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DESIGN OF THE SEISMIC RETROFIT OF A SCHOOL IN ACCORDANCE TO A LIFE CYCLE THINKING APPROACH

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ABSTRACT

The public consciousness of the seismic risk is continuously increasing, although the damage on existing and older buildings due to earthquakes is still high, due to a former structural design not accounting for the latest knowledge achieved in the seismic field. This is particularly true considering the damage recorded in the last earthquakes that hit Central Italy in August and October 2016.
The paper deals with the repair actions required in the elementary school of Pievebovigliana (Macerata-Italy) after the aforementioned seismic events. The school is a one-story building characterized by an irregular plan layout; masonry walls with regular blocks are the main supporting structure. An attempt is made to adopt a Life Cycle Thinking approach in the design of the intervention. The energy efficiency and environmental impacts related to different types of retrofit intervention are assessed. The retrofit interventions are conceived as carried out from the outside and using prefabricated solutions to minimize the building downtime and to facilitate the construction sequence. The structural retrofit is designed to reduce the damage to the existing masonry walls in the case of seismic events.

Keywords: Life Cycle Thinking; Integrated retrofit; Sustainability

1. INTRODUCTION

In the last years, the renovation of existing reinforced-concrete (RC) buildings has become a very important issue in order to meet international targets of energy saving and emission control and to foster safety amongst European communities. These buildings are characterized by anonymous architectural features, living discomfort and high impact on the environment (Marini et al. 2014). They often show material decay and inherent static and seismic vulnerability. In addition, damage assessment, buildings retrofit and repair actions have become essential after the earthquakes that hit Italian communities in recent years. In this contest, energy renovation and structural retrofit became essential actions that need to be tackled together.
This paper examines the school of Pievebovigliana (Macerata-Italy) which has been damaged by the

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earthquakes that hit Central Italy in August and October 2016. Demolition and reconstruction, if not mandatory, have a considerable environmental impact (Preservation Green Lab, 2012) as well as leading to excessively time-consuming interventions and long disruption of the building activities. Even introducing the sole structural retrofit would outcome in inappropriate results if done without considering the interaction with energy and environmental impacts. Similarly, it has been shown (Belleri and Marini 2016) that neglecting seismic aspects in energy improvement interventions leads to significant environmental impacts. For these reasons, different retrofit techniques are evaluated herein following the principles of a holistic approach (Feroldi et al., 2014; Passoni, 2016; Labò et al., 2017; Marini et al. 2018) pursuing environmental sustainability, safety and resilience. In this way, Life Cycle Assessment (LCA) becomes an important decision tool to highlight benefits and drawbacks of each retrofit choice for the reference building.

2. REFERENCE BUILDING

The reference building is the elementary school of Pievebovigliana (Macerata-Italy), shown in an aerial view in Figure 1a and highlighted in red in Figure 1b. The building, extremely irregular in shape, consists of a central core with two additional non-symmetric hexagonal wings. The school is a one-story building in which the side pavilions are higher than the central core. The rectangular central part is approximately 25m x 10m, while the maximum diagonal lengths of the lateral blocks are 18m and 13m. The building has a pitched roof made by RC beams with hollow-core clay bricks as lightening material. The bearing structure is provided by two-leafs masonry walls, 25cm thick.

a) b)

Figure 1. a) Aerial view of the considered area; b) map extract with the reference building case in red.

2.1 Seismic improvement interventions over the years

In the late 90s, following the earthquake that hit the Marche region in 1997, a stiffening structure made of steel lattice beams (IPE 140) was assembled to provide a light diaphragm. This structure was placed at 3.10m above the ground level corresponding to the height of the spandrel beams. Details of the planar distribution and the anchorage system of the stiffening structure are shown in Figure 2. During this operation, ribbon windows along the north face were also closed and replaced by small windows to improve the walls in-plane capacity.

