23. *The two structural units of the "Margherita" building block (a) and the passage corridor between buildings (b).*
Le due unità strutturali dell'edificio «Margherita» (a) ed il corridoio di collegamento tra i due blocchi (b).

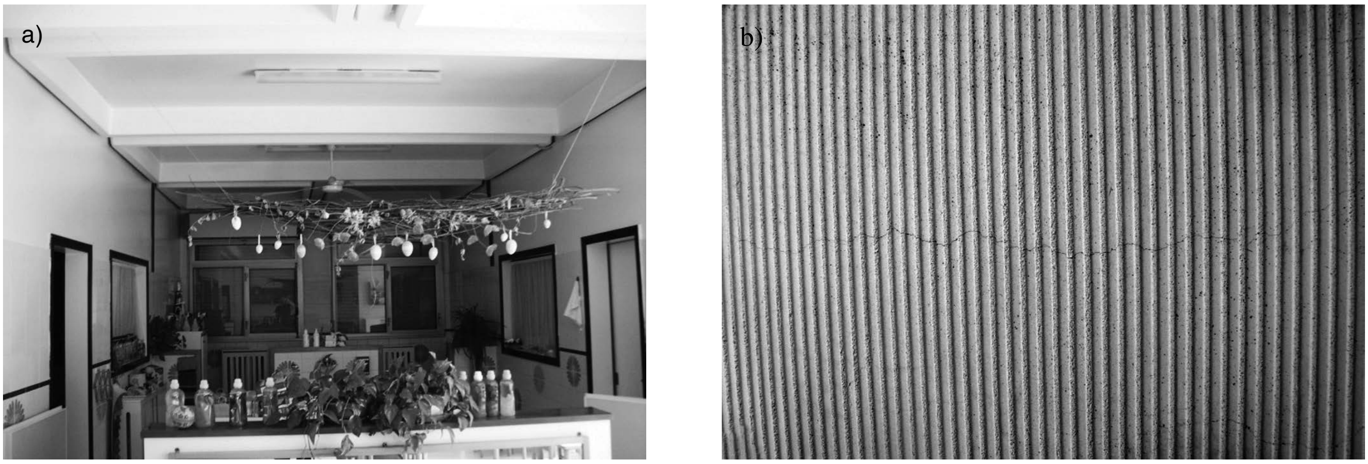


Fig. 24. *Internal view of the nursery (a) and horizontal cracks into a precast r.c. panel (b).*
Vista interna dell'asilo (a) e fessura orizzontale in un pannello in c.a. prefabbricato (b).

