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# PREFABRICATED RESPONSIVE DIAGRIDS FOR HOLISTIC RENOVATION OF EXISTING MID-RISE RC BUILDINGS

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**Abstract.** *The holistic renovation of existing buildings is nowadays acknowledged as an essential and urgent action to reduce the environmental impact and increase the resilience of the existing building stock. Such holistic interventions envision the adoption of an exoskeleton, entirely built from outside. In this paper, the exoskeleton is designed as an external diagrid, consisting in a lattice structure. Among possible structural typologies, diagrids are particularly interesting for their remarkable architectural potential and for the possible standardization of the components, which highly increases replicability of the retrofit solution. Furthermore, prefabrication of components speeds up the assembly process and reduces the construction time. In the paper, focus is made on the dynamic behaviour of a retrofitted building featuring a responsive diagrid. The responsive behaviour is attained by changing boundary conditions at the diagrid's base supports as a function of the earthquake intensity, while the diagrid lattice structure remains elastic. At the Operational Limit State, the diagrid is designed as hinged at the base, whereas at Life Safety Limit State, beyond a target base shear, hinges are conceived to downgrade into non-linear supports allowing for the controlled sliding of the diagrid's base. Non-linear restraints limit the maximum base shear force, while avoiding excessive horizontal displacements and second order effects. Non-linear time history analyses are carried out to study the responsive behaviour of a reference 3 storey building strengthened with an external responsive diagrid. Results show that responsive diagrids require preliminary interventions at the existing building ground floor to reduce the damage following the onset of the diagrid sliding. Such interventions are for instance the disengagement of the infills from the RC frame and the local increase of the column ends ductility.*

# 1 INTRODUCTION

Nowadays, the refurbishment of existing buildings has become a priority to meet international targets of energy saving and emission control and to foster safety amongst European communities. The existing building stock accounts for 40% of the total EU energy consumption while emitting 36% of the $CO_2$ [1], mainly as the result of obsolete envelopes and technologies. These buildings show remarkable signs of decay, leading to poor housing conditions with thermal and living discomfort. From a structural point of view, 40% of European buildings have already exhausted their nominal structural service life (50 years). Moreover, having been built before 1970s, such buildings were often built without any seismic regulation. This scenario refers also to industrial facilities [2], where the majority of these structures have shown inadequate seismic performance [3]. Besides being a safety hazard, damage to buildings or their collapse following natural disasters 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 [4]. These considerations contributed to move towards a holistic and sustainable renovation approach [5] [6] [7] [8], where the intervention is aimed at improving seismic resilience as well as energy consumption and architectural renovation. Such multidisciplinary aspects are accounted for during each step of the design process.

To this aim, an additional exoskeleton is proposed, which integrates the structural elements for the seismic upgrading, the insulation layer, and the new architectural layer. The intervention is built entirely from the outside, thus avoiding the relocation of the building inhabitants and the inhibition of the building functions [9]. Moreover, prefabricated components, recyclable materials, and easily demountable, repairable, and adaptable technologies are adopted to increase the sustainability of the intervention and to reduce the $CO_2$ emission throughout the building life cycle.

In this paper, the exoskeleton is designed as an external diagrid, consisting of a lattice structure which can change boundary conditions according to the earthquake intensity; such behaviour is referred to as "responsive diagrid" hereinafter. The dynamic behaviour of a responsive diagrid is analysed in the paper, showing how this type of solution controls the seismic response of the existing building by dissipating energy into localized devices or elements.

# 2 DIAGRID

Traditionally, the seismic upgrading of existing buildings is pursued by adopting local or global strengthening. In general, global interventions are based on the construction of a new seismic-resistant structure. Such interventions are most effective and reliable from the structural point of view and do not necessarily require the demolition of the architectural finishings. Some traditional global solutions integrate the existing frames with RC shear walls or steel bracing systems [10] [11] [12] [13] [14] [15]; as an alternative, the seismic resistant structure can be obtained by reinforcing the existing concrete walls with high performance jackets [16], or by transforming a single bay of the frame into a seismic resistant shear wall by strengthening the infill wall.

When working from the outside, structural performance design targets can be attained by complementing the encasing exoskeleton with shear walls or, more innovatively, by conceiving and exploiting the shell behaviour of the new façade [9].

