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Application of low-invasive techniques and incremental seismic rehabilitation to increase the feasibility and cost-effectiveness of seismic interventions

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Abstract

The high seismic risk connected to the existing construction heritage requires a wide-scale renovation action to ensure structural resilience and avoid future human and economic losses. Given the urgency and the scale of the problem and the lack of available resources, a new strategy for the renovation of the obsolete European building stock should be envisioned, accounting for both safety and environmental, social and economic sustainability. This research aims at exploring new cost-effective seismic retrofit solutions based on the principles of low-invasiveness and incremental seismic rehabilitation, as envisioned by FEMA P-420 (2009). The incremental rehabilitation approach allows to plan repair and retrofit actions along with the maintenance works expected during the building's lifetime, thereby spreading them in time and reducing costs. In addition, low-invasiveness of the solutions is required to reduce the impacts on the functionality of the building, thus cutting the costs connected to downtime. A possible solution is represented by the introduction of an exoskeleton entirely carried out from outside. In this paper, a new sustainable technique is proposed, where the existing structure is connected to a self-supporting exoskeleton adopting demountable dry techniques, which may be assembled and activated in different phases of the building lifetime. As a proof of concept, the approach is then applied to a school building.

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Keywords: Incremental rehabilitation; seismic retrofit; renovation strategy; low-invasive techniques; life cycle thinking; diagrid; school buildings.

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1. Introduction

In the last years, the balance of earthquake damages and victims worldwide is impressive (www.bbc.com, www.europarl.europa.eu). Considering the Italian territory, from August 2016 to mid-January 2017, magnitudes 5.9 to 6.5 earthquakes hit the Apennine chain in Central Italy (Abruzzo, Lazio, Marche, Umbria), 333 people died during these earthquakes and more than 30'000 people were relocated. Before these events, at least 300 people were killed on 6th April 2009, when a magnitude 6 earthquake struck the historic Italian city of L'Aquila. These are just examples highlighting the seismic vulnerability of the existing building stock and the required deep renovation actions to enhance safety. From a structural point of view, about 40% of the existing buildings in Europe were built before the 1960s, so they have already exhausted their nominal structural service life (50 years), moreover, such buildings do not follow any seismic regulation. Additionally, the existing building stock has a great impact on the environment, being responsible for 40% energy consumption and 36% CO₂ emissions in Europe (Marini et al., 2014). The structural vulnerability of such structures worsens then the situation, because the building collapse after a natural disaster has a great impact on the environment in terms of waste production and CO₂ emissions (Belleri & Marini, 2016).

In order to face these issues, two main strategies may be applied: demolish-and-rebuild or renovating the existing building. Under a sustainable perspective, however, it is necessary to account for some aspects when considering rebuilding. First, the construction of new buildings may require the use of new soil, the production of new materials, and thus the increase carbon dioxide emissions. Besides, the disposal of existing construction materials represents a very important issue nowadays. If demolition is thus not mandatory due to structural decay and obsolescence, the sustainable renovation of the existing building stock fostering safety, resilience, and sustainability should always be preferred (Marini et al., 2017). Despite the seriousness of the present situation and the great efforts put by the European Community for a more sustainable society, the average renovation rate of the reinforced concrete building stock is still only 1% (Economidou et al., 2011). The major barriers to renovation are the need for the inhabitant relocation, the excessively time-consuming interventions, often requiring long disruption of the building activities, and the high cost of the intervention (La Greca and Margani, 2018).

In order to overcome these barriers, a new holistic approach has been studied in the last years (Marini et al., 2016; Marini et al., 2017), proposing interventions carried out from outside, thus avoiding the users' relocation and minimizing the costs due to the partial demolition of building finishing. An example of solutions carried out from outside are diagrid solutions, which are structural exoskeletons usually adopted for high-rise buildings but recently proposed for the holistic renovation of the existing building stock (Passoni et al., 2016; Labò et al., 2017). Such solutions have indeed a remarkable architectural potential allowing maximum freedom in the remodeling of the building facades and the inclusion of new living spaces. In addition, they are sustainable dry technologies in agreement with the life cycle thinking (LCT) principles of demountability, recyclability, easy reparability and adaptability. As to further increase the feasibility of retrofit interventions, another strategy consists in spreading realizations and costs over years by adopting an incremental rehabilitation strategy (FEMA P-420, 2009). Light pre-fabrication of components and standardized connections of diagrid solutions make it a suitable solution for the adoption of incremental rehabilitation plans.