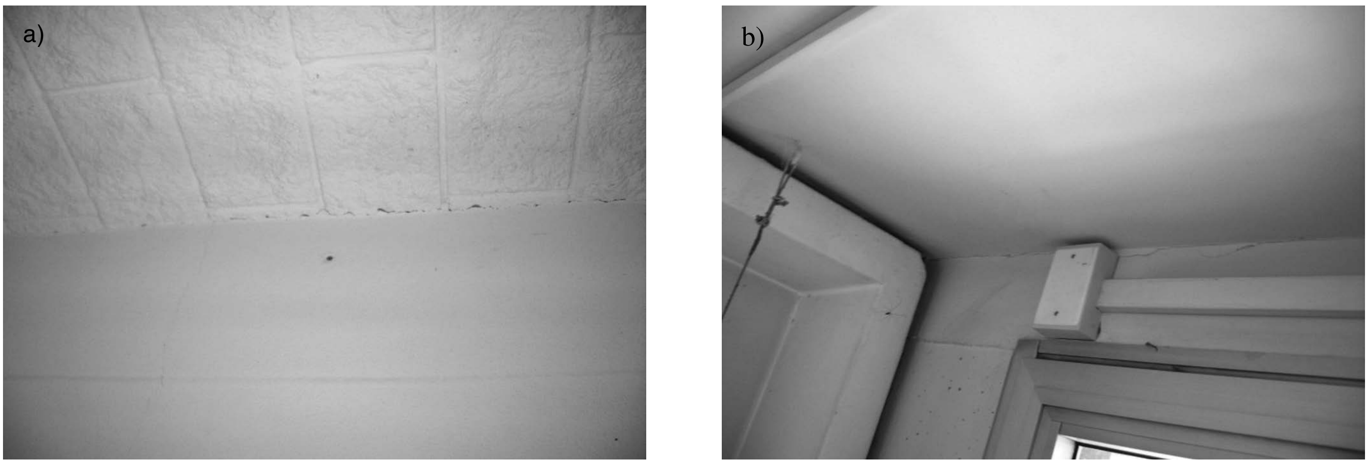


Fig. 25. *Wall-floor cracks (a) and small vertical damage between orthogonal walls (b).*
Fessure parete-soffitto (a) e leggero danneggiamento tra pareti ortogonali (b).

distance among two adjacent buildings, the main damages have been detected there. In fact, important plaster cracks have been observed both among adjacent columns (Fig. 29) and on the floor (Fig. 30a), as well as horizontal cracks have been recorded on the classroom pavement (Fig. 30b) close to the structural joint.

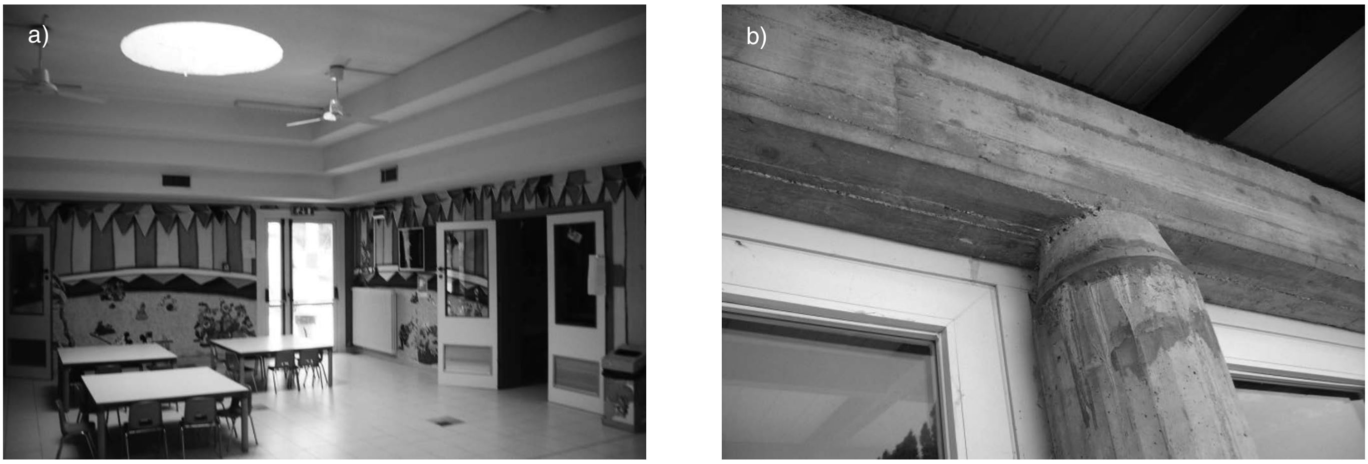


Fig. 26. *The nursery of the "Margherita" school building block (a) and a view of the beam-to-column joint (b).*
L'asilo dell'edificio scolastico «Margherita» (a) e una vista di un giunto trave-colonna (b).

