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Development and characterization of a system for the seismic and energy retrofit of existing buildings

Valentina Pertile[a,*], Lorenzo De Stefani[a], Roberto Scotta[a]

[a]Department of Civil, Environmental and Architectural Engineering, University of Padova, Via Marzolo 9, Padova 35131, Italy

Abstract

The integrated retrofitting of building heritage is a high interesting topic in Europe lately. Many calls of the researching program H2020 is focused on this topic. This work deals with a new technology that improve seismic and energetic performance of existing buildings by operating only on the outer surface.

The system consists in two layers of insulating material and between them a seismic resistant layer made with in-situ cast concrete. The structural connection is made with steel screws fixed on the existing structure and embedded in the cast concrete. The resistance and the stiffness are improved, the displacement is reduced and so is the damage of the existing structural elements. The building vulnerability is then reduced.

Analytical and numerical studies were carried out to assess the structural seismic performance. First a feasibility study has been conducted, analyzing different geometric configurations and boundary conditions. Analytical and numerical buckling analysis of thin concrete slabs were performed, and the results are presented. Then a sensitivity analysis was conducted to determine the sizing of retrofitting to the change in the intensity of seismic action and the height of the building.

Referring to the numerical and analytical results, a set of quasi-static cyclic tests on real-scale specimens was performed and the results are presented.

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Keywords: seismic retrofitting; existing buildings; energy efficiency; buckling.

* Corresponding author. Tel.: +39-049-8275619.
E-mail address: valentina.pertile@dicea.unipd.it

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1. Introduction

The study in the seismic field of civil engineering have reached a high level of comprehension of the structural element failure mechanisms. Many theories have been developed that have been converted in design codes and normative prescriptions.

Recently the vulnerability assessment and the retrofit of the existing structures have become interesting topics in scientific and social field. Referring to the Italian scenario, it is observed that there are seismic events of medium- high intensity on average every 5 years. These events cause the collapse of the weakest structures and extensive damages to the building stock. In fact, most of the structures were designed and built before 1980 when the legislative framework did not provide any seismic requirements. Therefore, many buildings, especially residential ones, present a strong structural deficit towards dynamic actions. The quantity and distribution of buildings on the national territory and the high seismic risk in many areas of the country lead to a high seismic vulnerability of the building heritage, highlighting the need for a concrete and extensive plan to ensure safety.

Then placing the attention on the energy aspect, it is observed that most of the existing buildings have high values of heat dispersion through the building envelope due to the presence of thermal bridge and lack of insulation. This is strictly linked to the age of the structures, ie when there was no national design code on the performance of the building envelope. The energy inefficiency means excessive costs in economic and environmental terms due to the heating and cooling system, an unsustainable long-term scenario.

Thus, most of the existing buildings have both structural and energy deficiencies. To date there are several seismic retrofitting techniques, specific for the different structural types (ElGawady et al., 2004), (Priestly and Seible 1995). There are also technologies for the envelope upgrading and the limitation of thermal dispersion (Ascione et al 2011). However, there is a growing need to identify and develop integrated retrofitting systems (Zhenjun et al., 2012), to act simultaneously on the two problems, such as the solution proposed in this work.

2. Description of the system

The technology presented in this work consists in the realization of a coating applied only on the outer surface of the building with both structural and thermal insulation function. This system is composed of an insulated formwork filled with concrete, that have a reduced thickness for both the insulating layer and the structural layer.

The structural connection with the existing building structure is done by means of connectors installed in the beams of the structural frame. At the connection, the layer of internal insulating material in contact with the wall is interrupted, creating a horizontal rib of increased thickness, as indicated in Fig. 1 vertical ribs can be made to increase the bending resistance and to avoid the risk of buckling.

The thickness of the concrete slab and the amount of reinforcement shall be designed according to the expected horizontal actions and the capacity of the existing structure to resist them. In the design it is assumed that the existing structure support live and dead vertical loads and the horizontal actions are divided according to the stiffness between the new structure and the existing one.