In this paper, incremental seismic rehabilitation principles have been explored and combined with the concept of renovation from outside, aimed at increasing the feasibility and cost-effectiveness of seismic retrofit interventions. The concept of minimum intervention to guarantee a minimum level of safety has been introduced for the first time in the incremental rehabilitation framework. This approach is then applied with reference to an existing school building, located in Northern Italy. A diagrid structure has been designed as seismic retrofit solution, the intervention has been split into steps following two different approaches and the minimum intervention has been selected.

2. Incremental seismic rehabilitation and principle of minimum intervention

The **incremental seismic rehabilitation** approach integrates an ordered series of discrete actions into ongoing facility maintenance over an extended period of time (FEMA P-420, 2009). It allows planning repair and retrofit actions along with the maintenance works expected during the building's lifetime, thereby spreading them in time and reducing initial costs and disruptions, and so the intervention initial impact.

While in Europe this approach has not been deeply envisioned yet, in the US some scientific research institutes together with the Federal Emergency Management Agency (FEMA) have already explored such strategy of intervention; as a result, they published some manuals for both building owners and design professionals. The main concept, starting from the mentioned barriers to seismic interventions, is that *incremental improvement is better than delayed improvement or no improvement at all*, and that *seismic retrofit would occur more frequently in existing buildings if initial costs and functional disruption could be reduced* (FEMA P-420, 2009).

As previously discussed, when possible, renovation represents a smarter and more sustainable strategy to solve the deficiencies of the existing building stock. Renovation can be pursued mainly in two ways, in a more traditional single-stage intervention or through an incremental rehabilitation.

When the intervention is carried out in a single step, all the economic investments and disruptions happen at once, and all the retrofit objectives are reached at the same time. On the other hand, incremental rehabilitation allows spreading the investment over time, while disruption is less invasive because associated with planned maintenance works. In this way, retrofit objectives are not reached at once, but following some steps (Figure 1).

When this second way is pursued, it is required that each retrofit action provides a positive contribution to structural behavior and that no action leaves the building worse than before; it is also required that single intervention avoid introducing structural and geometrical irregularities in the building. Furthermore, the guidelines specify that rehabilitation measures should be prioritized based on some structural, use, and integration issues with other programmed maintenance interventions. In this research, structural priority earns higher relevance following the principle that first retrofit actions should be those that have a high impact on the safety of inhabitants and prevent from heavy losses. A new concept to be combined with incremental rehabilitation is thus introduced, that is, the definition of **minimum intervention**. In fact, the order of retrofit actions should be planned according to the definition of some level of safety and performance to be guaranteed, especially for the first step of the process (Figure 1).

The minimum intervention can be defined as such intervention that completely removes the main critical aspects and so the heavy potential casualties, as building collapse and risks for inhabitants. To define a minimum intervention, it is necessary to investigate the seismic vulnerabilities of the building and identify those repair actions that solve the main ones. Those actions cannot be defined a priori for any building, but they would depend on the kind of structure and on its level of safety.

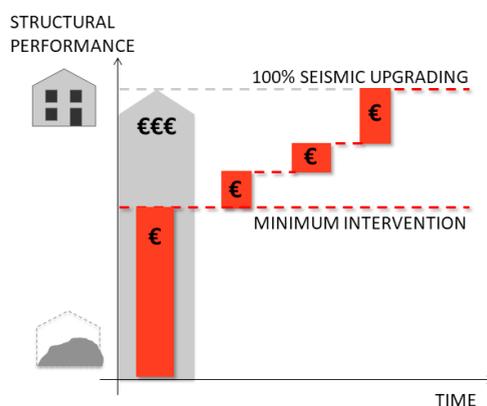


Fig. 1. Incremental seismic rehabilitation and definition of the minimum intervention

Incremental seismic rehabilitation, together with the definition of minimum intervention, would thus allow reaching a minimum level of safety in many buildings, avoiding structural collapse and so the loss of human lives in a pretty short time; the renovation of building stock will then be completed in a longer period of time.