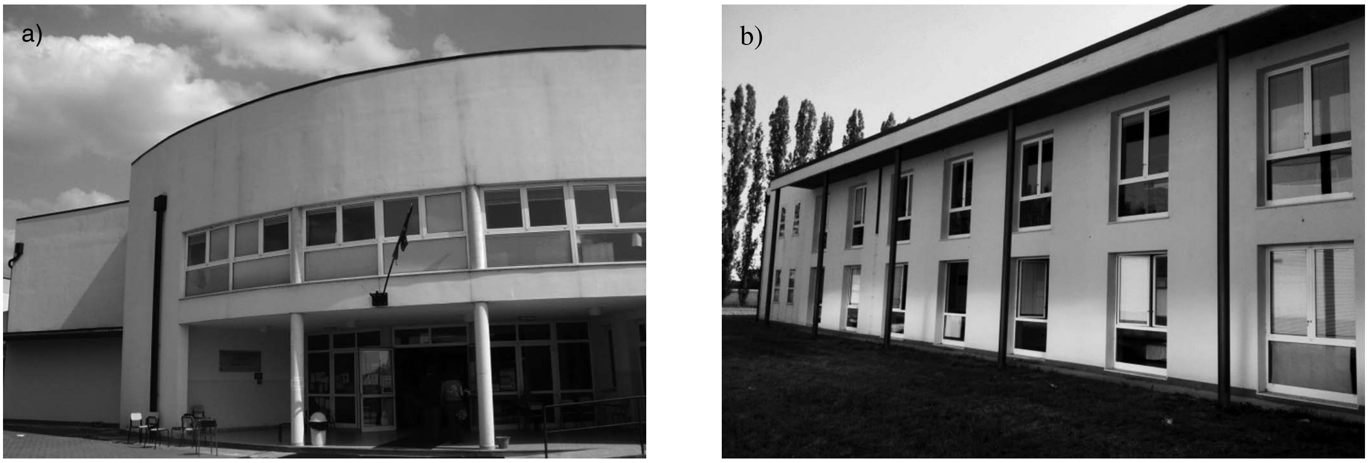


Fig. 27. *External views of the "Bonati" secondary school.*
Vista dell'esterno della scuola media «Bonati».

Fig. 28. *The "Bonati" secondary school: connection construction between school and gym (a) and plan view with indication of structural joints (b).*
La scuola media «Bonati»: collegamento tra scuola e palestra (a) e pianta dell'edificio con indicazione dei giunti strutturali (b).

After earthquake, despite detected damages, the building has been used as strategic construction in order to host homeless people.

4.4. *Gym building of the "Bonati" secondary school*

The gym building of the "Bonati" secondary school has a precast r.c. structure composed of beams simply

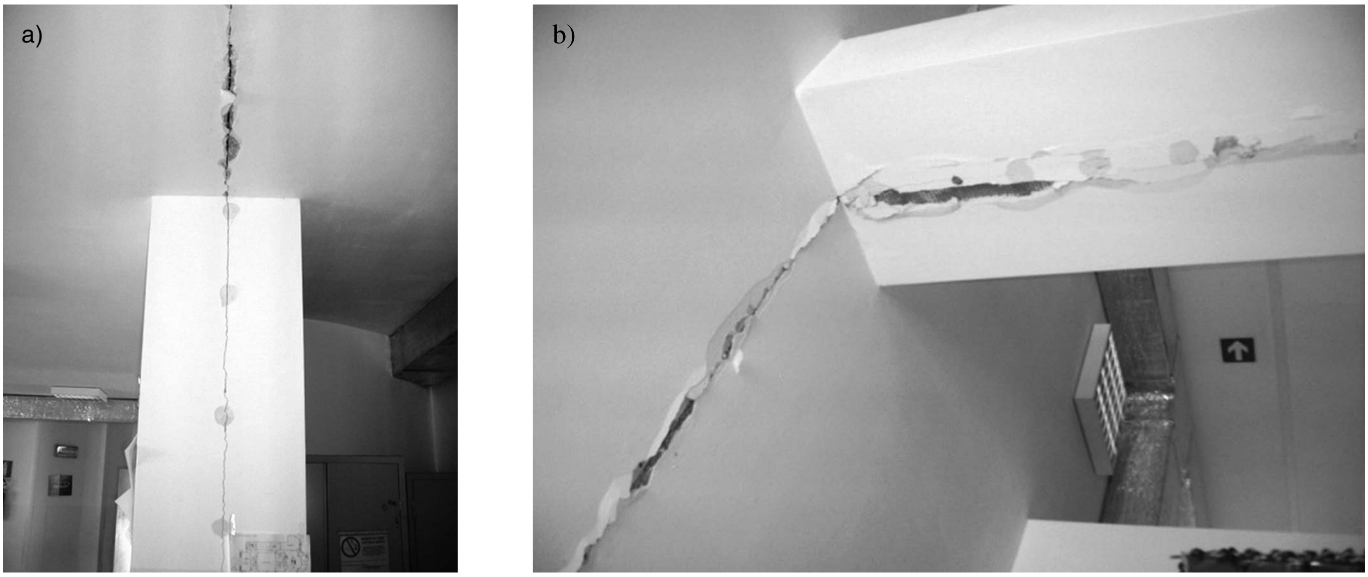


Fig. 29. *Vertical crack along the structural joint.*
Fessura verticale lungo il giunto strutturale.