The concrete slabs delimited by horizontal and vertical ribs can be subjected to out of plane instability phenomena due to the reduced thickness and the loading conditions. In this work will be investigate the critical buckling stress to determine the minimum pitch of the vertical ribs to prevent it. Different configuration of geometry, loads and constraint combinations will be analysed.

A sensitivity analysis will be using to develop sizing graph. The changing parameter in the sensitivity analysis are PGA and height of a typological building.

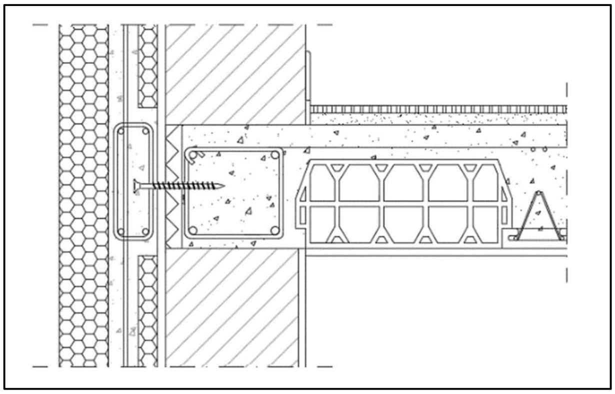

Fig. 1. Typical cross-section of the system under study.

3. Buckling analysis of thin concrete slabs subjected to pure shear

First, it is analysed the problem of a thin slab in plane stress condition. As the stress increases, when at least one of the main stress component of the plane stress condition is compression, buckling phenomena can occur. The critical value of the main compression stress depends on:

- the geometry of the slab;
- the constraint conditions;
- the ratio between compression and tension;
- the distribution of the stresses in various points;
- the bending stiffness;
- the slenderness of the slab.

The focus is now pointed on the effect of the plate geometry and constraint conditions. Consider a slab of height *h*, length *a* and thickness *t* simply supported on all the edges and subjected to pure shear stress.

The Eulerian buckling load is calculated referred to a unitary width stripe of length h with hinges at the ends and not bonded to the adjoining strips. The theoretical buckling stress in pure shear stress conditions is then determined.

It has been chosen five different configurations (Table 1). All the slabs have the same height *h* and different length *l* to study the effect of the aspect ratio on the buckling stress value. The concrete slab was modelled using four nodes plate elements with constant thickness equal to *t*. The material is linear elastic and the characteristics of the material are listed in Table 2.

First a model with four edges simply supported was considered (Fig. 2), then a model with two free edges was studied. Comparing the models with different constraint conditions it can be assessed the necessity of the vertical ribs to prevent buckling phenomena.

Table 1. Specimen dimension

Specimen	h (*mm*)	l (*mm*)	t (*mm*)
Slab 1	3000	1000	60
Slab 2	3000	2000	60
Slab 3	3000	3000	60
Slab 4	3000	4000	60
Slab 5	3000	5000	60

Table 2. Material characteristics

Element type	E (*MPa*)	ν	ρ (*kg/m*^{3})
Plate	30000	0.3	2400

In Fig. 3 the solutions for the four edges simply supported are shown. The numerical and the theoretical solution are overlapped for all the specimens analysed. The buckling value of the Slab 1 has been omitted because it is associated with a different shape of deformation with respect to the other specimens. The buckling stress values are higher than the design compressive strength of the concrete for all the slabs (f_{cd} = 14.16 MPa for C25/30 concrete). This takes to the conclusion that the failure of the structure will occur due to the compressive failure and not to out of plane instability.