In the case of shear walls, the additional structural stiffness and strength are concentrated into few elements. Shear walls can either adhere to or be perpendicular to the existing structure, thus enabling maximum flexibility in the architectural restyling and in energy upgrading solutions.

Shear wall solution is the more traditional intervention; however, in areas of high seismicity, it may not be a viable solution due to the excessive length or to the significant number of walls. With the shell solution, the shape and extension are exploited to reduce the cross-section area of each single structural component [6] [7]. The envelope can be innovatively designed to enable both energy efficiency upgrade and structural safety. Structural shells may be continuous or discrete (gridshells). When gridshells constitute the exoskeleton of new high-rise buildings, they are referred to as diagrids [17]. In this paper, the concept of diagrid and exoskeleton is extended. In particular, a diagrid exoskeleton is here conceived as a new envelope designed for the seismic upgrading of an existing building. Moreover, the solution is designed to be adaptive and responsive.

## 3 ADAPTIVE-RESPONSIVE DIAGRIDS

Traditionally, seismic retrofit solutions can be designed as dissipative or non-dissipative over-resistant. Focusing on post-WWII RC constructions clustered in urban outskirts, non-dissipative solutions may be considered the most viable option. In fact, the presence of stiff masonry infill walls and stairwells leads to very stiff and brittle structures, which may collapse prior to the activation of a damping system [7]. However, when over-resistant, stiff façades are added on existing structures, the building stiffness increase may lead to a substantial increment of seismic actions, resulting in a remarkable overload of floor diaphragms and foundations. In this scenario, 'passive-responsive' structures are here proposed.

Responsive structures may be designed to act as stiff systems for the Damage Limit State, and as dissipative systems for the Life Safety Limit State, therefore avoiding the damage for low-intensity earthquakes and reducing the loads transferred to the floor diaphragms and to the foundations in case of strong earthquakes.

In order to exhibit such a behaviour, the responsive structures are conceived to change their boundary conditions as a function of the earthquake intensity. For low intensity earthquakes, the diagrid is designed as hinged at the base; for high intensity earthquakes, beyond a target base shear, the boundary conditions will downgrade into special non-linear supports allowing for the controlled sliding of the diagrid base. Activation of these supports significantly reduces the stiffness of the structure, thus increasing its fundamental period; as a result, seismic loads decrease and building displacements increase. An excessive horizontal displacement and second order effects are avoided by limiting the maximum displacement of the supports with a bumper at the end of the gap. A sketch of the retrofitted building is shown in Figure 1 along with a scheme of the sliding support.
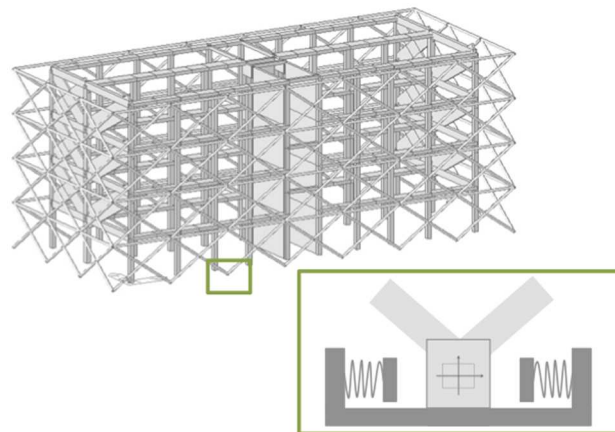


Figure1 –Sketch of the retrofitted building equipped with special sliding supports

The mechanism requires large displacement ductility of the first floor columns, which can be attained by deliberately creating and controlling a soft storey configuration (weakening the first level infills) and by increasing the columns rotational capacity (providing confinement, as for instance by means of fiber reinforced polymer wrapping or HPFRC Jacketing). The retrofitted building behaves as an isolated structure with the isolation concentrated at the ground floor to avoid an extensive damage of the existing structure.

This preliminary intervention allows to accommodate the displacements induced by the sliding system and to overcome all the uncertainties related to infills modelling and other details of the existing building, to the little knowledge of existing buildings, and to the correctness of the structural model [7]. Indeed, the controlled soft story behaviour will dominate the deformed shape of the building during the earthquake.