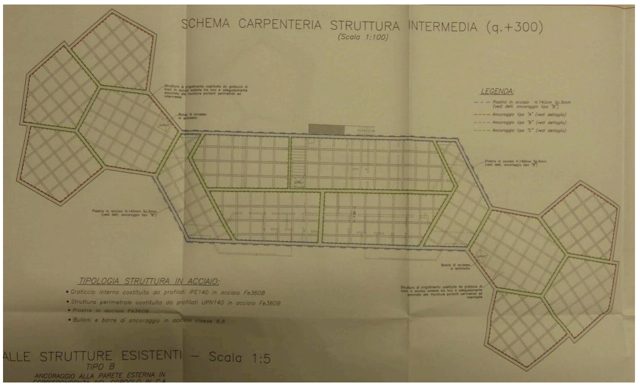

Figure 2. Stiffening Diaphragm representation. (Extract of the tables drawn up by the studio ACALE Srl e GLOBE Srl in: December 2016)

2.2 Post-Earthquake damage description

The data and figures analyzed refer to an inspection carried out on December 17, 2016. In particular, significant widespread damage on structural and non-structural elements was highlighted in the considered school. Diagonal cracks were evident in the main bearing walls. In the case of the perimeter walls, this mechanism led to the breakdown of the inner non-structural wall components and to bricks dislocation, while in the case of internal walls through cracks with amplitude wider than 1cm were recorded. Due to the dimensions of the masonry panels, the cracks had an angle less than 45° to the horizontal. During the inspection, damages on the partition walls and in the inner side of the perimeter walls were found. A detachment of the outer lining at the spandrel beam above an outer opening was also noticed. Few damages were highlighted in the roof and no apparent damage occurred in beams and columns. However, beam-column joints were not inspected. Similarly, the condition of the stiffening structure, which was not possible to inspect, needs to be verified. Finally, it is worth noting that the dislocation of the bricks compromised the opening of some doors and windows.

3. SEISMIC EVALUATION OF THE REFERENCE BUILDING

Following the Italian building code (NTC, 2008), the failure mechanisms of the masonry walls have been evaluated. These mechanisms, evaluated analytically, have been also compared with the available photographic documentation. The load demand, associated with the design earthquake, has been evaluated through a Finite Element Model of the building following a response spectrum analysis. Based on these results and on the capacity of the existing masonry walls, possible seismic and energy retrofit solutions have been proposed.
Finally, the environmental impact of each solution has been evaluated. Specifically, the purpose of this study is the comparison of the environmental impact between different retrofit solutions under a life cycle perspective.

3.1 Existing building model

The building has been modelled as a 3D structure through the software MidasGen (2015) as shown in Figure 3. Each masonry panel has been modelled with 2D elements (wall elements) considering its stiffness. The roof has been represented by “plate” elements with equivalent thickness in order to have the same weight of the roof itself. The roof has been considered rigid in the plan.

a)

b)

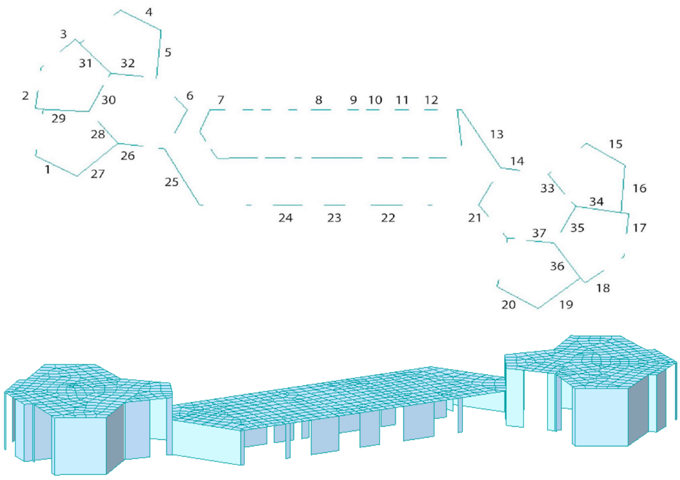

Figure 3. a) Projection of the Finite Element Model with wall panels numbers; b) Schematic representation of the Finite Element Model.

Regarding the masonry, the characteristics in Table 1 have been considered. These characteristics are in accordance with the values reported in Tab. C8A.2.1. of the application guidelines of the Italian Building code (D.M. 14/01/2008). The seismic demand on each wall was evaluated by means of a response spectrum analysis. In particular, the Life Safety Limit State of Pievebovigliana has been considered. Other data used to define the design spectrum are: soil category B, topographic category T_1, behavior factor q=1.5.

Table 1.f_m: Compressive Strength, τ_0: Shear strength, f_t: Tensile strength; γ_M: Partial safety coefficient.