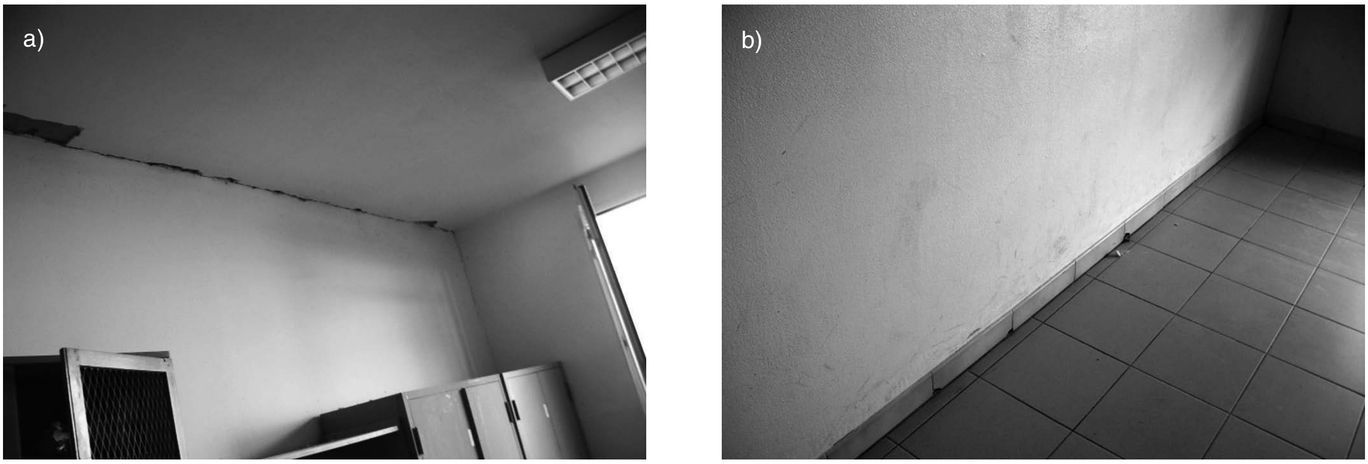


Fig. 30. *Cracks on the floor intrados (a) and extrados (b).*
Fessure all'intradosso (a) ed all'estradosso (b) delle solette.