Thanks to the preliminary interventions, the maximum allowable inter-story drift at the first level represents the main design parameter considered in the retrofit.

## 4  APPLICATION TO A 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 is reported in Figure 2.
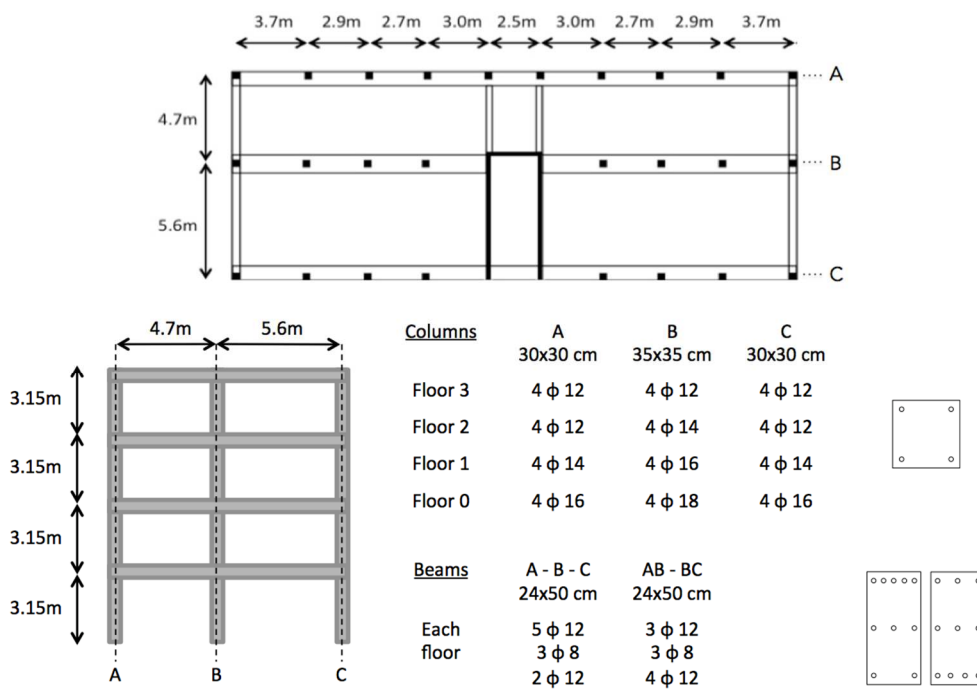


Figure 2 – Reference Italian building built in 1972, selected as representative of the European post-WWII RC building stock: plan view (top) and external transverse frame (bottom) of the 3D finite element model

The building is modelled as a tridimensional structure with the software MidasGEN v.2015 [18] (Fig.3a). The frame components are modelled as beam elements and the inelastic behaviour is accounted for by means of lumped plastic hinges. The flexural and shear resistance of the columns are both modelled with a degrading Takeda constitutive law [19]. The flexural plastic hinge is a trilinear curve followed by a degrading branch, and the shear plastic hinge has a linear

behaviour until the ultimate capacity; beyond that limit the curve decays very quickly thus exhibiting a sudden brittle mechanism. The ultimate shear resistance is also estimated according to the Italian [120] and European building codes [21]. In the beam, only the flexural plastic hinge is considered since the shear failure of these elements is very rare for the considered structural typology. The columns are fixed to the ground. The floors are modelled as rigid diaphragms [7] and the infill panels are modelled by means of two compression-only diagonal struts [22] converging in the beam-column joints. The hysteretic law describing the adaptive sliding support response in shown in Figure 3b where k is the stiffness, $F_y$ the yield strength, r is the post yield stiffness ratio, s the yielding exponent and o is the opening of the gap.