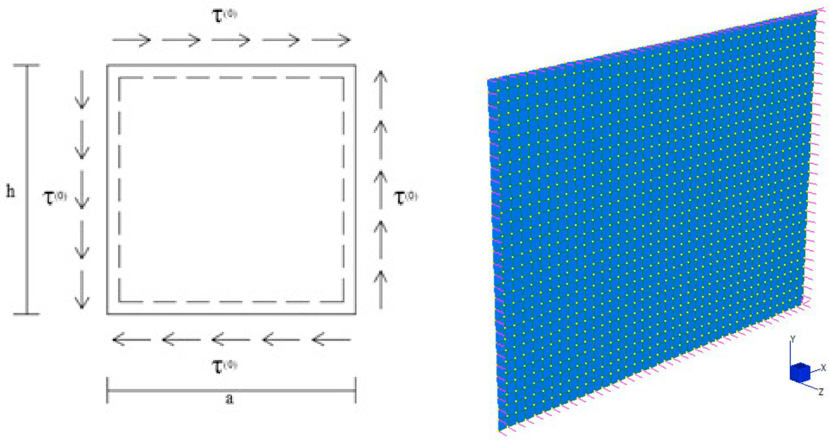

Fig. 2. Boundary and load conditions (left) and numerical model (right).

To determine the minimum number of vertical ribs needed, the model was modified by removing the supports at the two vertical sides and the same analyses were repeated. The values of the buckling stress obtained then are much lower than the previous case. The ultimate compressive stress is shown in Fig. 3 by the horizontal black line. Comparing the critical values of the buckling stress with the compressive strength, it is inferred that the latter is lower and, therefore, that the failure will occur due to material compressive strength and not due to instability.

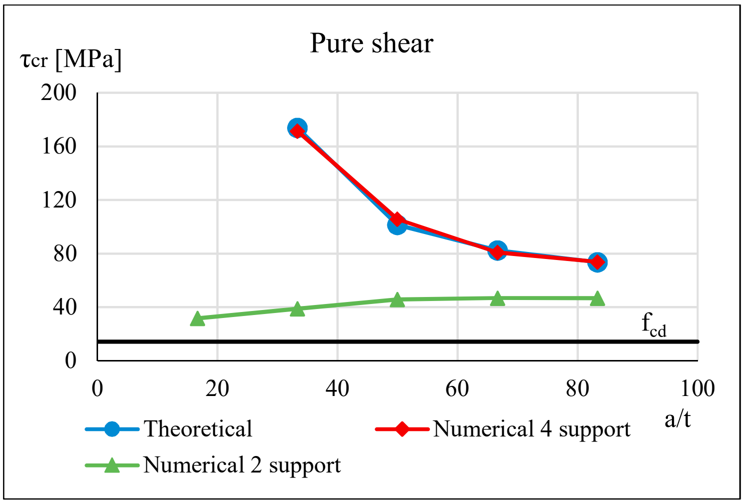

Fig. 3. Evolution of the critial stress based on the aspect ratio of the slab for pure shear stresses.

4. Instability of RC thin slabs subjected to shear and bending stress

The study seen in the previous section was extended introducing bending stress in addition to shear stress. In literature (Bernardini and Vescovi, 1982) there are several references for the construction of interaction diagrams for the verification of the sections, assuming the hypothesis of constant values of $\sigma^{(0)}$ and $\tau^{(0)}$ in the different sections observed.

The load condition shown in Fig. 4. was assumed, with $\psi = -1$. It should be noted that due to the geometry of the technology, the R.C. slab is not subject to static vertical loads other than the weight of the slab itself, as these remain entrusted to the existing structure.

To observe the influence of the bending intensity on the buckling stress value, three cases were analysed:

- $\sigma^{(0)} = \tau^{(0)}$;
- $\sigma^{(0)} = 2\,\tau^{(0)}$;
- $\sigma^{(0)} = 6\,\tau^{(0)}$.

The theoretical value of the critical buckling stress was calculated taking a point on the interaction diagram domain boundary and searching for the pair of $\tau^{(0)}$ and $\sigma^{(0)}$ that satisfy the equilibrium equation for the different slabs considered.

