Key Engineering Materials Vol. 624 (2015) pp 106-113
Online available since 2014/Sep/12 at www.scientific.net
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doi:10.4028/www.scientific.net/KEM.624.106

Submitted: 12.06.2014
Revised: 12.06.2014
Accepted: 13.06.2014

Seismic retrofitting by FRP of a school building damaged by Emilia-Romagna earthquake

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Keywords: Emilia-Romagna earthquake, school building, 3Muri model, non-linear analysis, retrofitting interventions.

ABSTRACT: A school building, located in Bomporto (Modena, Italy) and hit by the Emilia-Romagna Italian earthquake in 2012, has been investigated in the paper. The seismic vulnerability of the building has been evaluated by means of non-linear static analyses, which have been carried-out through the 3MURI calculation program. The comparison between the damage state produced by the earthquake and the simulation results put in evidence the reliability of the numerical analysis. On the basis of the detected seismic deficiencies of the damaged building, a structural reinforcement intervention of masonry walls has been designed by means of either FRP strips or steel ones. Finally, a parametric analysis by varying the material and the geometrical configuration of the FRP intervention (width and spacing of the strips) has been performed with the purpose to identify, through a cost-to-benefit comparison, the optimal retrofitting solution.

The Emilia-Romagna earthquake

In May 2012, two major earthquakes hit the Emilia-Romagna region in northern Italy. They started on Sunday 2012 May 20th and Tuesday 2012 May 29th and affected the provinces of Ferrara, Bologna, Modena and Reggio Emilia [1].

These earthquakes happened in the Po plain, a not very active seismic zone for Italian standards, which assumed for it a low to moderate hazard, but with a very high exposure. Previous seismic events were dated in 1346, where a magnitude 5.8 earthquake took place approximately at the location of the 2012 May 29th event, and from 1561-1574, where a sequence of 4 events was felt with intensity greater than 7 in the region, with the largest being the November 1570 event of a very shallow depth and magnitude 5.5 (EMS=7.5), occurring about 40 km east of the 2012 May 20th event [2]. A repetition of this event, could lead to even larger damage than that of the recent earthquakes, depending on the proximity of its epicentre to the city of Ferrara.

The first earthquake, registering magnitude 5.9, struck in the Emilia-Romagna region, about 36 kilometres (22 mi) north of the city of Bologna, at 04:03 local time (02:03 UTC). The epicentre was between Finale Emilia, Bondeno and Sermide. It was followed by several aftershocks, two having a magnitude of more than 5. From this earthquake 7 fatalities (4 direct, 3 indirect (heart attacks)), around 50 injured, 6000 homeless and 400-500 million Euros losses (0.3% of Emilia-Romagna's GDP) were recorded.

The main shock of the second earthquake, having a magnitude 5.8, happened at 9:00 a.m. and was also followed by two events of more than 5 magnitude on the same day. It caused an additional twenty deaths and widespread damage, particularly to buildings already weakened by the May 20th earthquake. The epicentre was in Medolla, at a depth of about 10 kilometres. From this second seism 17 fatalities, 350 injured, 9000 additional homeless and losses exceeding those of the first event (>500 million Euros) were detected.

Therefore, for both earthquakes, whose seismic sequences are reported in Fig. 1, felt intensities exceeded the value of 7 on the Modified Mercalli Scale, having the highest value equal to 12.

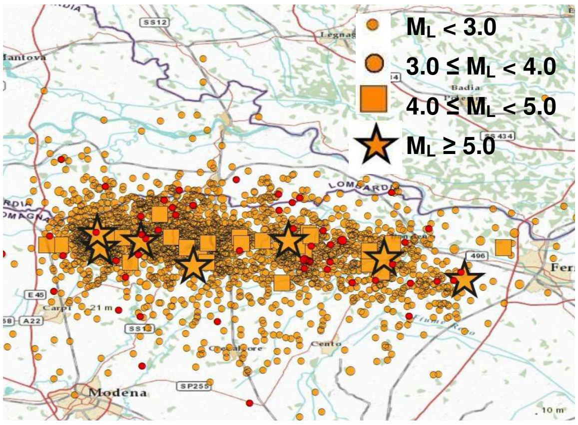


Fig. 1. Seismic sequence of Italian Emilia-Romagna earthquakes
(National Institute of Geophysics and Volcanology - INGV source)