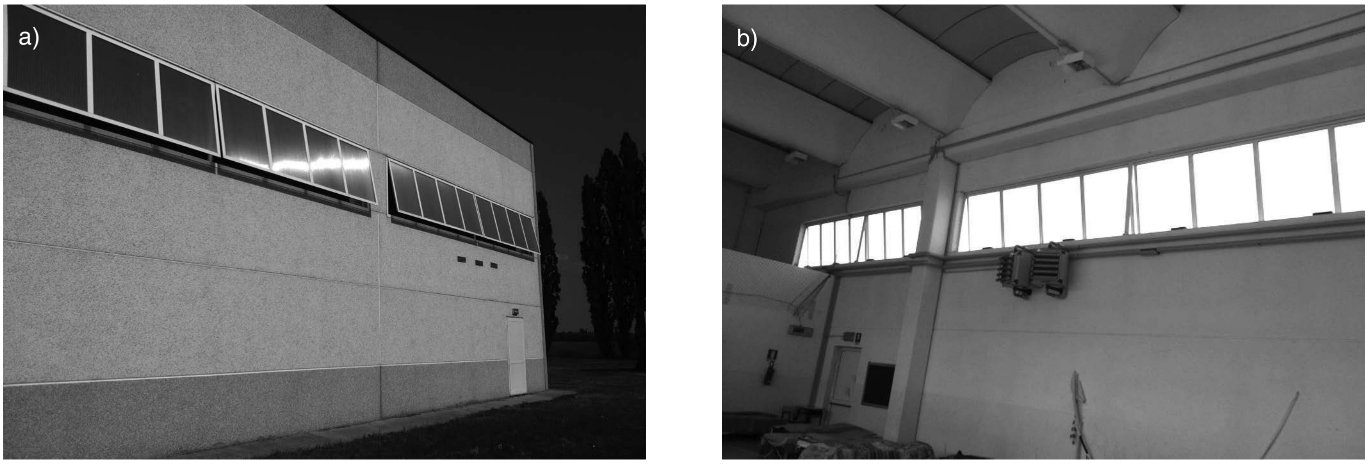


Fig. 31. *External (a) and internal (b) views of the gym building of the "Bonati" secondary school.*
Vista esterna (a) ed interna (b) della palestra della scuola «Bonati».

supported to columns and with prefabricated panels as claddings (Fig. 31).

Considered as a strategic building, the gym has cladding panels significantly damaged. In fact, some

Fig. 32. *Column-panel detachment (a) and vertical crack due to hammering effect among adjacent buildings (b).*
Distaccamento colonna-pannello (a) e fessurazione verticale dovuta a martellamento tra edifici adiacenti (b).

of them, badly connected to columns, have suffered an overturning out-of-plane mechanism which has produced detachment of panels from columns (Fig. 32a). In particular, a vertical crack developed along the entire building height at the panel-column interaction zone has been noticed. Also the hammering effect between gym and the connection structural body with the school building has been recorded (Fig. 32b).

As a whole, the observed damages, due to the absence of beam-to-column connections and the inefficiency of panel-to-column ones, make building susceptible to undergo severe damage under future earthquake, so to require appropriate seismic retrofitting interventions able to improve their global behaviour.

5. **Conclusive remarks**

The damages observed within investigated school buildings have shown the typical deficiencies of such constructions: lack of wall-floor connections and high masonry wall slenderness for masonry buildings and lack of beam-to-column, beam-to-beam and column-to-wall connections for precast r.c. ones.

Nevertheless, the survey of the examined masonry buildings has shown that the major part of them suffered low damages due to both the effective connection among walls and their large area-to-height ratio, whereas precast ones exhibited high vulnerabilities and undesirable seismic performances due to the above described lacks.

Finally, the identified seismic deficiencies of investigated buildings have allowed to individuate some simple interventions to be appropriately used for their retrofitting.

In particular, the global seismic performances of masonry buildings can be improved by the following interventions:

– Steel or r.c. tie-beams, in order to make effective wall-to-wall and wall-to-floor connections [Modena, 2007] (Fig. 33);

– Steel or r.c. jacketing of masonry walls, to be used when they are not able to sustain applied loads [Mazzolani, 2008] (Fig. 34).

On the other hand, helpful seismic retrofitting interventions for precast r.c. buildings are:

