Diagrid solutions for a sustainable seismic, energy, and architectural upgrade of European RC buildings

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Abstract: The refurbishment of the existing building stock is nowadays becoming a priority in order to meet energy-saving and emission-control international targets and to foster safety and resilience of European communities.

A new research recently introduced the concept of holistic seismic, energy, and architectural renovation of existing buildings targeting resilience, safety, and sustainability. Integrated retrofitting techniques have been proposed, and a new structural design procedure has been studied rethinking existing approaches by including sustainability principles.

With reference to post-WWII RC buildings, which are often mid-rise isolated buildings located at the city outskirts, additional exoskeletons implementing the technologies and devices for an integrated upgrade have been proposed. Exoskeletons are entirely built from outside, thus avoiding the temporary dismissal of the buildings and the relocation of the inhabitants.

Both 'shear wall' or 'shell' solutions, either dissipative or over-resistant, can be envisioned for structural retrofitting. In the first solution, shear walls can be integrated in the new exoskeleton, whereas energy efficiency upgrading is guaranteed by the envelope, thus the two structure-energy systems work in parallel. In the 'shell' solution, the building envelope has both energy and structural functions.

In this paper, both over-resistant and adaptive diagrids are introduced for the holistic refurbishment of existing buildings.

Over resistant diagrids are conceived for the seismic upgrade of those buildings having stiff masonry infill walls and staircase walls, for which dissipative solutions may be ineffective unless massive preliminary interventions are carried out to downgrade the existing building initial stiffness.

Adaptive diagrids are conceived as over resistant 'shell' structures to avoid any damage at the operational limit state, while dissipation is triggered through dissipative rigid-plastic supports to reduce shear at the grid foundations at the life safety limit state.

Selection of materials and technologies, enabling maximum adaptability, reparability and maintenance, and total demountability-recyclability/reuse at end-of-life is also discussed.

Keywords: Holistic renovation, Existing RC buildings, Seismic strengthening, Sustainability, Life Cycle Thinking

1. Introduction

About 40% of existing buildings in Europe were built before 1960s, and most of them were constructed in the outskirts of the major European cities as a result of the housing demand that followed the end of the Second World War (Marini *et al.*, 2014, Figure 1). About 50 years later, these buildings show remarkable signs of decay, poor housing conditions, thermal and living discomfort, high CO_2 emissions and energy consumption mainly due to obsolete envelopes and technologies. More, being inherently vulnerable to static and seismic actions and having exhausted their nominal structural service life they may represent a threat for the human safety, especially in seismic prone countries.

The present situation cannot be endured any further: under an energy point of view, reducing the emissions and energy consumption of this large portion of the building stock is the only viable solution to achieve the European sustainability targets driving the transition toward a low carbon society; under a structural point of view, these buildings do not often respect minimum safety target levels, thus worsening the conditions of a non-resilient society that does not pursuit preservation of the human life as a major target. Finally, building damages or collapses following natural disasters, besides being a safety hazard, have a great impact on the environment in terms of waste production and CO_2 emissions, greatly affecting the energy savings obtained with a sole energy retrofit intervention (Belleri and Marini, 2016).

Figure 1 – Typical post-WWII European Reinforced Concrete buildings: a five-storey building with architectural, energy, and structural deficiencies (left) and a typical suburb (panoramic view © Microsoft® Bing^{TM} Maps Platform 2016)

Traditionally, the only attempt to improve the conditions of these buildings has been pursuit through either demolition and reconstruction interventions or through episodic, non-integrated retrofit interventions, usually aimed at the sole energy efficiency upgrade. Both these approaches are highly inefficient. The demolition and reconstruction approach, unless mandatory, has a great impact on the environment (Preservation Green Lab, 2012) and, even more, on the building functionality. Very often, the need of relocating all building activities may be the strongest barrier to its renovation. On the other hand, the concept of uncoupled renovation is not viable since it is not sustainable under an economic, social, and environmental point of view.

Only recently, a new research proposed a holistic approach for the renovation of such kind of buildings, addressing and solving the architectural, energy, and structural deficiencies of buildings, whilst targeting resilience, safety, and sustainability (Figure 2) (Feroldi *et al.*, 2014; Angi, 2015). To this aim, an additional exoskeleton is proposed to reshape the building façade, to improve the thermal performances, and to sustain the static and seismic loads that exceed the capacity of the existing structure. The intervention is completely carried out from outside, thus avoiding the relocation of the building inhabitants and functions.

Besides preserving human life, coupling the structural and seismic retrofit to the architectural and energy upgrading of an existing structure entails a series of co-benefits: it allows the construction of upper stories, and, avoiding a possible collapse of the building, it reduces the impact on the environment and ensures a long term protection of the investment.

Moreover, adopting recyclable materials and easily demountable, repairable, and adaptable technologies increases the sustainability of the intervention, and reduces the CO_2 emissions throughout the building life cycle.