Symbol	Magnitude
f_m	2.20 MPa
τ_0	0.03 MPa
f_t	0.05 MPa
γ_M	4.05

3.2 In-plane failure mechanism

The failure mechanisms of the masonry walls have been evaluated in accordance with the Italian building code (D.M. 14/01/2008); indeed, the failure mechanisms associated with axial-flexure interaction, sliding shear and diagonal shear failure have been considered according to the following equations:

$$M_u = \left(\frac{L^2 \cdot t \cdot \sigma_0}{2}\right) \cdot \left(1 - \frac{\sigma_0}{0.85 \cdot f_d}\right) \quad (1)$$

$$V_t = L' \cdot t \cdot f_{vd} = a \cdot t \cdot (f_{vk_0} + 0.4 \cdot \sigma_m) / \gamma_M \quad (2)$$

$$V_t = L \cdot t \cdot \frac{f_{td}}{b} \cdot \sqrt{1 + \frac{\sigma_0}{f_{td}}} \quad (3)$$

where M_u is the flexural capacity in the case of axial force (therefore the shear limit will be equal to M_u/h); L is the length of the wall; t is the thickness of the wall; L' is the length of the compressed

portion of the wall. σ_0 is the average compressive stress on the cross-section area; f_d is the design compressive strength of the masonry, f_{vk0} and σ_m are the characteristic shear strength without axial force and the normal strength due to the vertical loads, respectively. Regarding the diagonal shear, f_{td} is the tensile strength for diagonal cracking and b is the corrective coefficient determined by the ratio h/L (bounded by 1 and 1.5).
The comparison between some of the calculated mechanisms and the photographic documentation (inspection 12/17/2016) is reported in Tables 2, 3 and 4 and in Figures 4, 5, 6. From the comparison, analytical results match well with the actual failure mode experienced by the walls.

Table 2. Wall 16.

n°	Geometry and Loads		Mechanism
16	h	5.13 m	**Sliding Shear (45.94 kN)**
	L	4.37 m	
	t	0.25 m	
	b	1.18	Diagonal Shear (50.26 kN)
	k	1.00	
	N_{TOP}	175.2 kN	
	N_{BASE}	309.4 kN	Eccentric axial force (71.49 kN)

Figure 4. Wall 16. Photographic documentation

Table 3. Wall 35.

n°	Geometry and Loads		Mechanism
35	h	5.13 m	Sliding Shear (31.88 kN)
	L	3.11 m	
	t	0.25 m	
	b	1.50	**Diagonal Shear (23.63 kN)**
	k	1.00	
	N_{TOP}	121.3 kN	
	N_{BASE}	214.7 kN	Eccentric axial force (36.25 kN)

Figure 5. Wall 35. Photographic documentation

Table 4. Wall 17

n°	Geometry and Loads		Mechanism
	h	5.13 m	Sliding Shear (23.19 kN)
	L	2.17 m	
	t	0.25 m	
	b	1.50	Diagonal Shear (20.43 kN)
17	k	1.00	
	N_{TOP}	94.8 kN	
	N_{BASE}	156.2 kN	**Eccentric axial force (17.78 kN)**

Figure 6. Wall 17. Photographic documentation

3.3 Retrofit design

For the retrofit design, the most loaded wall (number 17) has been considered. The retrofit solution consists in an additional structural panel coupled with a thermally isolating system: either a precast RC panel (Retrofit Solution 1) or cross-laminated (XLAM) timber panel (Retrofit Solution 2). The new panel and the existing one are conceived to work in parallel. Subsequently, both the existing and the new additional panel are modelled as two springs in parallel (Figure 7): the final stiffness of the retrofitted wall is the sum of the individual stiffness of the new and existing panels. In this way, considering a load in the existing panel corresponding to 80% of its capacity as a safety factor, the thickness of the new additional panel has been determined. More precisely, the capacity of the selected wall is 17.8 kN, while the load demand obtained from the Finite Element Model is 66.8 kN.

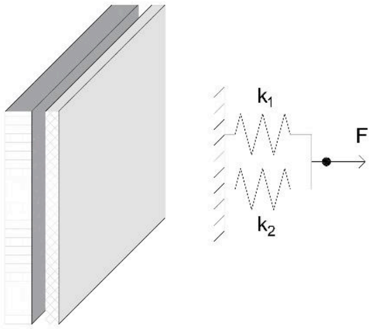

Figure 7. Wall representation like two springs in parallel

From the aforementioned assumptions, the lateral stiffness required by the additional panel is 3.7 times the stiffness of the existing one. Therefore, starting from the actual stiffness of the existing panel and according with the prescriptions of the considered building code, the thickness of the new panel can be directly evaluated. The resulting stratigraphy is shown in Figure 8 for both retrofit solutions.