The events listed above are located along an E-W trending line 40 km north of Bologna and have similar reverse thrust type source mechanisms. This indicates that they may lie on the same active fault, the so-called Mirandola fault. This is a 'blind fault', as it is covered by sediments of the Po plain and thus not visible at the surface. It was formed as a result of the NS-convergence between the African and Eurasian tectonic plates, which occurs at a rate of roughly 1 cm / year. The rather complex interplay between these plates and the Adriatic microplate lead to flexuring of the crust and N-verging seismically active faults in the Southern Po plain. As a consequence, the Mirandola blind thrust was identified as a potential source for a M>5.5 earthquake, as it was verified in 2009 May.

Some of the smaller towns close to the epicentres saw massive breakages. The earthquakes caused heavy damage to rural and industrial buildings, as well as to buildings and historical monuments, quantified as 12 billion and 202 million euro. Definitively, damage estimated was higher than one provoked by L'Aquila earthquake [3, 4]. Even the school buildings were hit by the fury of earthquakes, with 223 buildings partially or severely damaged and about 71000 students involved. For this reason, in the present paper attention is directed to this type of buildings, for which a case study is herein presented with the purpose to design, starting from seismic assessment non-linear static analyses, effective retrofitting interventions by FRP.

The investigated school building

According to a post-seismic investigation activity performed on the Emilia-Romagna school buildings [5], the masonry constructions located there, designed to withstand gravity loads only, have structure schemes and construction details not in line with the provisions of the Italian new seismic code on constructions (M.D., 2008) [6]. All the schools examined in [5] showed similar seismic deficiencies, such as poor connections among walls and between walls and floors, but exhibited a good overall behaviour that prevented their collapse under earthquake.

The economic-social importance of school buildings and, therefore, the need to evaluate their seismic performance in order to avoid failures under earthquakes, was already taken into account by Authors [7] within the EU COST Action C26 "Urban Habitat Constructions under Catastrophic Events, which was concluded in 2010 with a final conference in Naples**.** In this framework, the Vesuvius area was selected as a pilot case study and Torre del Greco, one of the most populated town of that zone, was chosen for the seismic and volcanic vulnerability of masonry, r.c. and mixed masonry-r.c. schools [8, 9], whose investigation was carried out through both a quick survey activity performed from outside and detailed numerical investigations.

As in the case of the Vesuvius area, the study on the seismic vulnerability of Emilia masonry schools was conducted with reference to a case study representative of the local construction technique.

The selected building was built around the second half of the nineteenth century and is placed in a large park site in Solara, a fraction of Bomporto located in the district of Modena. In principle, the building was the manor house of the Luppi family. In the early '70s the municipality of Bomporto bought its property aiming at transforming it into a school through restructuring works started in 1973. For the architectural merit, the school is currently covered by the bond of Superintendence for Cultural and Architectural Heritage. The structure is characterized by the typical two-head walls sustaining horizontal structures made of beams with deformable slab without tie beams and chains.
The building is spread over two levels (Fig. 2) plus an attic and has a total height of about 9.94 m with respect to the foundation level. Some pictures of the school facades are depicted in Fig. 3.
After earthquake, in the building few damages among walls and floors were detected, but vertical cracks in masonry walls (Fig. 4) and horizontal cracks in some vaults were noticed.

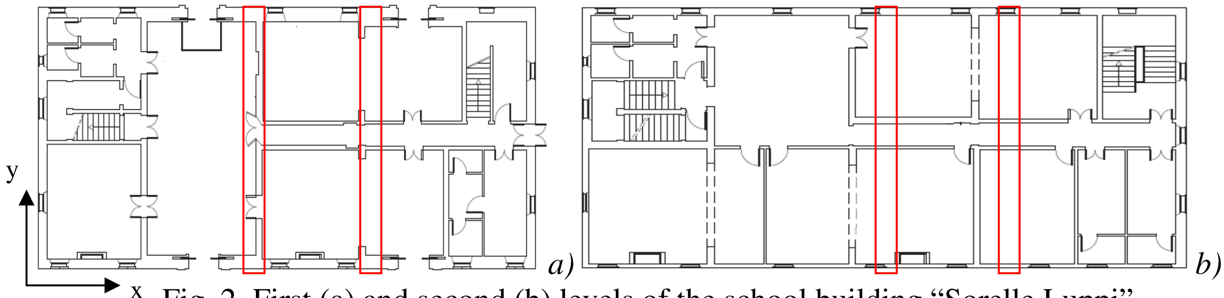


Fig. 2. First (a) and second (b) levels of the school building “Sorelle Luppi”