The numerical model used is like the one used in the previous study except for the load conditions. The bending stress was obtained by applying a linearly distributed load along two sides. For all the cases analysed, the numerical solution of the four simply supported edges approximates very well the theoretical solution.

The slabs subjected to bending and shear stresses have lower τ_{cr} value than those obtained for slabs subjected to pure shear stress.

For the sake of brevity, the individual graphs of all the cases studied are not reported, it is presented a summary chart that allows the comparison of the results obtained. It was observed that, with the increase of bending, for slabs with the same aspect ratio, the value of the critical buckling stress decreases. When the bending stress is clearly higher than the shear stress, for slabs with aspect ratio greater than 1, the critical stress is very close to the value of the compressive strength of the material. This denotes that there is a buckling risk.

As seen for the pure shear case, it was analysed the case with the two non-constrained vertical sides. It is confirmed that as the bending increases with respect to the shear, the buckling stress is lowered. It should be noted that if the bending is prevalent with respect to the shear, the τ_{cr} values of the critical stresses are lower than the compressive strength of the material. These results indicate that in the application of the system under study, it is necessary to create vertical ribs linked to the existing structure to prevent local instability phenomena due to the thin concrete slabs which are the structural part.

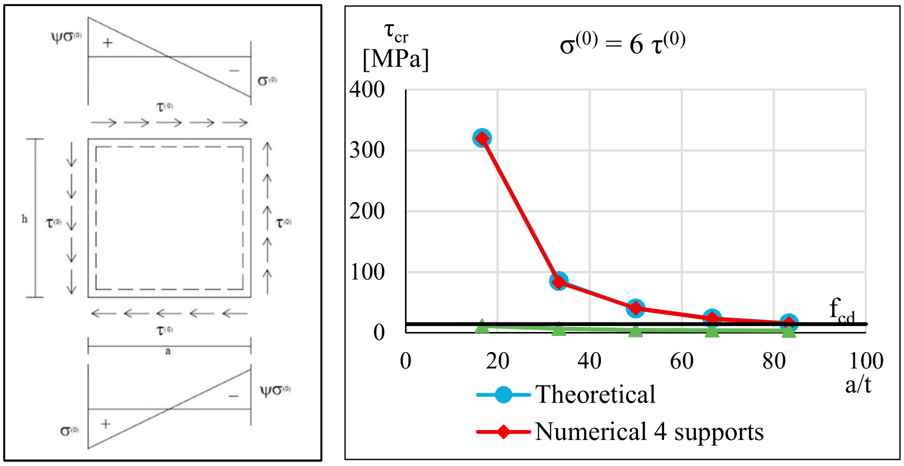

Fig. 4. a) Loading condition of a slab subjected to shear and bending stresses; b) Values of the critical pressure of the buckling when the ratio of length to thickness of the plate varies by $\sigma^{(0)} = 6\,\tau^{(0)}$.

Due to the geometry and the connection type of the technology in study, the axial load is applied to the existing building and the slabs are subjected only to their own weight. To study the effect of the weight load on the buckling stress it was considered a three-story building. It is observed that the compression load does not affect much the results and they are very close to those obtained in the absence of compression.

5. Design hypothesis

In this section will be presented the design method for the technology studied in the present work.

The geometry of the described technology and the system of connection allow to assume that the vertical static actions are applied only to the existing structure. The thickness of the concrete layer and the arrangement of the reinforcing bars will therefore be determined only as a function of the horizontal seismic design forces.

The design of the connection system with the existing structure must be correctly sized so that the two structural systems work together during the seismic event. Having assumed that the new reinforcement system is only stressed by horizontal seismic forces, the connectors will be designed by defining the diameter and pitch to withstand only shear forces. Attention must be paid to the base connection. It will be advisable to check the existing foundations to determine if they are able to withstand the increase in stress due to the increase in rigidity of the structure. To connect the new structure to the existing one it shall be created a perimeter curb, connected to the existing foundation, from which footing rebar for the new wall come out. A barycentric rebar mesh will then be introduced spread over the entire area of the wall. In the horizontal and vertical ribs, with increased thickness, stirrup and high-bond rebar will be set.