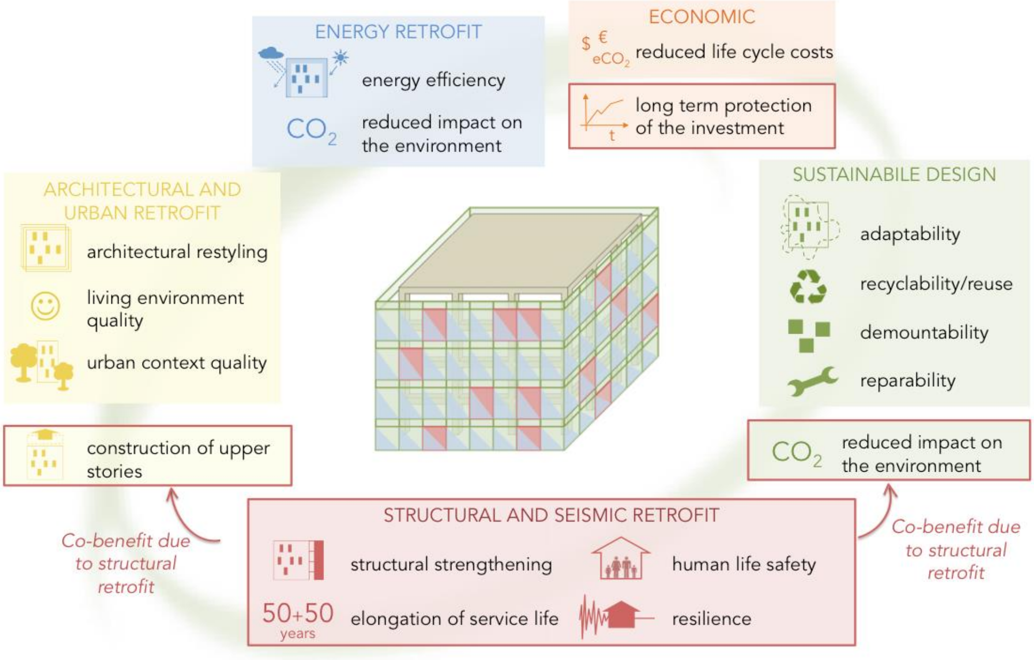


Figure 2 – Holistic architectural, energy, and seismic upgrading of existing buildings targeting safety, resilience, and sustainability: a concept

In this paper, possible structural solutions for the design of the additional exoskeleton are further investigated. Among different possibilities, diagrids, a particular type of gridshell structures, have been chosen for their high structural efficiency and for their high architectural-reshaping potential.

Although the research is necessarily multidisciplinary, emphasis is made mainly on the structural issues in this study.

2. Diagrid as exoskeleton for the seismic upgrading of existing buildings

The considered post-WWII buildings typically feature one-way RC frames with stiff masonry infills and stiff staircase wells. They are often characterized by plan or vertical irregularities and poor structural details, which makes those buildings located in seismic prone areas highly vulnerable.

The seismic upgrading of existing structures is traditionally pursued adopting local or global strengthening. Although local strengthening techniques are quite widespread, they imply the partial or total demolition of the building finishing, thus increasing the costs of the intervention and the requiring the temporary dismissal of the building. Global interventions should thus be preferred. Relying on the construction of a brand new seismic resistant system, they may be applied from outside by connecting the new resisting elements to the existing vertical structure without interrupting the building functionality. Usually, the new structural system is made by vertical elements that, being stiffer than the existing structure, collect the seismic action from the floors and transfer it to the new foundations.

Noteworthy, the global systems need rigid floor diaphragms to be activated. The capacity of the existing floors should thus be estimated. The retrofit of the existing floors may be in contrast with the concept of acting from outside exclusively. Nevertheless, recent researches have shown that even the heterogeneous beam and block floor systems (UNI EN 15037) may resist to low-medium seismic loads by developing a tied-arch resistant mechanism (Feroldi, 2014; Passoni, 2016). On the other hand, in the case of strong-intensity earthquakes, the same researches proposed an alternative dry solution made of steel truss work connected to the floor intrados and concealed at the sight with false ceilings, also taking advantage of the higher inter-storey height typical of the analysed buildings.

As regards the new vertical elements, 'wall' or 'shell' structural solutions may be adopted. In 'wall' solutions (Figure 3a), the additional stiffness and resistance are lumped into few elements placed perpendicular or in adhesion to the building façades, such as shear walls or bracing systems. However, in the case of very stiff existing structures or in high seismicity areas, the wall system may not be a viable solution since a significant number – or an excessive length – of walls may be required. Moreover, since the additional strength and stiffness are lumped into few elements, the foundations may be insufficient as to withstand the high seismic loads, and massive interventions may be required. In order to reduce the cross section area of each single structural component of the new façade and to avoid the overload of the foundations, 'shell' solutions have thus been proposed (Figure 3b,c) (Marini *et al.*, 2015b; Passoni, 2106). This approach exploits the shape and the extension of the façade to force a box-structural behaviour of the retrofitted building (Giuriani, 2008).

Structural shells may be continuous or discrete (gridshells). In the former case, the shell behaviour relies on the capacity of the shell sub-components and their mutual connections to withstand and transfer shear actions and bi-axial stress state (Figure 3b); while in the latter, it is ensured by a lattice structure made of truss sub components (Figure 3c). Gridshells are usually adopted for the construction of freeform lattice structures (roofs, façades, solar screens, etc.) thanks to their ability to easily adapt to any 3D shape. When gridshells constitute the exoskeleton of buildings, they are referred to as diagrids – or diagonal grids. Diagrids have been developed in recent years for high-rise buildings as an alternative to exterior braced-frame structures. In these structures, the triangular module of the grid is studied to maximise the gravity and horizontal load bearing capacity and the vertical columns on the perimeter are eliminated. A comparison between so-called gridshell and diagrid structures is shown in Figure 4.