This strategy would represent a fundamental investment not only for building owners but also for the whole community. Incremental seismic rehabilitation is, in fact, more suitable for large-size structures or those structures that many people use in daily life, like public services as health and education or workplaces. For those structures, a one-stage retrofit intervention would require a very long time and a large initial capital investment, which often represent an insurmountable barrier. In addition, this strategy is useful for those building typologies that have limited period of inactivity, which may be exploited for the retrofit works.

As an example, some building typologies suitable to be renovated through this innovative approach are:

- Hotels and tourist establishment, where intervention can be planned during low season periods.
- Hospitals, where interventions can be localized in some specific area, to reduce consumer disruption.
- Office buildings, exploiting summer and holiday closure.
- Industrial buildings, even if disruption period is limited in time, few specific minimal actions can be planned to reduce seismic risk, safeguarding workers lives.
- School buildings, where closure periods during summer holidays are quite long and regular in time.

Especially for school buildings, today, energy and technological upgrading is always more necessary, being often management cost the main expense for such buildings. A holistic energy and structural retrofit may thus be proposed as to solve contextually all the building deficiencies. In addition, as to increase the economic and social sustainability of the solution, the intervention may be carried out from outside, planned in some incremental steps, and be respectful of LCT principles, thus following all the principles presented in this paper. In the following paragraph, a reference school building is analyzed and a retrofit intervention is proposed. An additional exoskeleton is conceived to be applied entirely from outside. The proposed retrofit intervention is divided into some steps in order to reach firstly an acceptable level of safety (i.e. minimum intervention) and then a complete retrofit solution suitable to spread costs over time.

3. Incremental seismic rehabilitation: application to a reference building

Incremental rehabilitation principles introduced in the previous paragraphs and by FEMA 395 (Incremental Seismic Rehabilitation of School Buildings) (2003) could be easily applied in scholastic buildings because of the possibility to realize the interventions during the summer closing period.

An application of these principles is here made with reference of a school located in Brescia (Northern Italy). The school is a three-story rectangular RC precast structure typical of the Italian scholastic architecture of the ‘90s. The structure is composed of three one-way longitudinal frames and no transversal lateral frames. The geometry of the building is reported in Figure 2 along with the details of the RC frame elements and the materials. The information was derived from the original construction documents.

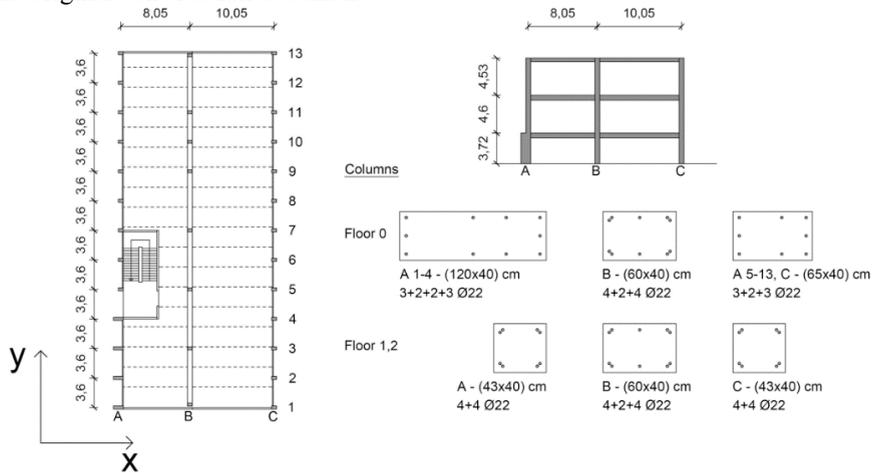


Fig. 2. Geometry and materials of the main frame

The building is modeled as a three-dimensional structure with the software MidasGEN v.2017 (Midas GEN, 2017); the frame components are modeled as beam elements and the inelastic behavior is accounted for by means of lumped plastic hinges calculated in accordance with the Italian Building Code (NTC, 2008). In particular, for the columns, both shear and bending behavior are considered by introducing Takeda Tetralinear plastic hinges (Otani, 1974). The shear behavior has been assumed to be elastic up to the capacity of the element and then decay very quickly in order to represent an extremely fragile collapse. The flexural plastic hinge is a trilinear curve followed by a degrading branch. Floor slabs are considered as rigid diaphragms, and the structure is fixed at the base.