For the design of the system it is assumed that the plate is fixed at the base. The assessment of axial, bending and shear stresses capacity must be carried out by the rules of national code.

6. Sensitivity analysis

A first case study has been analysed. A 10 m long and 6 m wide masonry building has been studied, performing a sensitivity analysis with increasing PGA and number of stories of the building. Different thicknesses for the concrete slab and different diameters of the reinforcing bars were considered to obtain the resistance values necessary as the forces increase. The reinforcing bars are distributed horizontally and vertically with constant pace of 150 mm and 200 mm respectively. The analysed building presents a perimeter masonry wall 28 cm thick. A seismic linear static analysis was performed and the story forces were calculated accordingly to Italian national design code for structures.

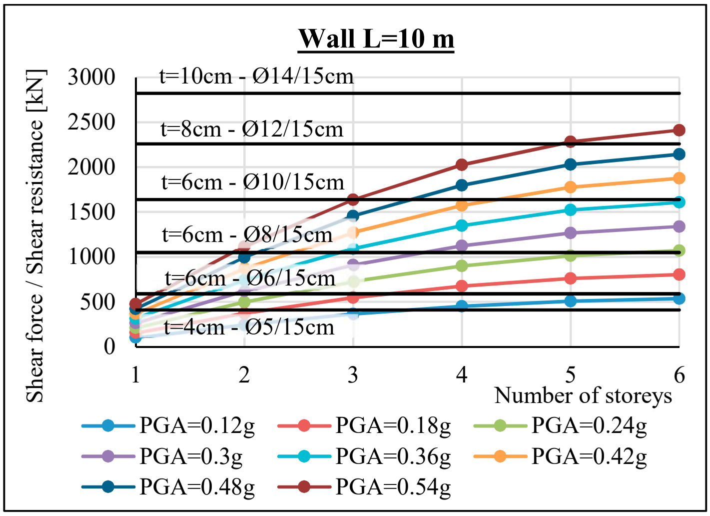

Fig. 5. Sizing graph for walls 10 m long.

The total weight of the six stories building was $W = 6302.5$ kN. Assuming a behavior factor equal to $q = 1.5$ (typical for existing buildings) and adopting a coefficient $\lambda = 0.85$, the force F_h was determined for different PGA values.

The bending moment and shear at various story for each PGA analysed were calculated. Then, the shear and bending resistances of the walls were calculated according to the Italian code. In this application the strength of the existing masonry wall was neglected.

By comparing the stresses and the calculated resistances, pre-sizing schedules were obtained for shear stresses. The horizontal lines represent the resistance of the system to varying the thickness of the slab and the diameter of the reinforcement, while the curves represent the stresses on the wall according to the number of floors and the PGA. In Fig. 5 it can be seen that for walls of length 10 m, for each acting force it is possible to find a configuration of the reinforcement system capable of withstanding the shear force.

The case study shows that the proposed solution lends itself well to medium-sized buildings in a medium-seismic area.

7. Full-scale test

A quasi-static cyclic-loading test was performed on full scale specimens to define the seismic response of the reinforcing technology studied. The specimens are made of a R.C. planar frame to represent the existing building structure reinforced on both sides with a thin R.C. slab cast in insulating formwork. The frame column had section dimensions equal to 25x25 cm and 300 cm height. The inner insulating layer of the formwork was 4 cm thick and the outer was 10 cm thick. The concrete slab inside the two layers was 6 cm thick and the specimens had a total thickness of 65 cm.