It is worth noting that the staircase core is not designed to withstand seismic loads; therefore, the staircase walls cannot be considered as RC seismic walls, but should be considered as stiff walls with low ductility. In the finite element model the staircase walls are modelled with beam elements whose non-linear behaviour is considered by lumped plastic hinge at each floor. The staircase foundation does not guarantee a fixed support and it is therefore modelled with rotational spring supports to account for the flexibility of the soil [5].



a)                                                          b)
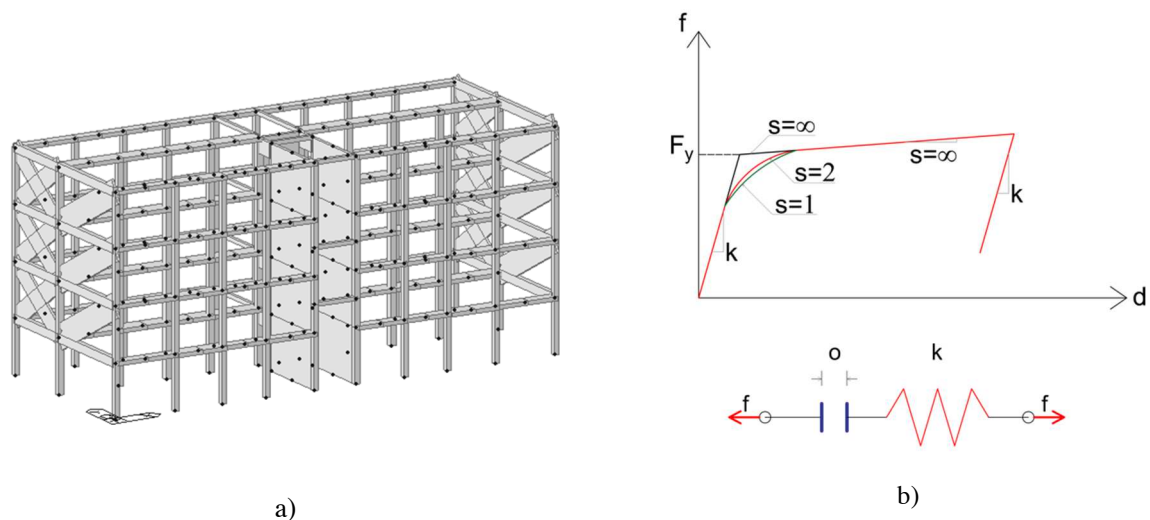
Figure 3 – a) Finite element model (MidasGEN v.2015); b) Hysteretic cycle of the sliding support as sum of an elasto-plastic support (top) and a gap system (bottom)

The Life-safety Limit State (LLS) is selected to define the performance level and the seismic input. In this case, due to the presence of the infills and staircase, a target drift of 0.1% is imposed to maintain the structure into the elastic range. Eventually a maximum shear flow at the foundation up to 150 kN/m is considered acceptable.

## 4.1 Design of innovative passive adaptive solution

The building is supposed to be located in a high seismicity zone (L'Aquila, Italy). According to the roof drift target (0.1%) associated to LLS, a commercial tubular profile with D=219.1mm and s=16mm is selected supposing a one-floor high grid module. An angle of about 35° is taken for the diagrid module, as it is considered the optimal angle for low-medium rise buildings according to Moon [23].

Regarding the new supports, they are designed as to be initially rigid and to behave as an elastoplastic system beyond a base shear flow of 60kN/m. In addition, an elastic bumper is provided

to limit the diagrid displacements at the ground level; the bumper is activated for base displacements greater than 20mm. The hysteresis shape of the diagrid base restraints is shown in Figure 4.
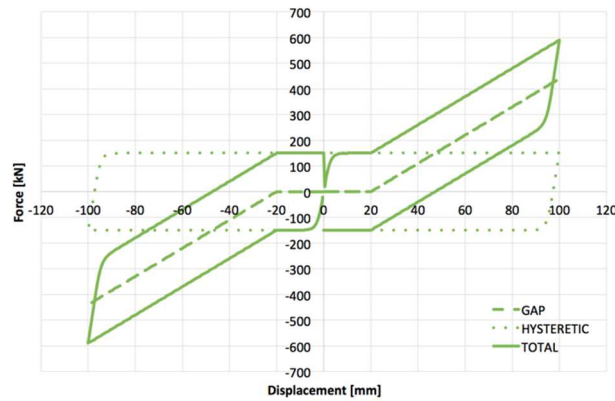


Figure 4 – Hysteretic cycle of the sliding support as sum of an elasto-plastic support (dashed line) and a gap system (dotted line)

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. In particular, vertical sliding joints are inserted in the masonry infills and in the RC walls of the staircase wells with a technique similar to what proposed by Preti et al. (2012) [24]. Moreover, in order to ensure the required ductility, the shear capacity and the end rotation ductility capacity of the columns are increased by means of fiber reinforced polymer 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.