Fig. 3. The main facades of the school building "Sorelle Luppi"

Fig. 4. Details of some internal and external cracks

Numerical seismic assessment and retrofitting analyses

The numerical activity on the inspected school has been carried out with the 3Muri calculation program, which uses a three-dimensional equivalent frame as the reference model for masonry constructions, where the walls are interconnected with horizontal partitions on the floors. In particular, the walls can be schematized as a frame, in which the resistant elements (piers and spandrel beams) are assembled with rigid nodes, which are parts not susceptible at damages under earthquakes. The spandrel beams can be modelled only if they are adequately toothed by the walls, supported by structurally efficient architraves, and, if possible, exhibiting a strut resistant mechanism.

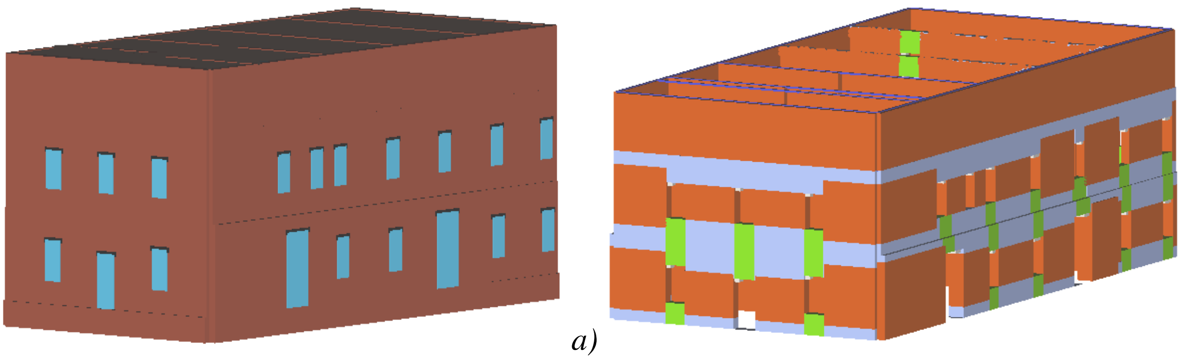
From the observation of masonry buildings damaged by seismic events, two different damage mechanisms, namely shear (diagonal and sliding) and compression-bending, emerge.

The shear mechanism is described by the Mohr-Coulomb model which, through the classic elasto-plastic behaviour of masonry panels, is able to collect their progressive degradation in terms of strength and rigidity. This constitutive law adopted for masonry panels, considered as non-linear beams, can be therefore used for pushover analyses. The ultimate shear deformation is based on the maximum drift value expected in the code, equal to 0.4%.

On the other hand, the compression-bending mechanism is rigorously examined, considering the effective redistribution of the compression due to both section choking and reaching of the maximum compression resistance. The last displacement associated with the compressive-bending mechanism is based on the maximum drift value expected for this mechanism, that is 0.6%.

The execution of seismic non-linear analysis involves the use of a specified algorithm, where a mixed force - displacement is imposed to the structure, starting from the beginning of the analysis, in order to ensure equilibrium and evaluate its residual strength with increasing deformation level.

So, in the initial analysis phase the structure geometrical model is defined (Fig. 5a) and, consequently, the mechanical properties are assigned to masonry elements. The computational model (Fig. 5b) is obtained by dividing the walls into macro-elements, which are representative of deformable masonry piers and spandrels and rigid joints not prone to be damaged under seism.



a) *b)*

Fig. 5. The school geometrical (a) and computational (b) models setup with 3Muri

Afterwards, 24 pushover analyses on the study building have been performed by considering, as stated by the current Italian code, all the possible variable eccentricities of the barycentre, equal to 5% of the maximum building side perpendicular to the earthquake direction, and the usual two lateral force distributions, proportional to either masses or first vibration mode displacements. On the basis of the poor information on the building, a limited knowledge factor with a confidence factor of 1.35 has been assumed for structural analysis.