In addition to the structural aspects, the improvement of the energy performance has also been addressed. Therefore, a limit transmittance for opaque surfaces equal to 0.32 W/m^2K has been imposed in accordance with Italian regulations for a building located in the climatic zone D (D.M. 06/26/2015). The stratigraphy shown in Figure 8 satisfy this limit. It is worth noting that, as far as the structural aspects are concerned, the RC panel meets the required stiffness by means of a lower thickness than the XLAM panel. On the other hand, the XLAM panel allows to reduce the thickness of the insulating material given its significantly lower conductivity compared to reinforced concrete.

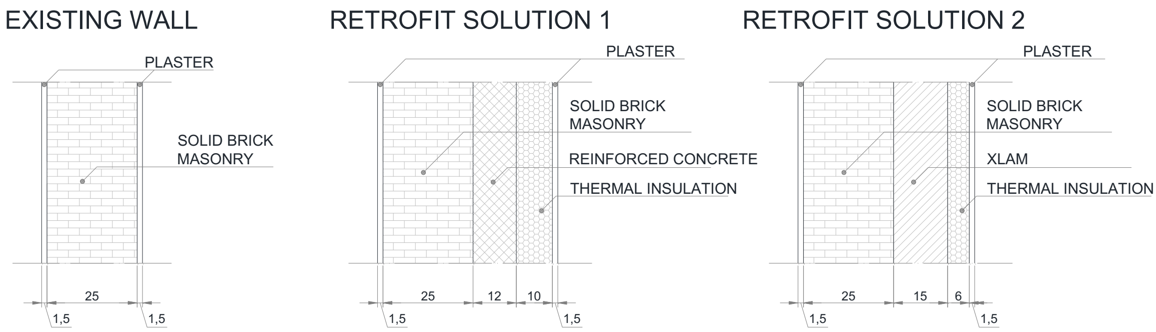

Figure 8. Stratigraphy of the existing wall and the retrofit interventions proposed.
Note: dimensions in mm.

4. LIFE CYCLE ASSESSMENT

The LCA methodology has been applied in accordance with the international standards of the ISO 14040 series (ISO 14040, 2006; ISO 14044, 2006) to assess the energy and environmental impact of the two retrofit solutions. A panel unitary surface has been evaluated with a "cradle to gate" approach, whose impacts are shown in Table 5. The specific impact related to the material of each retrofitting panel refers to the Ecoinvent environmental database (Frischknecht et al, 2007a) (Table 6). The Cumulative Energy Demand (CED) (Frischknecht et al, 2007b) has been used to estimate the primary energy consumption while the environmental impacts have been estimated using the characterization factors of the EPD 2013 method (SEMC, 2015).

Table 5. Energy and environmental impacts of the two panels.

Impact Category	Panel 1 R.C.	Panel 2 XLAM
Primary energy consumption (MJ)	506.13	2633.90
Global warming potential (100 years) (kg CO2eq)	68.02	52.68
Acidification (kg SO2eq)	1.13E-01	2.28E-01
Eutrophication (kg PO43-eq)	2.45E-02	8.68E-02
Photochemical oxidation (kg C2H4eq)	6.18E-03	1.58E-02
Ozone layer depletion (kg CFC-11eq)	6.00E-04	3.62E-04

Table 6. Secondary data information

Material	Secondary Data
	R.C. Panel
Steel	Reinforcing steel, at plant
Concrete	Concrete, normal, at plant
Insulating Layer	Polystyrene, extruded (XPS), at plant
	XLAM Panel
Insulating Layer	Polystyrene, extruded (XPS), at plant
Wood	Glued laminated timber, indoor use, at plant

Results show how there are no improvements in the whole set of energy and environmental indicators selected using one type of panel compared to the other. In particular, the XLAM panel is characterized by an energy impact about 5 times the reinforced concrete one. This high value (of which 70% is renewable energy compared to 3% renewable energy for the reinforced concrete panel) is mainly associated with the lower calorific value of wood, which involves high quantity of energy subtracted from the nature that remains stored inside the panel (feedstock energy). Therefore, the energy values presented refer to the sum of the energy used in the production process plus the energy stored in the product, which is potentially recoverable at the end of life (see for example XLAM panels discussion in Villa and Mapelli 2012).

Finally, the reinforced concrete panel is more sustainable as far as the impact categories of acidification, eutrophication and photochemical oxidation is concerned; vice versa it has higher impact values for the global warming potential and the ozone layer depletion.