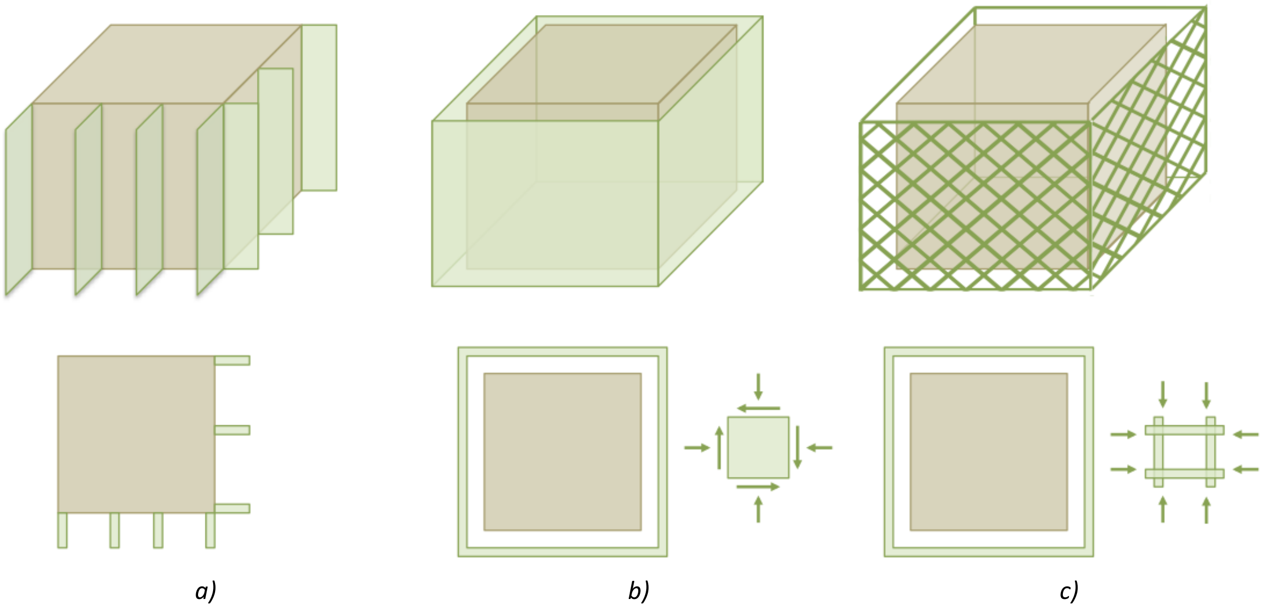


Figure 3 – Possible structural layouts of the additional exoskeleton for the holistic renovation of the building stock: a) 'wall' system; b) 'shell' system; and c) 'gridshell' system. Diagrids are a particular case of gridshell structures

Figure 4 – Examples of a gridshell structure: Yas Viceroy Abu Dhabi Hotel ©Asymptote Architecture (left); and a diagrid structure (a particular type of gridshell): Hearst Tower, New York ©Foster+Partners (right)

Both 'wall' and 'shell' systems can constitute the resisting structure of the exoskeleton that also implements the architecture and energy upgrading measures. In wall solutions, the walls serve the structural function, while the envelope serves the energy upgrading function; in shell and gridshell structures, the integration of all intervention targets is taken to the highest level since the additional skin serves the structural, energy, and architectural functions contemporarily.

In the following, focus is made on the more innovative diagrid solution. The architectural potential of gridshell (and diagrid) solutions is higher than that of a shear wall solution since it allows maximum freedom in the remodelling of the building façades and allows including new living spaces. In addition, these freeform structures may encase new diaphragms in the depth of the façade, when needed. Although the research is necessarily multidisciplinary, the sole anti-seismic function of the new exoskeleton is addressed in this paper.

3. Adaptive -responsive- structure: from over-resistant to sliding diagrids

The seismic retrofit of an existing structure may be designed as either dissipative or non-dissipative. The former solution controls the seismic response of the existing building by dissipating seismic energy into new devices, which may be either façade components or localized dampers (hysteretic, viscoelastic, viscous, etc.). Conversely, non-dissipative solutions meet the required targets by adding very stiff and over-resistant external elements, which limit the displacements of the existing structure and withstand the whole seismic action.

Both solutions have both advantages and drawbacks. By damping the system, dissipative solutions often allow reducing the cross section of the structural components, thus optimizing material consumption; and localize the damage into few replaceable elements. On the other hand, the devices can be expensive, and the design process may be quite difficult and the need for larger deformation capacity of the existing structure may require additional preliminary interventions triggering larger ductility in the structural nodes. Non-dissipative solutions are easier to design since the retrofitted structure is envisioned as linear elastic, but this implies bigger cross section areas and a high material consumption.

In the considered building stock, the seismic retrofit of structures can be very challenging. The presence of stiff masonry infills and staircase walls not designed to withstand the horizontal loads should be taken into consideration in the retrofit design. Although these non-structural elements are usually neglected in the building modelling, they are responsible for a significant change of the building capacity curve, increasing considerably the stiffness of the system and reducing its global ductility. When infilled frames rather than bare frames are considered in the design of the intervention, massive structures when stiff antiseismic systems are envisioned; whereas dissipative structural strengthening may be ineffective since displacement-activated dampers may not reach yielding and remain inactive whilst the infill walls may reach their ultimate resistance for displacements of few millimetres (Uva *et al.*, 2012).

Non-dissipative solutions may thus be considered the most viable option for this peculiar kind of existing buildings. However, when over-resistant, stiff façades are added to an existing structure, the reduction of the building period may lead to a substantial increase of the seismic action on the structure, resulting in a remarkable overload of floor diaphragms and of foundations.

In this scenario, 'passive-responsive' structures are proposed in the following.

Responsive structures are structures conceived to adapt their properties to external changing conditions. In this particular application, responsive structure are intended to adapt to the intensity of the earthquake. Usually, this kind of structures, known as 'smart structures', is provided with controllers and actuators actively inducing the envisioned property change (Morales-Beltran and Teuffel, 2013). The innovation proposed in this paper is to enforcing the system responsivity in a passive way, by adopting localized sacrificial elements that act as fuse for the structure and do not require input energy, nor massive energy storage for the system to be ready to use.

In particular, the concept is here applied to the holistic retrofit system, by proposing a passively-responsive diagrid. The new diagrid exoskeleton acts as a stiff three-dimensional grid that changes boundary conditions at the base supports as a function of the earthquake intensity, allowing to cap the maximum base shear force. At the Damage Limit State, the diagrid is designed as hinged at the base; whereas beyond a target base shear, i.e. at Life Safety Limit State, hinges are designed to downgrade into rollers (Figure 5a), whose displacements are controlled through bumpers, avoiding excessive horizontal displacements of the diagrid. The hysteretic law describing the adaptive sliding support response is shown in Figure 5b.

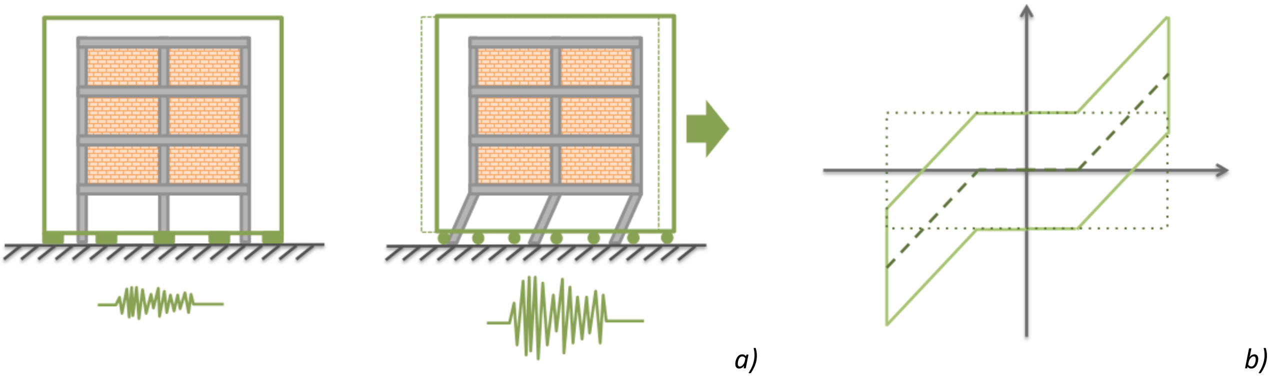

a) *b)*

Figure 5 – Diagrid exoskeleton with adaptive sliding supports: a) the grid is hinged at the base for low intensity earthquakes, but it slides beyond a certain earthquake intensity; b) hysteretic cycle of the innovative support, which is the sum of a traditional elasto-plastic support (dashed line) and a gap system (dotted line)