In Fig. 6 the worst pushover curves in directions x and y, where the maximum displacements required by the Life Safety limit state earthquake are 11.8 mm and 11 mm, respectively, are plotted. Moreover, in Fig. 7, the damage state of the school corresponding to the above analyses, with reference to the maximum displacement attained (last analysis step), is represented together with the crack pattern exhibited under earthquake. From the comparison it is apparent the capacity of 3Muri to predict the earthquake effects with a good accuracy.

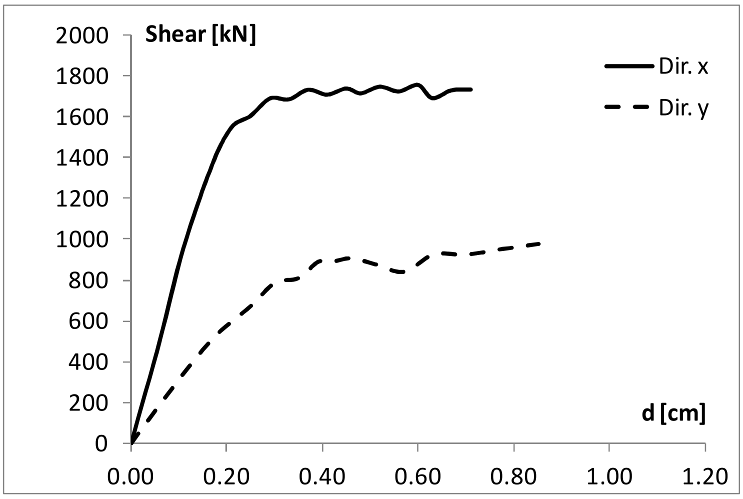


Fig. 6. Pushover curves related to the worst analyses in directions *x* and *y*

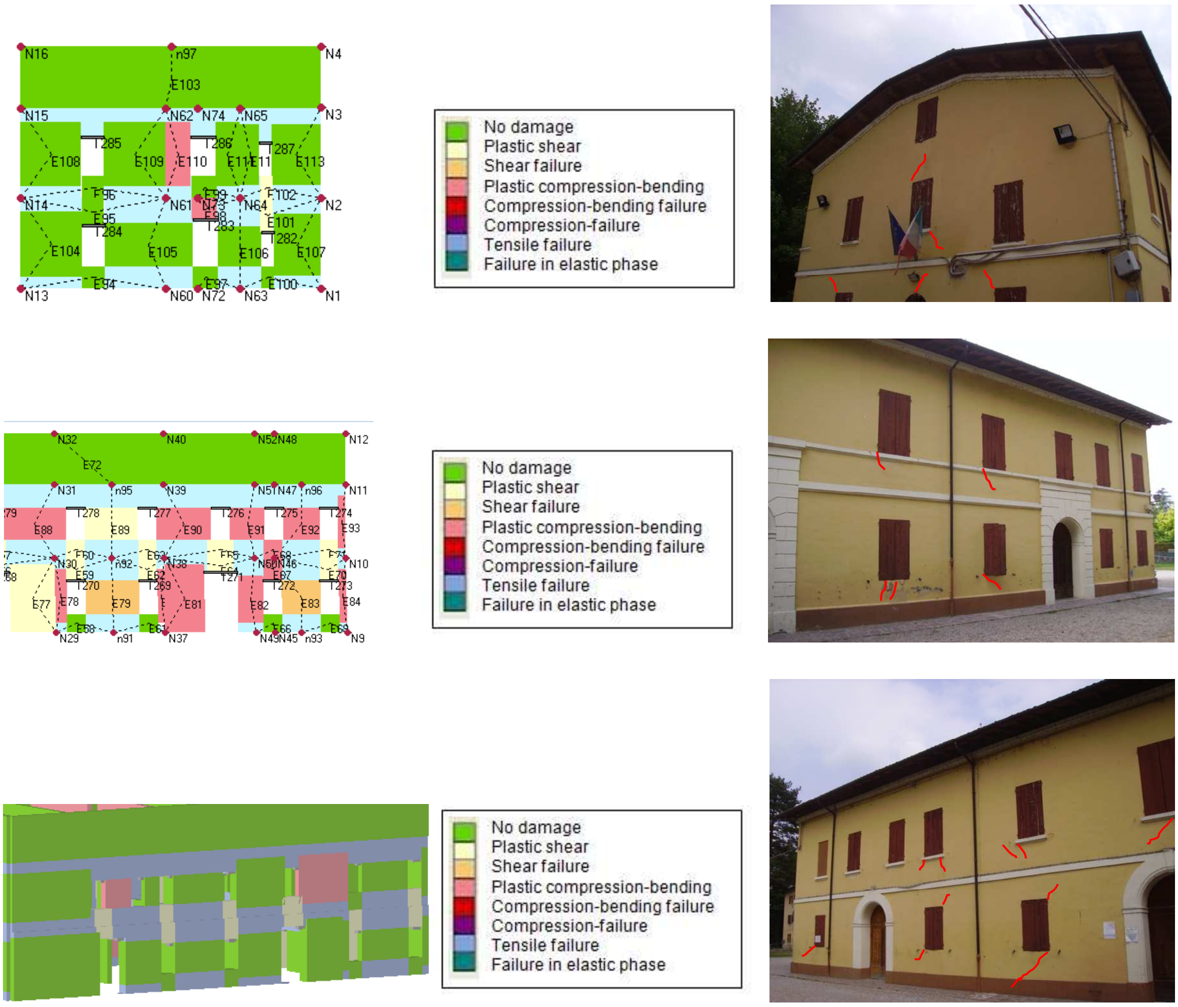


Fig. 7. Comparison between numerical damages deriving from pushover analyses and real ones

From analysis results, considering that demand displacements are greater than capacity ones, it is evident that the building needs structural consolidation interventions. Therefore, the two longitudinal walls and the two transverse ones surrounded with a red rectangle in Fig. 2 have been reinforced at the first two levels with Fibre-Reinforced Polymer (FRP) materials under form of bidirectional strips having thickness of 0.167 cm, width of 20 cm and pitch of 50 cm (Fig. 8a). The used fibre-reinforced materials have the following mechanical properties: E = 280000 MPa, f_{fd} = 4100 MPa and ε = 1.46 %.