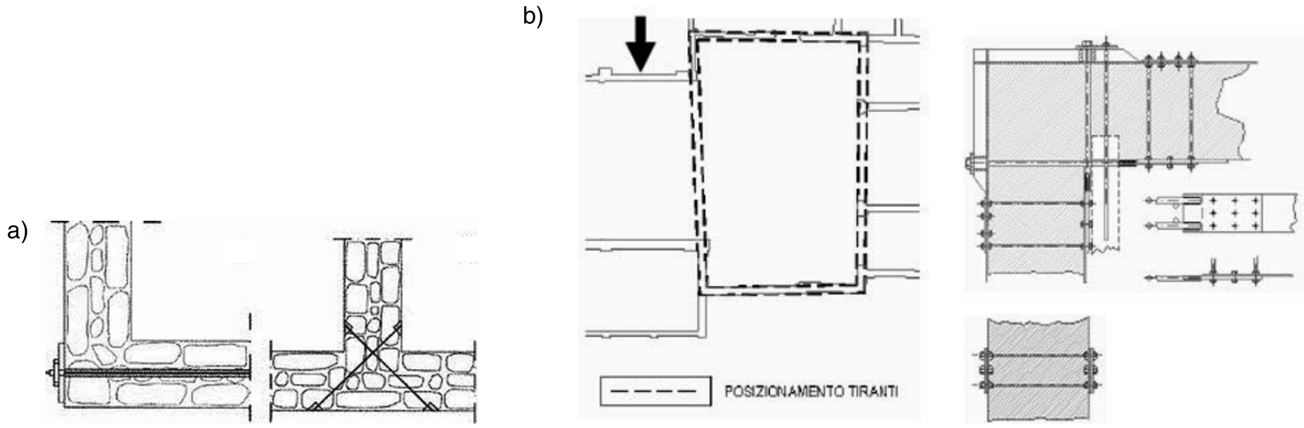


Fig. 33. *Steel tie-beams for wall-to-wall (a) and wall-to-floor (b) (Modena, 2007).*
Collegamenti metallici tra muri (a) e muri-orizzontamenti (b) (Modena, 2007).

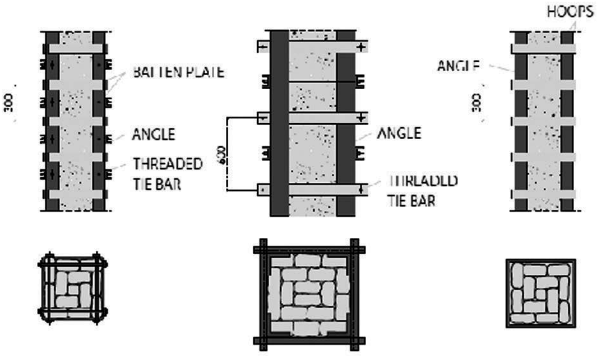


Fig. 34. *Steel jacketing of masonry columns* [*Mazzolani, 2008*].
Cerchiatura metallica di colonne in muratura (Mazzolani, 2008).

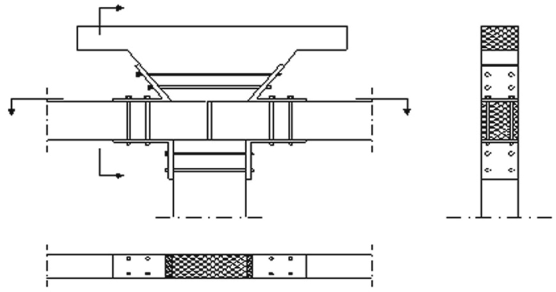
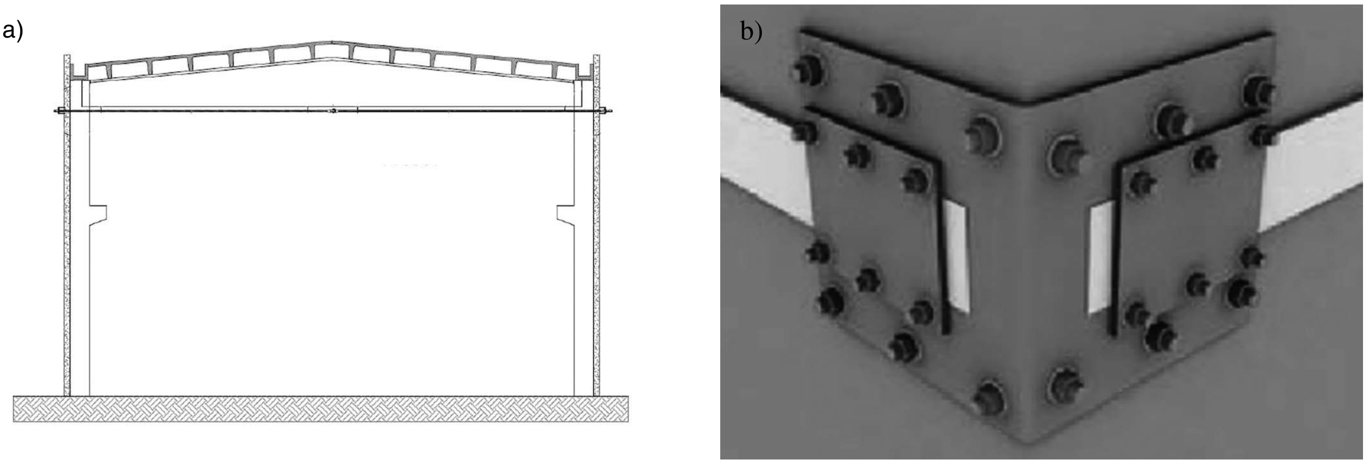


Fig. 35. *Beam-to-column and beam-to-beam steel connections for precast r.c. buildings.*
Connessioni trave-colonna e trave-trave per edifici in c.a. prefabbricati.

a)



b)

Fig. 36. *Steel systems for column-to-panel connections of precast r.c. buildings.*
Sistemi metallici per connessioni colonna-pannello di edifici in c.a. prefabbricati.