The diagrid also requires preliminary interventions to be carried out on the existing structure. In order to avoid an extensive damage of the existing structure, a controlled soft storey mechanism is activated by disconnecting the infills at the ground floor. Without such an intervention, the whole seismic force would be taken by the ground floor elements leading to severe damage of the building prior to the activation of the envisioned retrofit scheme. The mechanism requires larger ductility of the base columns, which can be attained by ensuring a ductile failure by confining the elements for example wrapping the column ends with fibre reinforced polymer sheets – or similar. The maximum allowable interstorey drift at the ground floor after the intervention thus represents the main design parameter of the retrofit.

The preliminary design of the diagrid structure should be based on the stiffness of the diagonal elements, but the distribution of the axial forces in the elements is less predictable than in a traditional braced frame due to the lack of vertical elements. An iterative procedure should be carried out in order to optimize the design.

As a first step of the retrofit design, targets in terms of maximum roof drift and maximum base shear must be defined. The inclination and layout of the diagonal elements should then be selected. Moon *et al.* (2007) showed that 35° is the optimal inclination angle of a diagrid for a low-medium rise building, which behaves like a shear beam. This angle is obtained by maximizing the horizontal stiffness K_h of a traditional braced structure, in order to maximise the efficiency of the façade withstanding the horizontal loads:

$$F = 2F_d cos\alpha = 2K_d d_h cos^2\alpha \tag{1}$$

$$K_d = \frac{E_d A_d}{d} = \frac{E_d A_d}{h} sin\alpha \tag{2}$$

$$K_h = 2\frac{E_d A_d}{h} sin\alpha cos^2\alpha \tag{3}$$

where α is the inclination of the diagonal members, F and F_d are the horizontal and diagonal forces, d_h is the horizontal displacement, K_h and K_d are the horizontal and diagonal stiffness, E_d, A_d, and d are the elastic modulus, the cross section area, and the length of the diagonal members, and h is the height of the diagrid modulus, corresponding to the interstory height in the proposed application.

The diagrid is designed to achieve the roof drift target at the considered earthquake intensity and to limit the shear flow transfer to the new foundation system. As a starting point, the grid cross-section is selected in order to meet the load associated to the constant acceleration region of the pseudo-acceleration spectrum. At this stage, the grid is considered elastic and hinged at the base. Then an iterative design procedure is carried out by means of nonlinear time history analyses in order to determine the optimal cross section of the diagrid elements. As mentioned before, the focus is to limit the average roof displacement in order to be equal or less the target displacement, and to limit the shear flow at the base of the grid in order to to be less than the maximum flow withstandable by the foundation at the Life Safety limit state. If the shear force target is not met, which might occur especially for high-intensity earthquakes, the structure should be designed as adaptive, by adopting sliding diagrid supports. In this case, supports must behave as hinges at the Serviceability Limit State and as dissipating rollers at the Life Safety Limit State. The maximum interstorey drift at the ground floor must be checked in order to avoid soft story failures; at this regard, the structural nodes need to be careful detailed to avoid early failure of the existing building columns. A parametric analysis is required to select the mechanical characteristics of the sliding support in order to meet roof drift, ground floor drift, and base shear targets.

4. Application to a reference building

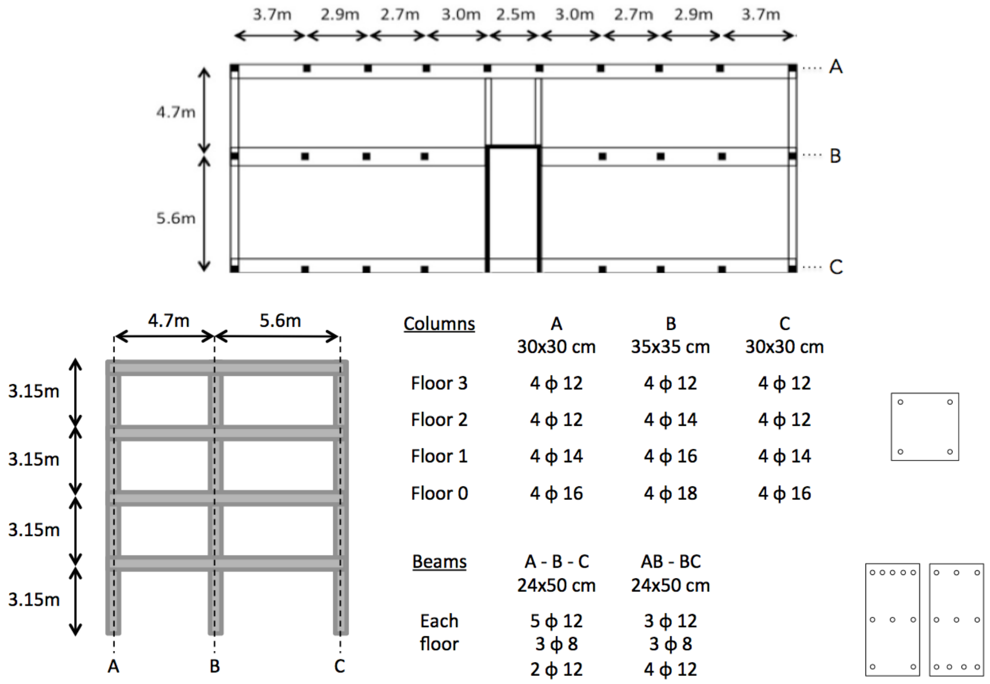
The procedure for the design of the holistic retrofit is here applied to an Italian RC building, typical of the post-WWII European stock, assumed as reference building.