The use of these bidirectional strips has satisfied all seismic analyses, conferring to the building a better seismic performance in terms of strength and, especially, of ductility. Thereafter, in order to ensure the same invasiveness and, more or less, the same global response drawn with the use of composite materials, a further structural reinforcement intervention through bidirectional S275 steel strips, fixed to the walls by steel bars and having thickness of 2 mm, width of 7 cm and the same pitch of FRP strips, has been designed. Subsequently, steel strip thickness has been changed from 2 mm to 10 mm in order to individuate, through a sensitivity analysis, the best thickness solution.

The comparison among retrofitting curves is shown in Fig. 8b, where it is noticed that 7 mm thick strips are the optimal solution, they allowing to increase significantly the building base shear with respect to that achieved with FRP and with lesser cost than 10 mm thick strips one.

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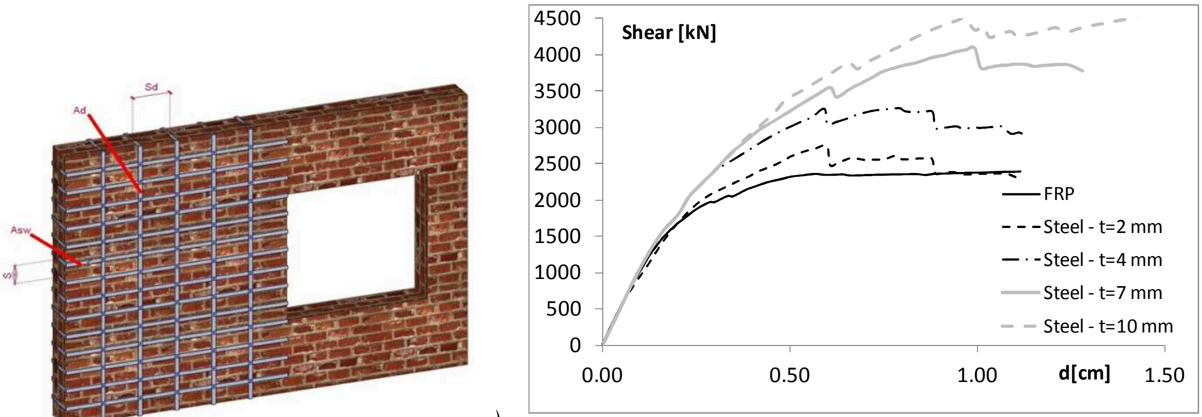