Four different specimens were made. Wall 1 and wall 2 had both horizontal and vertical ribs, while wall 3 and wall 4 had only horizontal ribs. Wall 1 and wall 3 are 3 m long and 3 m high, wall 2 and wall 4 are 4 m long and 3 m high and have a central door hole (see Fig. 6. a). The connection between the slabs and the beam of the frame was made with self-threading screws that work as shear studs.

The test was performed in displacement control and it was applied increasing amplitude at each cycle.

In Fig. 6. b) the resulted of the Wall 4 are presented. The theoretical resistance of the section is reported, looking at the curve related to the displacement of the frame and the slab it can be seen that the specimen had a resistance higher than the theoretical one. It can be noticed that the specimen remained in the elastic field. The technology led to an increase of the stiffness of the system that can be balanced by the higher resistance.

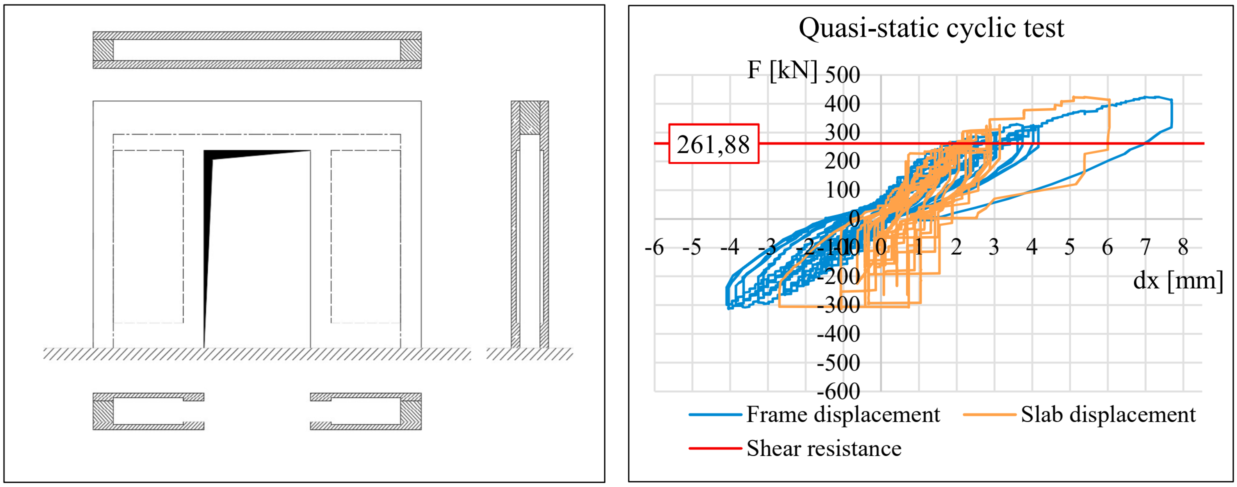

Fig. 6. a) Geometry of full scale specimens. b) Results of the experimental test.

8. Conclusions

With this work we wanted to demonstrate the feasibility of the proposed system for the structural and energy requalification of existing buildings. To this end, linear buckling analyzes were performed on finite element models of plates in different load and constraint configurations and a parametric study on a standard building to obtain pre-dimensioning schedules.

The results obtained confirm the feasibility of the system, indicating the need to limit the ratio between height and length of the wall to prevent out-of-plane instability. It is necessary to underline that these results have been obtained in the hypothesis of linear elastic material and slab considering an elastic modulus of the whole concrete, without reduction due to possible cracks. To obtain results that are closer to reality, it is necessary to introduce into the model the elastic-plastic behavior of the reinforced concrete and the presence of imperfections.

The analysis of the case study presented in this paper shows that the proposed system is particularly effective when applied to medium-sized buildings located in areas of average seismicity.

In the future we intend to continue with the development of this system by defining a dedicated calculation method. Furthermore, a new set of experimental tests is being planned for the characterization of the technology's behavior and the validation of the calculation method that will be proposed.

9. Thanks

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