The reference building is a four-storey rectangular structure featuring three one-way longitudinal frames and two infilled lateral frames. The geometry of the main frame and the reinforcement detailing in each element are reported in Figure 6.

The elements of the frame are modelled as beam elements with lumped plasticity implementing Takeda hysteresis rule (Otani, 1974). Floor slabs are considered as rigid diaphragms, and the structure is fixed at the base. The brick masonry infills are modelled using struts converging in the nodes and implementing the Decanini *et al.* (1993) axial force-displacement rule. Finally, the staircase walls are modelled as RC elements with lumped plasticity.

As a first step, the capacity of the existing building is determined and the structural building targets are defined. Static nonlinear pushover analyses are performed on the three-dimensional model of the building. The influence of the stiffening elements, such as masonry infills and staircase walls, is assessed by comparison to the behaviour of a bare frame. The results are shown in Figure 7. The capacity curves show that the seismic response of the reference building is strongly dependent on the initial assumption on the behaviour of the so-called ‘non-structural’ elements. Knowing that the provision of diagrids with lower than required stiffness may result in an ineffective intervention, on the safety side, the stiffest and less ductile curve is chosen as reference for the seismic response of the existing building before retrofitting.

Once the capacity curve of the reference building is selected, targets in terms of maximum roof drift and maximum base shear are chosen. Since the presence of the infill and staircase walls highly increases the initial stiffness of the building, a total drift of 0.1% (13 mm) is imposed for the Life Safety Limit State. Obviously, considering such a small roof displacement lead to very high stiffness of the diagrid, and this implies an increase of the seismic action. A maximum shear flow at the foundations equal to 150 kN/m is accepted for the Life Safety Limit State. For the considered case study the roof displacement and the shear flow at the foundations for the Serviceability Limit State are considered implicitly met.



Columns	A 30x30 cm	B 35x35 cm	C 30x30 cm
Floor 3	4 ϕ 12	4 ϕ 12	4 ϕ 12
Floor 2	4 ϕ 12	4 ϕ 14	4 ϕ 12
Floor 1	4 ϕ 14	4 ϕ 16	4 ϕ 14
Floor 0	4 ϕ 16	4 ϕ 18	4 ϕ 16

Beams	A - B - C 24x50 cm	AB - BC 24x50 cm
Each floor	5 ϕ 12 3 ϕ 8 2 ϕ 12	3 ϕ 12 3 ϕ 8 4 ϕ 12

Materials: Concrete - C25/30; Steel - FeB44 (fyk=430MPa)

Figure 6 – Reference Italian building built in 1972, selected as representative of the European post-WWII RC building stock: plan view (top) and external transverse frame (bottom) of the 3D finite element model

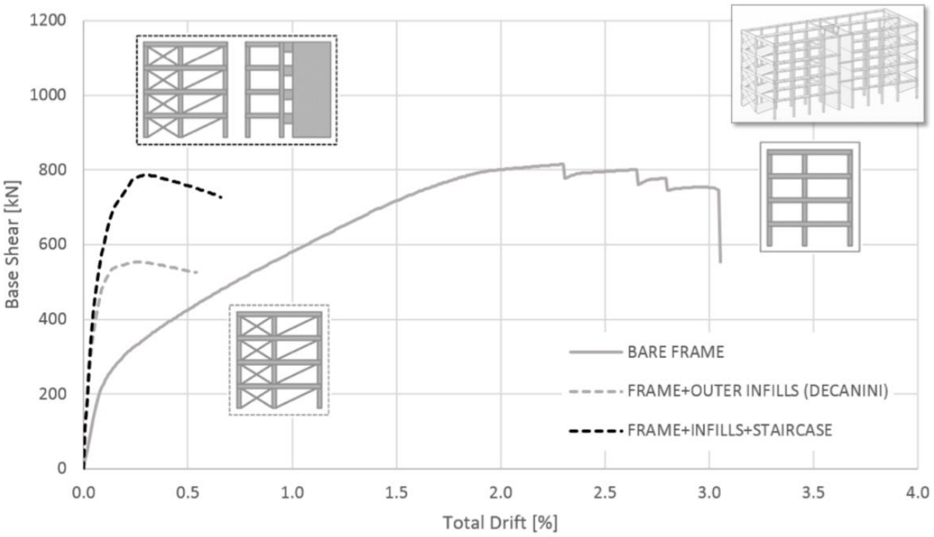


Figure 7 – Influence of masonry infills and RC staircase walls on the seismic nonlinear response of a three-dimensional frame (the curves are interrupted at the collapse of the infills to account for short column induced failure)

4.1 Design of traditional non-dissipative solution: diagrid exoskeleton hinged at the base

According to the roof drift target (0.1%), a parametric analysis is made on the sole diagrid by varying the dimension of the grid elements. A 35° inclination is assigned to the diagonal members, and the optimal commercial profile is selected supposing a one-floor high grid module. The building is supposed to be located in a high seismicity zone (L'Aquila, Italy), and subject to a Life Safety Limit State earthquake. A commercial tubular profile with D=219.1mm and s=16mm is selected.

Seven nonlinear time history analyses are performed on the retrofitted structure considering a set of records compatible with the L'Aquila earthquake at the Life Safety Limit State having PGA=0.347g (NTC, 2008; Iervolino *et al.*, 2010). The results, reported in Figure 8, show a remarkable reduction of the building drift, with no damage to the existing structure, which remains in the elastic field. However, as expected, the shear at the base obtained adding the diagrid is so high that cannot be withstood by a traditional foundation system. As a consequence, a sliding support system is proposed to enable a stiff elastic behaviour of the retrofitted building at the Damage Limit State and to enable energy dissipation for stronger earthquakes.