Seven nonlinear time history analyses are performed on the retrofitted structure. Supposing the building is located in L'Aquila – with site class C and topology T1 –, a set of seven natural records compatible with NTC and EC8 spectrums are selected [25]. To evaluate the performance of the structure at the Damage Limit State (DLS), another set of accelerograms is adopted [25].

Results obtained for the adaptive diagrid solution are plotted in terms of total roof displacement and base shear in Figure 5a and 5b respectively, with reference to a single accelerogram for representation purpose. Figure 5a shows that the behaviour changes as soon as the target displacement is reached, with a consequent shift of fundamental period and change of the amount of displacement of the building. In the first part, the solution is stiff, the period is very short, and the displacements are very small. In Figure 5b, the base shear time histories of the bare frame and of the retrofitted building at the LLS and at the DLS are compared. It may be noted that the maximum value of the base shear is very close for both the considered limit states, thus the activation of the base sliders results in a significant reduction of the seismic action on the structure.

The hinge distribution resulting from the time history analyses (Fig.6) shows that there is no damage in columns at DLS. However, non-linear behaviour of the plastic hinges at the first level columns occurs at the LLS, in accordance with the activation of the non-linear supports. In both cases, there is no damage to the infills.

The average and maximum results of the seven accelerograms in terms of roof displacement and total base shear are shown in Figure 7.

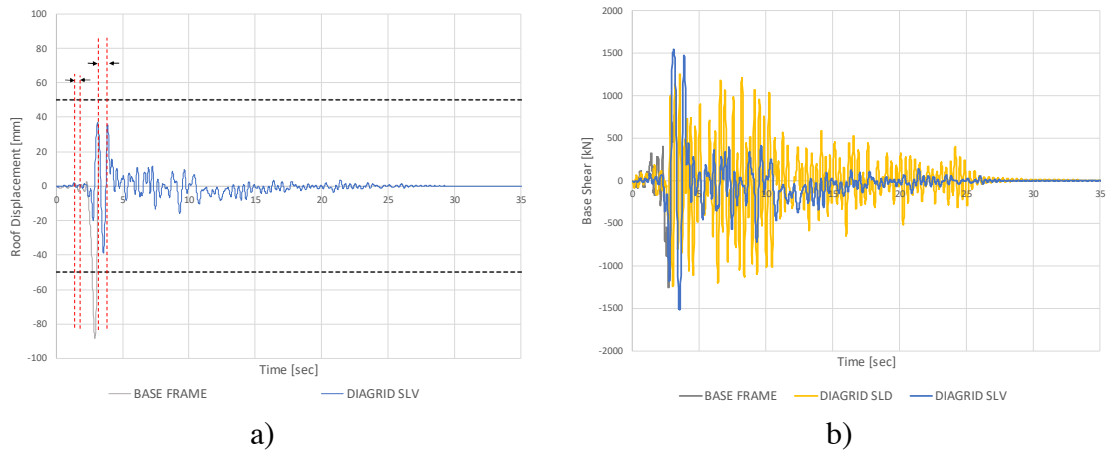a)                                                    b)