a) *b)*

Fig. 8. Retrofitting intervention with bidirectional strips (a) and comparison among building capacity curves with different reinforcing interventions (b)

Parametric analysis: the choice of the best FRP retrofitting solution

In the final research phase, a parametric analysis on FRP strips with different geometry has been carried out with the purpose to individuate the best retrofitting solution.

In particular, the strip thickness (0.167 cm) has been considered as a fixed parameter, whereas four different strip widths *w* (5, 10, 15 and 20 cm) and five different pitches *p* among strips (20, 40, 60, 80 and 100 cm) have been considered as random parameters.

The combination of these variable geometrical factors has led towards 20 analyses, whose results have been compared each other in terms of a risk index. In particular, this index, prescribed by the Italian OPCM 3362 code (2004) [10], is called α_{uv} and is considered as an indicator of the building collapse risk. It is calculated as the school capacity acceleration at the Life Safety limit state over the acceleration demand, that is the site PGA. Values of α_{uv} less than one are related to buildings that do not withstand the earthquake actions, whereas if they are equal or greater than one the building can be considered as totally retrofitted from seismic point of view.

In Fig. 9 the seismic risk index has been calculated for different retrofitting solutions with FRP strips. First of all, from these pictures it is apparent that all solutions provide index greater than one in direction *x* only, whereas in direction *y* some interventions do not confer to the school the capacity to sustain the design seism. Moreover, it is noticeable that in direction *x* the strip width increase gives an increase of the seismic performance, while in direction *y* all considered strips provide more or less the same seismic safety grade. This is due to the greater extension of the retrofitting intervention in direction *x* than in direction *y*. Therefore, the optimal strip width is equal to 10 cm in direction *x* and 5 cm in direction *y*, since these solutions allow to achieve the maximum benefit with the lesser cost.

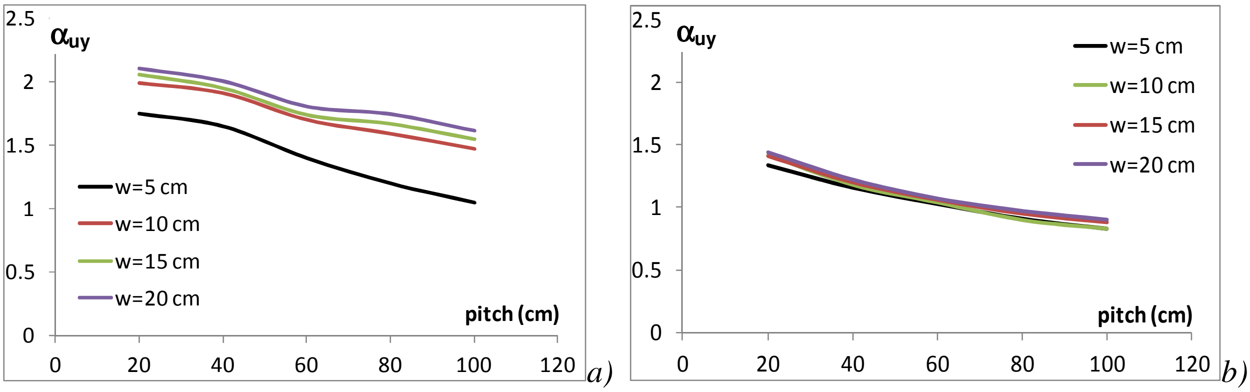

Fig. 9. Seismic risk index vs. pitch among strips for the school retrofitted with different FRP strips in directions *x* (a) and *y* (b)

Furthermore, in Fig. 10 the seismic risk index has been plotted versus the strip width in order to individuate the optimal strip pitch to be used in the school building two directions. From these pictures it appears that in directions *x* and *y* the minimum pitch able to attain a unitary seismic risk with the lesser cost is 100 cm and 60 cm, respectively.