The building is located in Brescia, on a soil category C and topography class T1 with reference to the Italian Building Code (NTC, 2008). The capacity curve of the reference building has been evaluated through pushover analysis along the weakest direction (Y in Figure 2); indeed, in X direction the first columns of the A alignment (Figure 2) have bigger dimensions and the non-structural elements contribute to improve the building response in terms of strength and stiffness. The Life-safety Limit State (LSLS) is chosen to define the performance level and the evolution of the inelastic behavior of the structure. As shown in Figure 3, the reference building does not satisfy the displacement demand and, therefore, a structural retrofit is required. In addition, considering both the precast nature of the building and the limited capacity of the beam-column connections, it is necessary to carefully evaluate the structure deformability in order to avoid the loss of the beam support. Considering that actual connections are not compatible with maximum interstory drift greater than 2%, the structure is not verified at the LSLS (Figure 4).

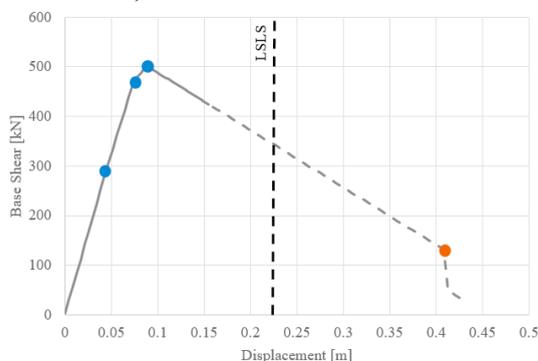


Fig. 3. Capacity curve of the existing building; Blue dots: progressive yielding of the columns. Red dot: soft-story collapse mechanism.

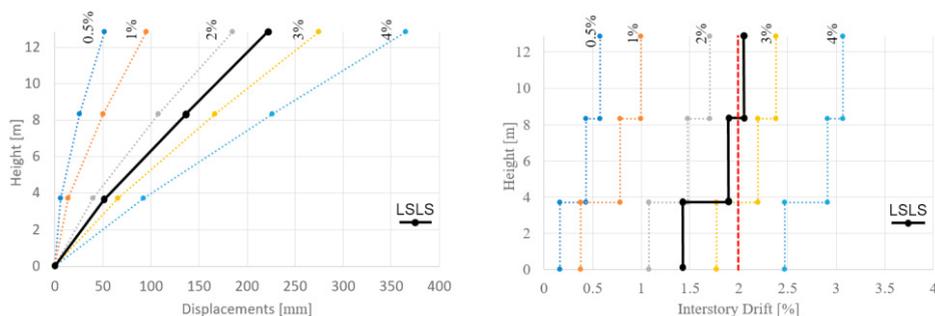


Fig. 4. Story displacement (left) and interstory drift (right) due to different displacement history. In percentage the ratio between the top displacement of each displacement history and the top displacement of the capacity curve peak.

3.1. 3.1-Retrofit solution

A target drift of 0.5% is imposed in the retrofit design procedure to maintain the structure into the elastic range and to reduce the damage into non-structural elements following the principles of reparability and demountability typical of LCT. In order to achieve the retrofit objectives, the holistic diagrid retrofit solution has been adopted (Labò et al., 2017). The diagrid structure can be carried out from outside and easily integrated with energy efficiency systems and architectural aspects. In detail, according to the roof drift target (0.5%), a commercial tubular profile with $D=168.3$ mm and $s=8$ mm is selected supposing a grid module spanning half-floor high. An angle of about 40° is taken for the diagrid module, as it is considered the optimal angle for low-medium rise buildings according to Moon (Moon, 2008). The diagrid is designed as to minimize the invasiveness and the weight of the external structure; in particular, in this case, controlled buckling of some elements has been considered. In order to evaluate the behavior and the effectiveness of the retrofitted solution, a non-linear static analysis and non-linear time history analyses were carried out. As for non-linear dynamic analyses, using the software REXEL 2.2beta (Iervolino, Galasso, & Cosenza, 2010), compatible combinations with the Brescia response spectrum at the Life Safety Limit State (LSLS) were determined.