Figure 5 –Roof displacement at the Life Safety Limit State (a) and base shear (b) of the frame with the sliding diagrid solution at the Life Safety Limit state in comparison with the shear at the Damage Limit State
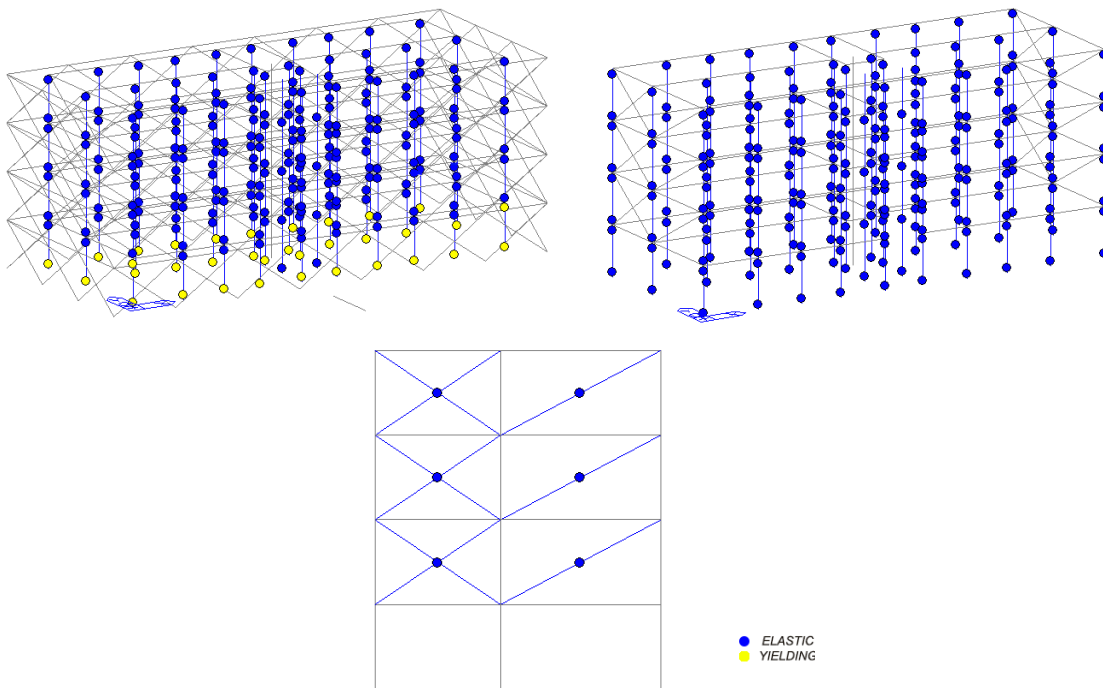


Fig. 6 Damage in the reinforced building at the end of the time history analyses: a) Columns plastic hinges at SLV, b) Columns plastic hinges at SLV, c) Infills plastic hinges in both cases.
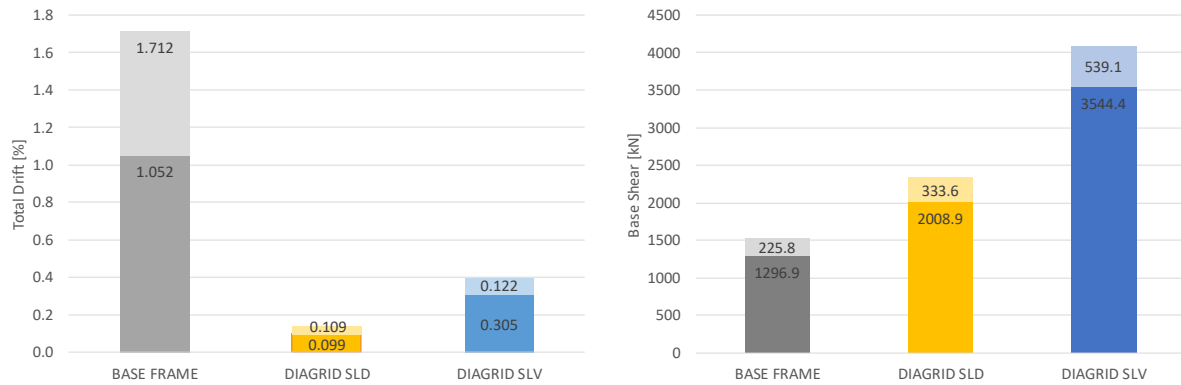
Figure 7 –Life Safety Limit State. Average and maximum roof displacement (left) and total base shear for the base frame SLV (grey), SLD (orange), SLV (blue)

Finally, the floor drift and floor shear are reported in Figure 8. The drift distribution shows how the building shifts to a soft storey mechanism in the adaptive sliding solution at the Life Safety Limit.