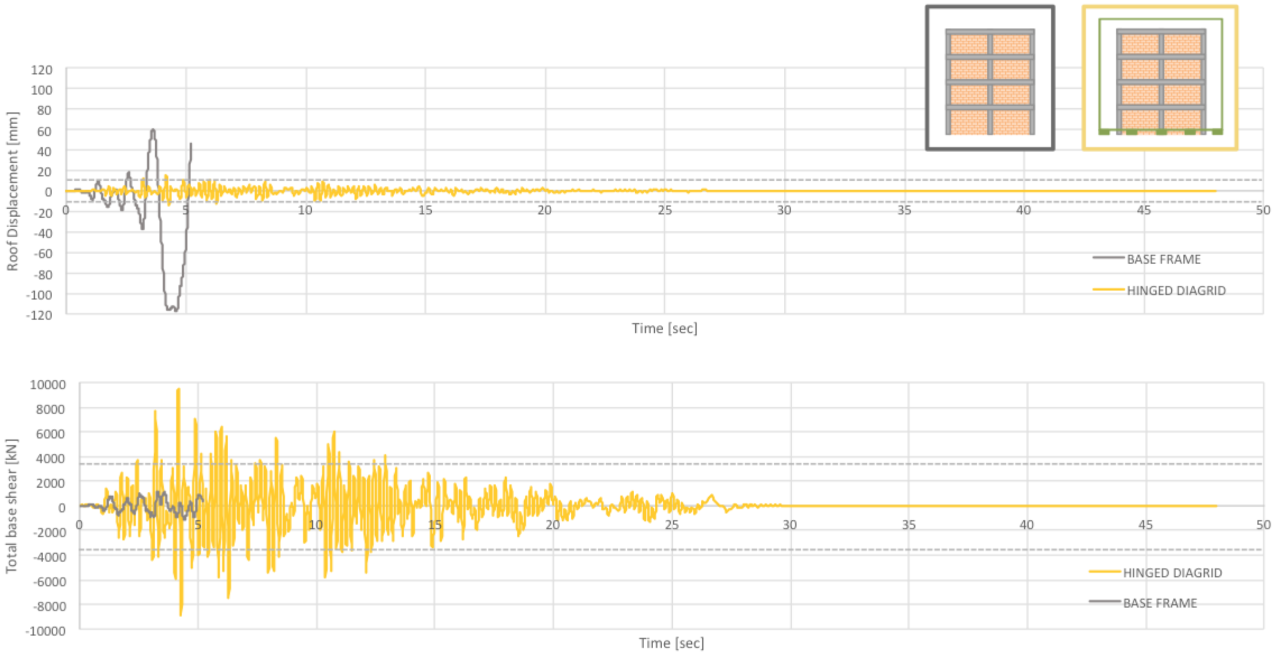


Figure 8 – Roof displacement (top) and total base shear (bottom) for the same earthquake record for the base frame and the base frame plus the hinged diagrid solution. The target roof drift of ±0.1% and the target base shear of ±150kN/m are reported with dotted lines (the curves of the base frame are here interrupted at the collapse of the infills to take into consideration the possible triggering of short column failures)

4.2 Design of innovative passive adaptive solution: diagrid exoskeleton with adaptive sliding supports

The proposed adaptive solution is applied to the existing reference building. The same dimension of the diagonal elements is maintained, and an iterative design procedure is applied in order to calibrate the optimal properties of the new sliding supports. In particular, the new support is initially rigid and behaves as an elastoplastic system beyond a base shear flow of 60kN/m. In addition, an elastic bumper is provided in order to limit the diagrid displacements at ground level; the bumper is activated for base displacements greater than 20mm. A sketch of the retrofitted building and of the hysteresis shape of the diagrid base restraints are shown in Figure 9.

As a preliminary intervention, the stiff elements are disconnected from the existing RC frame at the ground floor to avoid interference with the lateral displacements. Vertical sliding joints are inserted in the masonry infills and in the RC walls of the staircase wells, as proposed by Preti *et al.* (2012). It is worth noting that with such an intervention, all the deformations of the existing building will be lumped at the ground floor, and the drift target will be determined by the maximum drift capacity of the columns at the base. In order to ensure the required ductility, the shear capacity and the end rotation ductility of the columns are increased by means of fibre-sheet wrapping, a maximum target drift of the ground floor equal to 1.5% is here considered, which corresponds to a 0.36% total roof drift.

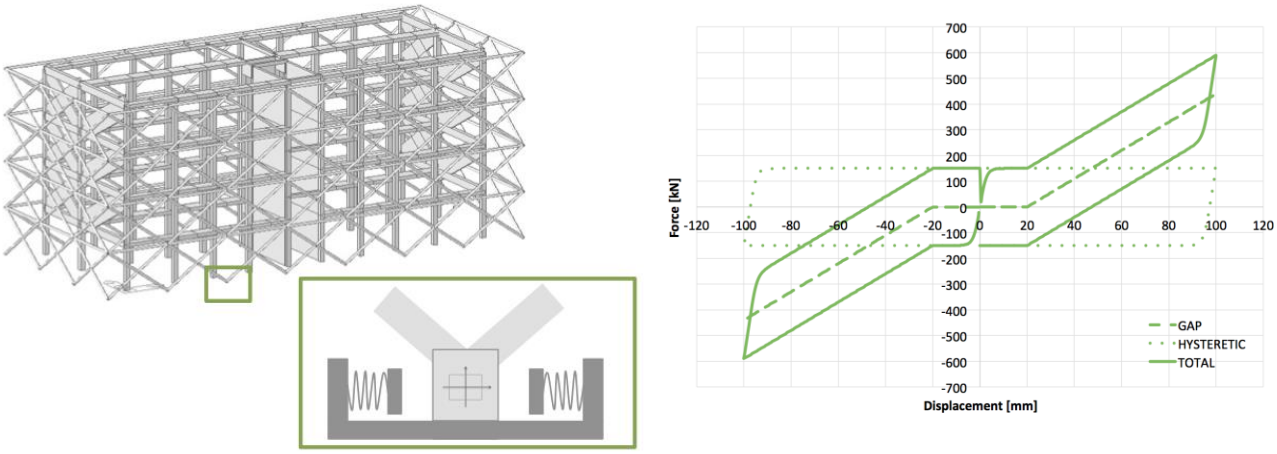


Figure 8 – Sketch of the retrofitted building equipped with special sliding supports (left) and hysteretic cycle of the sliding support as sum of an elasto-plastic support (dashed line) and a gap system (dotted line)

Results obtained for the adaptive diagrid solution are plotted in terms of total roof drift and total base shear in Figure 10 with reference to a single accelerogram. Results compared to those obtained with the hinged diagrid solution and for the base frame. In the case of adaptive diagrid solution, targets are met both in terms of maximum allowable drift and base shear, and the existing structure always remains in the linear elastic field. A substantial change in the building fundamental period may also be noted for the three different configurations.