In this case, a maximum scale factor of 2 and upper and lower tolerance equal to 30% and 10% have been imposed. In Figure 5 the chosen combination is reported. The capacity curve resulting from the pushover analysis is reported in Figure 6. The seismic behaviour of the structure is significantly improved; in particular, the hinge distribution reports no damage in columns at the considered limit state but just the buckling of some diagrid diagonals at the ground floor.

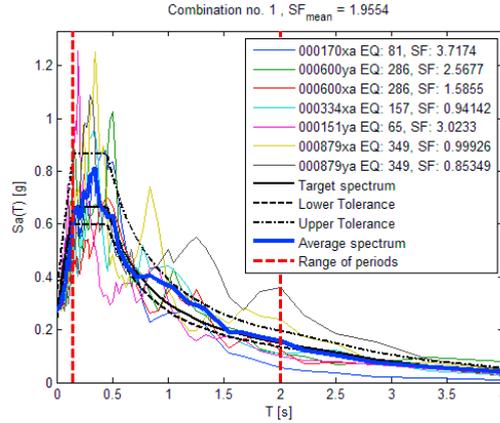


Fig. 5 Sets of seven records considered in the nonlinear dynamic analyses (from: REXEL 2.2beta - Iervolino, Galasso, & Cosenza, 2010)

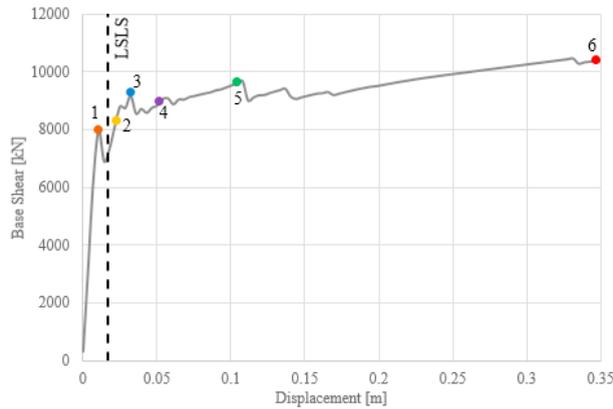


Fig. 6 Capacity curve of the retrofitted building: 1. controlled buckling of some diagrid diagonals at the ground floor, 2. yielding of the first diagonal, 3. buckling of all the ground floor diagonals, 4. yielding of some columns 5. First-floor diagonal buckling, 6. Column failure. Dotted line: LSLS displacement demand.

The average results obtained from the 7-non-linear time history are plotted in terms of total roof displacement and interstory drift of the bare frame and of the retrofitted structure in Figure 7. As a result, a significant displacement reduction of the retrofitted structure is observed, which respects the target of 0.5% of interstory drift and guarantees the elastic behavior of the existing building, thus resolving the previously evaluated vulnerabilities.

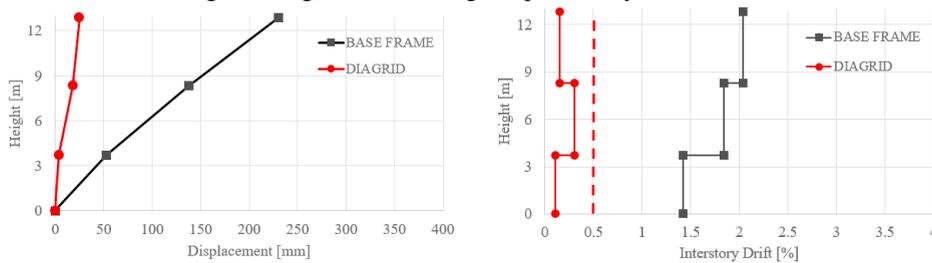


Fig. 7. (left) Story displacement and (right) interstory drift of the retrofitted building in the LSLS displacement configuration.