As for the floor shear loads, the capacity of existing floors to transfer the seismic action from the floor diaphragms to the vertical resisting structure should be verified. Recent research has shown that even the heterogeneous beam and block floor systems (UNI EN 15037) may resist low-medium seismic loads by developing a tied-arch resistant mechanism [5] [7]. Considering the reference case study after retrofit, the shear capacity of the floors is about 625 kN. Although the floor loads are reduced with the sliding diagrid solution with respect to a traditional stiff solution, the retrofit of the existing floor diaphragms is still required.
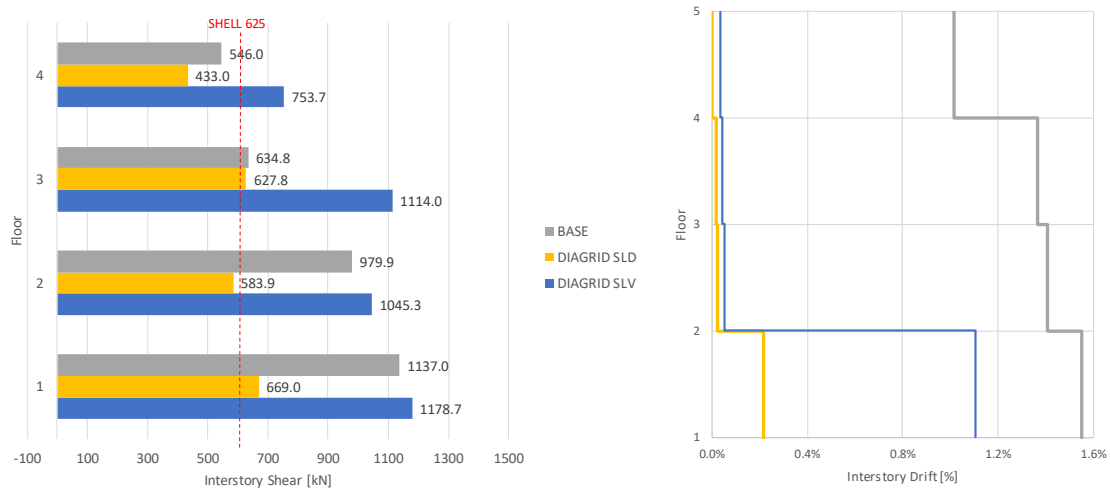


Figure 8 – Average inter-storey drift and floor shear along the building height for different solutions

## 5   CONCLUSION

The present work is part of an ongoing research focusing on the holistic renovation of existing buildings. In this study the feasibility of structural retrofit from outside is currently being evaluated considering European RC buildings. Preliminary results of the analyses highlighted that there are some aspects that may represent an obstacle for the seismic retrofit from outside, as for instance extremely high seismic actions and the need of special foundation system [7]. In

this context the performance of passive-adaptive diagrid has been presented herein. In general, diagrids present great flexibility in construction geometry, and may be easily coupled with the energy and architectural retrofit. Diagrid elements are conceived as totally demountable, modular and provided with standardized connections.

The "responsive diagrid" retrofit technique presented herein consists in a lattice structure conceived to change its ground boundary conditions from hinges to sliders depending on the earthquake intensity, allowing a controlled soft-story mechanism of the existing structure. The existing structure requires preliminary interventions at the ground floor, such as the increase of the deformation capacity of the first level columns and infills.

It is important to note that the performance evaluation of a retrofit solution is affected by the non-structural elements modelling. The proposed retrofit scheme overcomes all the uncertainties related to the infill models thanks to the controlled soft-story behaviour that will dominate the inelastic deformed shape of the structure.

A reference building located in a high-seismicity Italian city has been selected, and a diagrid system has been designed to meet specific performance targets. The diagrid behaves as hinged at the base at the Damage Limit State; conversely, beyond a target base shear, the boundaries downgrade into special non-linear supports. By means of nonlinear time history analyses the behaviour of adaptive diagrid solution has been examined. The comparison of the structural response of the retrofitted frame at the Damage Limit State and at the Life Safety Limit State has been evaluated.

The results show that the responsive-diagrid avoids damage at the Damage Limit State. After exceeding the design target, the activation of the non-linear support limits the maximum base shear and the damage above the first level while avoiding excessive horizontal displacement at the ground floor. This also allows to meet specific performance targets in terms of damage distribution, inter-storey drift and base shear. The seismic inertia loads in the floors need to be transferred to the diagrid system. The in-plane shear transfer capacity of existing floors needs to be evaluated. Indeed, in the case demand exceeds capacity, specific floor strengthening interventions need to be implemented.

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