5. CONCLUSIONS

The renovation of existing buildings and the repair of the buildings affected by earthquakes is nowadays an essential and urgent action that requires an increasingly coupled approach between various disciplines. Compared to traditional retrofit techniques, the retrofit solution choice should be based on the Life Cycle Thinking principles. Sustainability should be evaluated considering synergy between energy, structural and environmental aspects through different parameters that affect the entire life cycle of the solution. In general, the structural performance, the energy improvement, the environmental impacts of the materials and the potential reuse or recycling of these materials at the end-of-life should be considered in the selection of the retrofit solution. The retrofit choice is therefore the result of a complex process that can be supported by the application of the LCA.

In this particular case study, two possible solutions for coupled seismic-energetic improvements have been evaluated in the aftermath of the earthquakes that hit Central Italy in 2016. Considering the same seismic and energy performance as reference unit of the retrofit solution, the LCA methodology allowed to evaluate the primary energy consumption of the two panels highlighting a higher contribution of feedstock (renewable) energy for the XLAM panel compared to the reinforced concrete one. Finally, the reinforced concrete solution is shown to be more sustainable for the impact categories of acidification, eutrophication and photochemical oxidation, while it has a higher impact values for the global warming potential and the ozone layer depletion. It is worth noting that the results are preliminary, because the data presented refer to "cradle-to-gate" analysis and do not consider the on-site construction process and end-of-life scenarios.

5. REFERENCES

Belleri A, Marini A (2016): Does seismic risk affect the environmental impact of existing buildings. *Energy and Buildings*, 110:149-158

D.M. 14/01/2008, "Norme Tecniche per le Costruzioni", *Gazzetta Ufficiale*, n.29 del 14/02/2008 – supplemento ordinario n.30 (in Italian).

D.M. 26/06/2015, "Adeguamento linee guida nazionali per la certificazione energetica degli edifici", *Gazzetta Ufficiale,* n. 162 del 15-07-2015 – supplemento ordinario n.39 (in Italian).

Frischknecht R, Jungbluth N, Althaus HJ, Bauer C, Doka G, Dones R, Hischier R, Hellweg S, Humbert S, Köllner T, Loerincik Y, Margni M, Nemecek T (2007b): Implementation of Life Cycle Impact Assessment Methods.

Frischknecht R, Jungbluth N, Althaus HJ, Doka G, Dones R, Heck T, Hellweg S, Hischier R, Nemecek T, Rebitzer G, Spielmann M (2007a): Overview and Methodology - *Ecoinvent Report No. 1, ver.2.0, Swiss Centre for Life Cycle Inventories*, Dübendorf, CH.

ISO 14040 (2006): Environmental Management – Life Cycle Assessment – Principles and Framework.

ISO 14044 (2006): Environmental Management – Life Cycle Assessment – Requirements and Guidelines.

Labò S, Passoni C, Marini A, Belleri A, Camata G, Riva P, Spacone E (2017): "Prefabricated responsive diagrids for holistic renovation of existing mid-rise RC buildings" *Proceedings of the 6th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, M. Papadrakakis, M. Fragiadakis (eds.), Rhodes Island, Greece, 15–17 June 2017.

Marini A, Passoni C, Belleri A, Feroldi F, Metelli G, Preti M, Giuriani E, Riva P, Plizzari G (2017): "Combining seismic retrofit with energy refurbishment for the sustainable renovation of RC buildings: a proof of concept". *European Journal of Environmental and Civil Engineering*, DOI: 10.1080/19648189.2017.1363665

Marini A, Passoni C, Riva P, Negro P, Romano E, Taucer F (2014): Technology options for earthquake resistant, eco-efficient buildings in Europe: Research needs, *Report EUR 26497 EN. JRC87425. ISBN 978-92-79-35424-3. doi:10.2788/68902*. Publications Office of the European Union.

MidasGEN (2015) Gyeonggido, Korea: MIDAS Information Technologies Co. Ltd

Passoni C (2016): Holistic renovation of existing RC buildings: a framework for possible integrated structural interventions. *Ph.D. thesis*, University of Brescia.

Preservation Green Lab (2012). The Greenest Building: Quantifying the Environmental Value of Building Reuse. http://www.preservationnation.org.

Villa N, Mapelli A (2012): "Analisi LCA del pannello X-LAM legno toscano".
http://www.calet.it/doc/LCA_Legno_Toscano.pdf