3.2. 3.2-Incremental Retrofit solution

Once the retrofit solution has been designed and its effectiveness verified, different incremental rehabilitation strategies have been considered; in particular, two different incremental approaches are presented and evaluated through non-linear static analyses.

The first solution (CASE A) plans to connect each floor at a time, therefore completing the intervention in three incremental steps. This is an effective solution in order to ensure an improvement in the global behavior at each incremental step, without introducing new vulnerabilities in not-retrofitted floors.

The second solution (CASE B), instead, is vertically developed, retrofitting, in the first step, part of the Y direction in order to fix the main vulnerabilities of the structure in the weakest direction. Subsequently, with the second step, the two façades in the X direction are completely retrofitted in order to solve also the vulnerabilities associated with the less vulnerable direction. Finally, with the third incremental step, the retrofit solution is completed in the Y direction. Through a step-by-step evaluation of the structural behavior obtained from the Pushover analysis for both the strategies described (Figure 8), a gradual improvement of the incrementally retrofitted building has been highlighted demonstrating the structural feasibility of the incremental seismic rehabilitation plan.

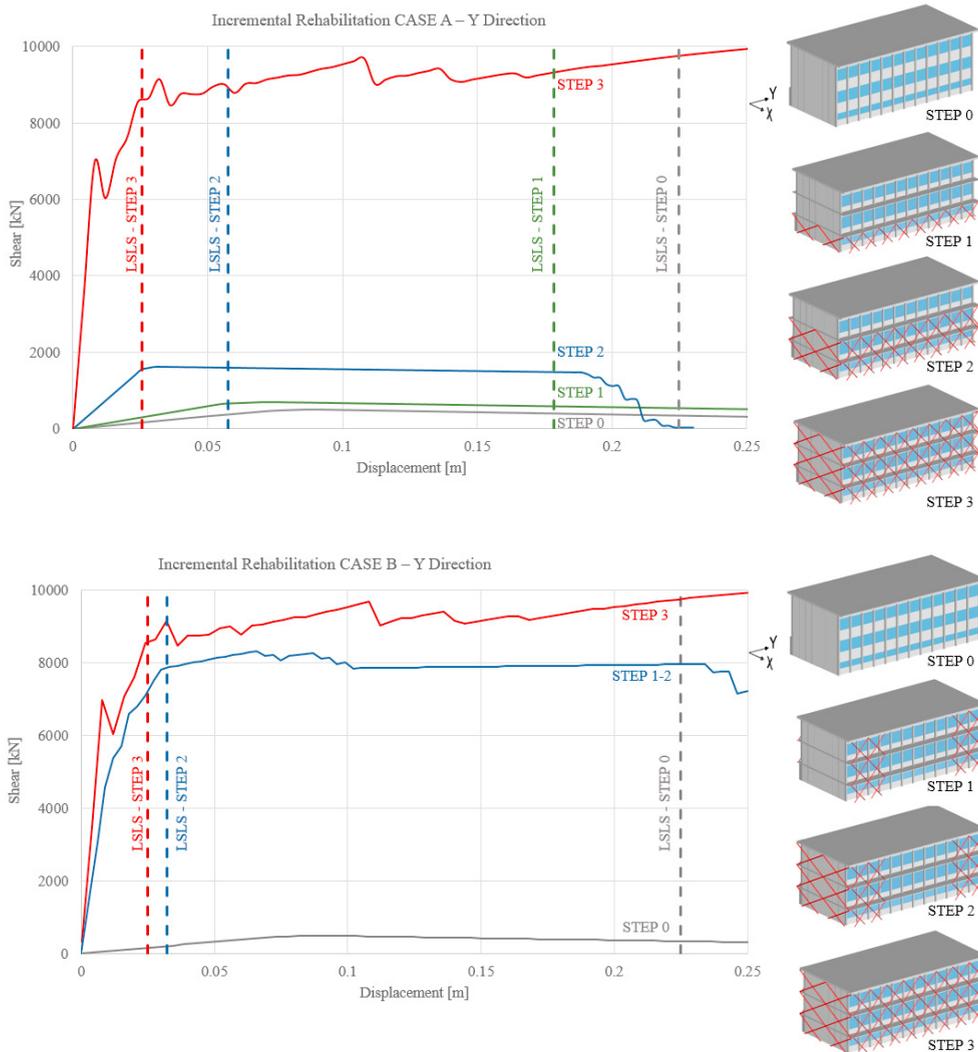


Fig. 8. Capacity curves of the incrementally retrofitted buildings and the relative displacement demands for the case A and case B respectively. 0. Existing building, 1,2,3 First, second, and third steps of the two selected incremental strategies.