A comparison of the maximum and average results in terms of total drift, base shear, and shear at the base of the existing building obtained for the seven accelerograms is reported in Figure 11 for the base frame, the hinged diagrid solution, and the adaptive sliding diagrid solution. It may be noted that the roof drift target, which is the main design parameter, is always achieved, and the total base shear, which is not acceptable for the hinged solution, may be reduced by adopting the sliding supports. The shear at the base of the existing building is lower in the hinged solution, which is stiff and collects the greater part of the seismic action. Conversely, when the sliding solution is applied, the existing building is subject to a larger shear than in the unretrofitted condition, but, in this case, the stiff and brittle elements at the ground floor do not represent a threat anymore, and the base shear can be taken by the existing frame without any damage to the structural elements.

Finally, the floor drift and floor shear are reported in Figure 12. The drift distribution shows how the building behaves as a stiff box in the hinged solution and shifts to a soft storey mechanism in the adaptive sliding solution. As for the floor shear, the sliding solution highly reduces the stresses into the existing floors. It should be noted that, supposing a tied-arch mechanism developing in the floor depth to withstand floor actions, shell solutions represent a particularly severe condition for the diaphragms, since they imply the formation of a unique arch spanning between the two façades. Based on previous researches (Feroldi, 2013; Passoni, 2016) focusing on the shear capacity of beam and block floor system of the reference building, the maximum floor capacity for diagrid solutions is 625kN. Although the shear floor loads are reduced with the sliding diagrid solution, the retrofit of the existing floor diaphragms is still required.

As for earthquakes at the Damage Limit State, seven other analyses are performed in order to verify that the special sliding devices always are inactive and supports remain in the hinged configuration.

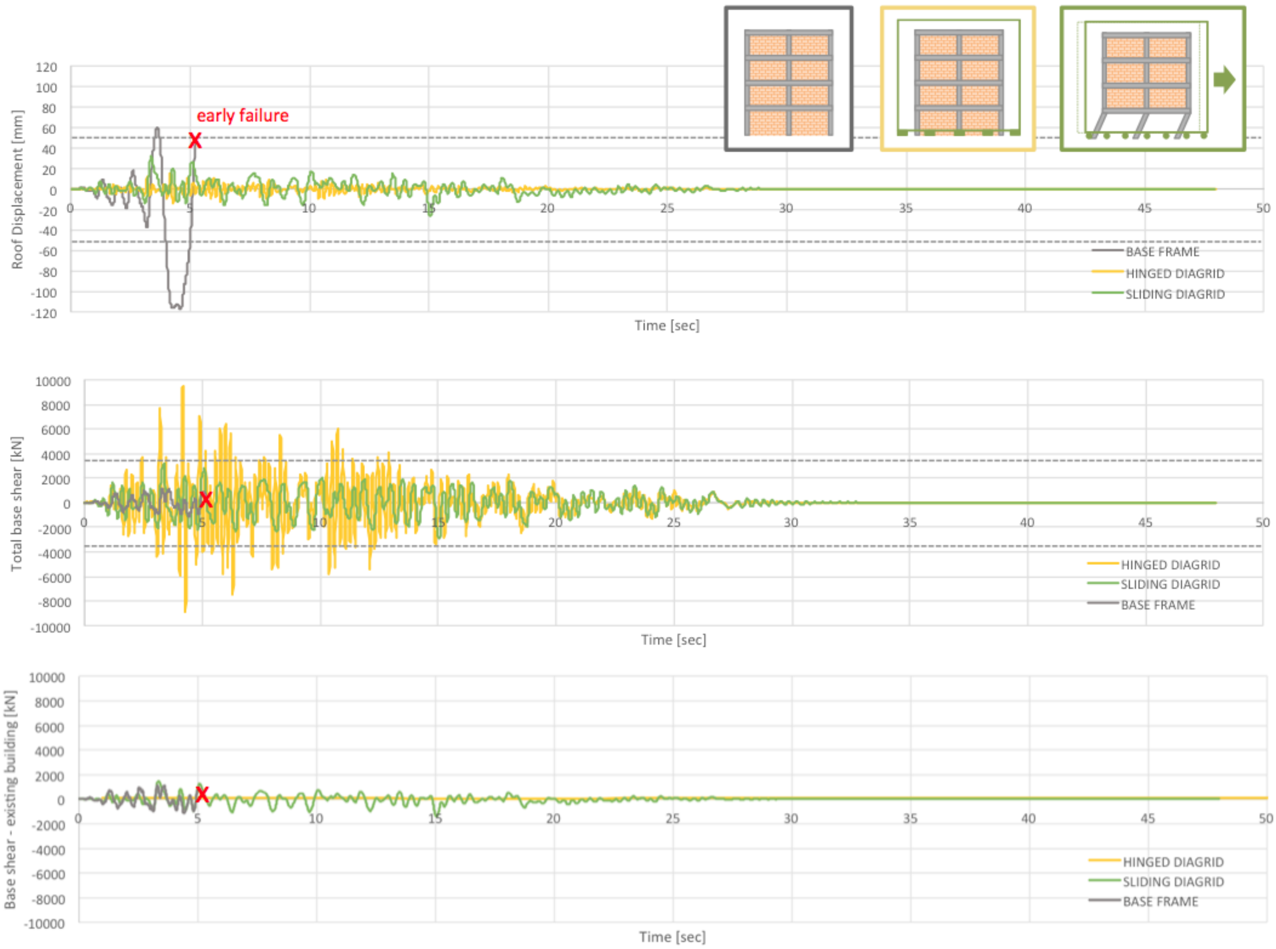


Figure 10 – Life Safety Limit State. Roof displacement (top), total base shear (centre) and shear at the base of the existing frame (bottom) for the same earthquake record for the base frame, the hinged diagrid solution, and the sliding diagrid solution. The 0.36% target roof drift (equal to ±1.3% the ground floor drift) and the target base shear of ±150kN/m are reported with dotted lines (the curves of the base frame are interrupted at the collapse of the infills to account for possible triggering of short column failures)