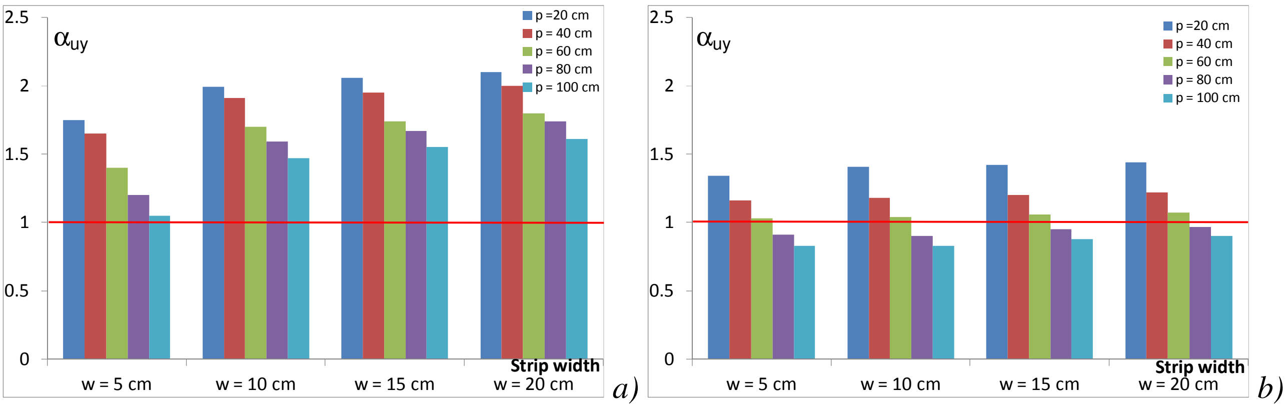

Fig. 10. Seismic risk index vs. strip width for the school retrofitted with different FRP strips in directions *x* (a) and *y* (b)

Therefore, the parametric analysis has provided as best retrofitting solutions 10 cm wide strips with pitch of 100 cm and 5 cm wide strips with pitch of 60 cm in the school building directions *x* and *y*, respectively.

In conclusion, considering that the school seismic risk indexes before retrofitting are 0.61 and 0.77 in directions *x* and *y*, respectively, the interventions with FRP have provided an increase of seismic performance higher in direction *x* (65%) than in direction *y* (30%).

Summary

After the 2012 May 20th and 29th Emilia-Romagna seismic events, usability check and seismic analysis on a masonry school building placed in Bomporto (neighbourhood of Modena, Italy), carried out under the support of both the ReLUIS Universities Consortium and the Italian Civil Protection Department, have been reported in the current paper.

Non-linear static seismic analyses on the inspected building have been conducted by means of the 3Muri calculation program. The achieved results have shown that the used software is able to foresee well the damages occurred under earthquake.

Later on, the analysis of the seismic deficiencies on the school has led to design and apply two different retrofitting solutions for masonry walls, namely jacketing with fibre composite materials and reinforcement with two-direction steel strips. The comparison between the retrofitting building capacity curves has demonstrated that steel strips allows to attain the same ductility and a strength level greater than that offered by composite fibre strips. Moreover, a sensitivity analysis conducted on steel strips with different thicknesses has provided, as the best solution, the one characterised by 7 mm thick elements.

Finally, a parametric analysis on FRP strips with different width and spacing has been carried out with the purpose to identify the best retrofitting solutions, represented by 10 (width) x 100 (pitch) cm and 5 (width) x 60 (pitch) cm strips in the directions *x* and *y* of the building, respectively.

Acknowledgements

The authors thanks the economic support provided by the ReLUIS-DPC project (2010-2013) for the usability check of the investigated school building.

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