3.3. 3.3-Minimum intervention

The minimum safety level of the intervention is then evaluated, aimed at avoiding the structural collapse and guaranteeing the inhabitants safety. To choose the minimum intervention target, the design criterion should focus on the vulnerabilities found in the weakest direction (Y).

In particular, in this case, the worst potential damage is the excessive deformability that leads to the loss of beam support. Therefore, considering the maximum displacement capacity of the existing connection equal to 2%, an interstory drift of 1.5% has been chosen as the first incremental step limit to reduce the existing building displacements. Eventually, through 7 Time History analyses, the two proposed incremental strategies have been evaluated as reported in Figure 9.

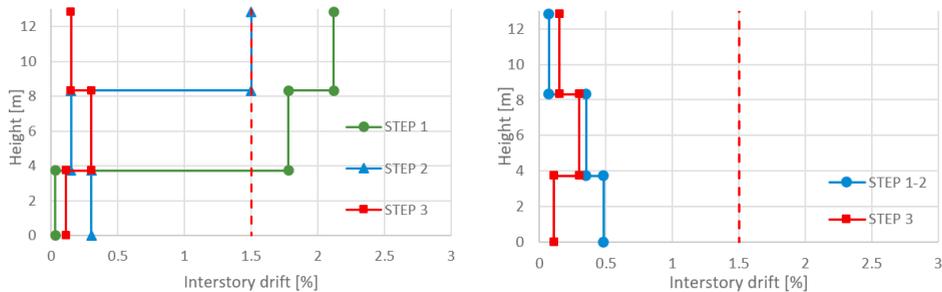


Fig. 9. Interstory drift of the retrofitted building in the LSLS displacement configuration for each step in case A (left) and in case B (right).

As shown, in CASE A the minimum intervention would consist in completing the first two incremental steps, or the first two diagrid levels. On the contrary, for CASE B, the first step is sufficient to guarantee the target displacement imposed. Under an economic point of view, this would mean that for the CASE A it is sufficient the 69% of the total weight of the steel needed for the complete diagrid to reach the minimum level of safety, and for the CASE B the 26%.

4. Conclusions

This work is part of an ongoing research on the integrated retrofit of the post-WWII RC buildings solving their main architectural, energy, and structural deficiencies, with the major aim of fostering a safe, resilient, and more sustainable society. In particular, a retrofit solution, carried out from outside and in agreement with the Life Cycle Thinking (LCT) principles have been here explored.

Above all, in this paper, an incremental rehabilitation strategy is applied to spread construction costs and downtime over time by adopting a diagrid solution. Additionally, the concept of minimum intervention has been introduced, with the aim to reach a minimum level of safety in the building heritage in a pretty short time. In this perspective, the first step of the incremental process should be conceived as the minimum intervention required to avoid heavy human and economic losses. In particular, incremental seismic rehabilitation has been here applied to a school building. More precisely, focusing mainly on structural aspects and incremental rehabilitation principles, two different strategies have been evaluated and the concept of minimum intervention has been selected for this structure. Finally, based on these principles, the best retrofit strategy has been determined. Through this case study, the benefits associated with the incremental rehabilitation approach have been shown, and the importance of the minimum intervention to make this strategy even more efficient has been highlighted.

The incremental seismic rehabilitation can represent also an innovative approach under a social perspective because everyone has a specific role in the decision-making and strategy planning process. Capital investments for seismic renovation would be accepted more easily by owners because combined with ordinary investment on building capital value. Incremental rehabilitation can thus represent a good answer to the urgent need of renovation of Italian and European building stock.

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