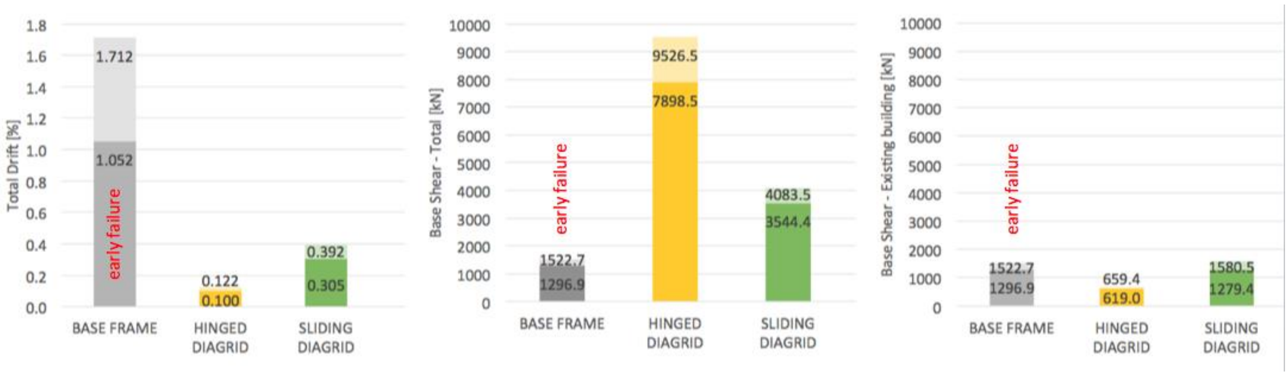


Figure 11 – Life Safety Limit State. Average and maximum roof displacement (left), shear at the base of the existing building (right), and total base shear (centre) for the base frame (grey), hinged diagrid (yellow), and adaptive sliding diagrid (green)

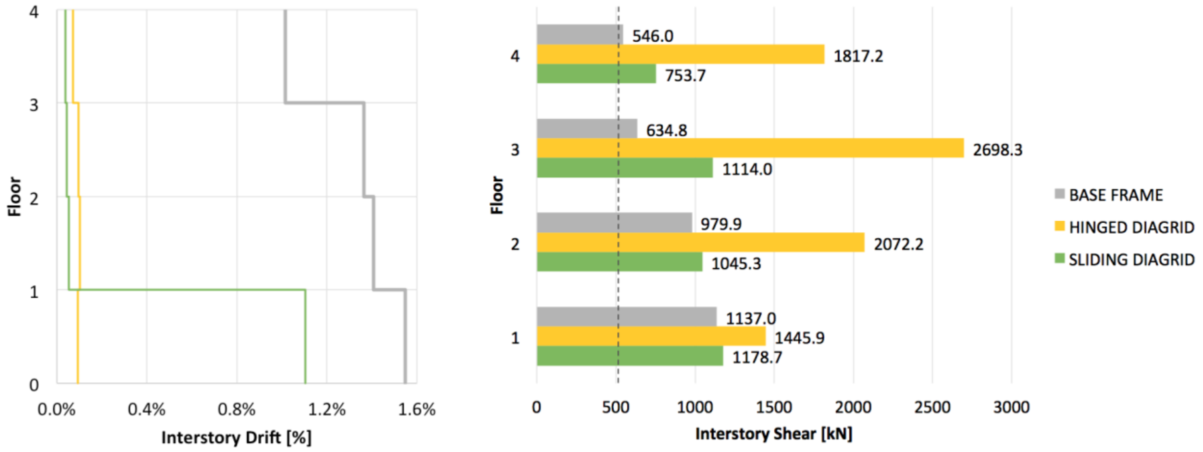


Figure 12 – Average interstorey drift and floor shear along the building height for different solutions

5. Concluding remarks

The present work is part of an ongoing research focusing on the holistic renovation of post-WWII European RC buildings, solving their main architectural, energy, and structural deficiencies, with the major aim of fostering a safe, resilient, and more sustainable society (Marini *et al.*, 2015a).In this scenario, this paper introduces an innovative technology for the seismic upgrading of these constructions, entirely carried out form outside the buildings, relying on diagrid exoskeletons. In particular, the potentialities of diagrids, a type of gridshell, as structural exoskeleton are explored.

Focusing on the sole structural point of view, 'wall' and 'shell' systems may be adopted for the global seismic retrofit of structures. 'Shell' solutions are shown avoid stress concentration in the additional elements and foundations, enabling a substantial reduction of the thickness of the additional skin.

Previous researches have shown that non-dissipative solutions may be considered more reliable than dissipative solutions for the seismic retrofit of existing RC buildings. This is due to the high stiffness of this kind of buildings and to the uncertainties connected in the definition of the numerical model of a frame in which non-structural elements play such an important role in the determination of the building response (Passoni, 2016). The behaviour of two kind of diagrids was studied in this paper: a) stiff hinged diagrids hinged at the base, that do not require any additional intervention on the existing building; and b) passive-adaptive diagrids changing their support conditions from hinges to sliding devices depending on the earthquake intensity, imposing a controlled soft-storey mechanism of the existing frame, thereby requiring preliminary interventions at the existing columns at the ground floor. The latter solution is specifically proposed for buildings located in high-seismicity areas, where the stiff hinged solution would imply extremely high seismic actions and special foundation systems.

The structural design of these two types of diagrids was discussed in this paper. A reference building located in a high-seismicity Italian city was selected, and both diagrid systems were designed in order to meet specific retrofit performance targets. By means of nonlinear time history analyses, the efficiency of the adaptive diagrid solution was highlighted through comparison with a stiff hinged diagrid.

As for the sustainability of the intervention, steel diagrids are conceived as totally demountable, modular, and provided with standardized connections. Such detailing enables maximum adaptability of the solution to future needs, including possible exterior reshaping, and easy maintenance and reparability. It also enables easier management of the construction at its end of life with easy disassembly and possible reuse or recycle of the structural components.

Ongoing developments of the research is focusing on the design of the rigid connections between the diagrid and the exoskeleton, and the engineering of the innovative sliding support of the passive-adaptive solution.

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