– beam-to beam and beam-to-column connection systems, based on the use of steel angles and bolts, whose dimensions and numbers should be determined case by case (Fig. 35);

– pre-stressed steel tie-beams [Workgroup on seismic usability of industrial buildings, 2012] (Fig. 36a) or jacketing with steel strips, angles and bolts (Fig. 36b), for connecting columns and panels each other.

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RIASSUNTO ESTESO

Analisi di danno di edifici scolastici a seguito del sisma dell'Emilia Romagna del 2012

A. Formisano

Il problema dell'analisi della sicurezza sismica degli edifici scolastici è stato molto sentito a partire dal tragico collasso della scuola "Francesco Iovine" di San Giuliano di Puglia. Sebbene gli indirizzi normativi abbiano da quel momento richiesto la valutazione della vulnerabilità sismica di tale categoria di edifici, tale attività investigativa non è stata condotta ancora in maniera esaustiva.

Infatti, in occasione del terremoto abruzzese del 2009, si sono registrati ingenti danni sia negli edifici scolastici in muratura che in quelli in c.a..

Nella memoria vengono riportati i risultati delle verifiche di agibilità effettuate dalla squadra n.166, costituita nell'ambito del Consorzio Universitario Reluis per fornire il proprio supporto per le verifiche di agibilità degli edifici colpiti dal sisma Emiliano del 20 e 29 Maggio 2012, su edifici scolastici in muratura e cemento armato ricadenti nel territorio dei comuni di San Pietro in Casale (BO), Bondeno (FE) e Bomporto (MO).

Tutti gli edifici investigati, sia del tipo in muratura che in c.a., (ordinario e prefabbricato) presentano schemi strutturali e dettagli costruttivi che non rispettano le disposizioni della normativa sismica vigente.

I danni registrati hanno evidenziato le tipiche lacune di tali costruzioni: assenza di collegamenti pareti-solai ed elevata snellezza dei maschi murari negli edifici in muratura; assenza di collegamenti trave-colonna, trave-trave e colonna-pareti di tamponatura in quelli in cemento armato prefabbricato.

Nonostante le descritte deficienze, gli edifici in muratura hanno evidenziato dei danni molto contenuti grazie al buon grado di ammorsamento fra pareti ortogonali e l'elevato rapporto fra l'area coperta dall'edificio e l'altezza dello stesso.

D'altro canto, gli edifici prefabbricati in c.a. hanno mostrato un'elevata vulnerabilità sismica a causa delle sopra descritte deficienze.

Pertanto, il comportamento degli edifici esaminati ha consentito di individuare alcuni semplici interventi finalizzati al loro adeguamento sismico.

In particolare, è possibile migliorare le performance degli edifici scolastici murari oggetto di indagine mediante i seguenti interventi basati sull'impiego dell'acciaio:

– Inserimento di catene metalliche o cordoli per migliorare i collegamenti fra le pareti e fra le pareti e gli impalcati.

– Incamiciatura di pareti murarie mediante membrature metalliche, allo scopo di incrementare la capacità portante delle stesse.

Per gli edifici prefabbricati in c.a. possono essere invece adottate le seguenti tecniche di adeguamento sismico che sfruttano le potenzialità applicative della carpenteria metallica:

– Sistemi di collegamento trave-trave e trave-colonna, da realizzare mediante squadrette e bulloni di acciaio.

– Catene metalliche pre-tese o confinamento mediante piatti, squadrette e bulloni di acciaio, per consentire un efficace sistema di collegamento fra le colonne ed i pannelli di tamponatura.